National Park Service
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Assessment of Natural Resource Conditions
Sleeping Bear Dunes National Lakeshore

Natural Resource Report NPS/NRPC/WRD/NRR—2009/097

ON THE COVER
View from the Dune Overlook on the Pierce Stocking Scenic Drive, including the Sleeping Bear Dunes, the parking lot for the Dune Climb, Day Mill Pond, Little Glen Lake and the surrounding hills, and Lake Michigan's Sleeping Bear Bay.
Photograph by Dave Mechenich

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Commonly Used Abbreviations

AIRS/AFT	Aerometric Information Retrieval System Facility Subsystem
AIS	aquatic nonindigenous species
BBD	beech bark disease
BLDHD	Benzie-Leelanau District Health Department
BP	before present
BTEX	benzene, toluene, ethylbenzene, and xylene
C	Celsius
CAA and CAAA	Clean Air Act and Clean Air Act Amendments
CASTNet	Clean Air Status and Trends Network
CE	climate envelope
cm	centimeter
CPI	Change Potential Index
CPOM	coarse particulate organic matter
DO	dissolved oxygen
DOC	dissolved organic carbon
DR	disturbance regime
EA	even-aged
EAB	emerald ash borer
EPT	Ephemeroptera-Plecoptera-Trichoptera index
ERD	Environmental Response Division
ESRI	Environmental Systems Research Institute
FPOM	fine particulate organic matter
FRI	fire return interval
GCM	general circulation model
GLENDA	Great Lakes Environmental Database (USEPA)
GLERL	NOAA Great Lakes Environmental Research Laboratory
GLIFWC	Great Lakes Indian Fish and Wildlife Commission
GLKN	Great Lakes Inventory and Monitoring Network
GWPC	Ground Water Protection Council
ha	hectare
HACCP	Hazard Analysis and Critical Control Point
HFO	heavy fuel oil
HUC	Hydrologic Unit Code
HWA	hemlock woolly adelgid
IADN	United States-Canada Integrated Atmospheric Deposition Network
IFMAP	Integrated Forest Monitoring Assessment and Prescription
IJC	International Joint Commission
IMPROVE	Interagency Monitoring of Protected Visual Environments
INDU	Indiana Dunes National Lakeshore
IPCC	International Panel on Climate Change
kg	kilogram
km	kilometer
L	liter

Commonly Used Abbreviations (continued)

L sec^{-1} m^{-1}	liter per second per meter (measure of specific capacity)
LaMP	lakewide management plan
LMMBP	Lake Michigan Mass Balance Project
LMTC	Lake Michigan Technical Committee
LP	Lower Peninsula (of Michigan)
LTA	landtype association
LUST	leaking underground storage tank
m	meter
$m^3 day^{-1}$	cubic meters per day
$m^3 sec^{-1}$	cubic meters per second
$m^3 year^{-1}$	cubic meters per year
MCGI	Michigan Center for Geographic Information
MDCH	Michigan Department of Community Health
MDEQ	Michigan Department of Environmental Quality
MDN	Mercury Deposition Network
MDNR	Michigan Department of Natural Resources
MEC	Michigan Environmental Council
MEDC	Michigan Economic Development Corporation
mg/L	milligram per liter (part per million)
MIRIS	Michigan Resource Information System
MLCVEF	Michigan League of Conservation Voters Education Fund
MNFI	Michigan Natural Features Inventory
MSU	Michigan State University
MTBE	methyl tertiary butyl ether
MTESP	Michigan Turfgrass Environmental Stewardship Program
N	nitrogen
NADP	National Atmospheric Deposition Program
NADP NTN	National Atmospheric Deposition Program National Trends Network
NCDC	National Climatic Data Center
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NOx	nitrous oxides
NPDES	National Pollutant Discharge Elimination System
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NWMCOG	Northwest Michigan Council of Governments
NWMOWTF	Northwest Michigan Onsite Wastewater Task Force
NWI	National Wetlands Inventory
NWR	National Wildlife Refuge
OSDS	onsite sewage disposal system
OSRW	outstanding state resource water
PAH	polyaromatic hydrocarbon
PCB	polychlorinated biphenyl
PM	particulate matter

Commonly Used Abbreviations (continued)

PWC	personal watercraft
SLAMS	State and Local Air Monitoring Network
SLBE	Sleeping Bear Dunes National Lakeshore
SLSMC	St. Lawrence Seaway Management Corporation
SPM	Special Purpose Monitoring (air station)
SSURGO	Soil Survey Geographic database
TMDL	total maximum daily loading
TN	total nitrogen
TP	total phosphorus
TRI	toxic release inventory
TSI	Trophic State Index
UEA	uneven-aged
µg/L	microgram per liter (part per billion)
µS/cm	microSiemens per centimeter (units of specific conductance)
UP	Upper Peninsula (of Michigan)
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USDA ERS	United States Department of Agriculture Economic Research Service
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
USGAO	United States General Accounting Office
USFS	United States Department of Agriculture, Forest Service
USGS	United States Geological Survey
VHS	viral hemorrhagic septicemia
VOC	volatile organic compound
WDNR	Wisconsin Department of Natural Resources
WQI	Water Quality Index
WRD	NPS Water Resources Division
WTD	white-tailed deer

Executive Summary

Sleeping Bear Dunes National Lakeshore (SLBE) is located on the eastern shore of Lake Michigan in the northwestern part of Michigan's Lower Peninsula. SLBE is 28,851 hectares (ha); 24,067 ha of land and 4,784 ha of water. The land category consists of 23,206 ha of federal land and 5,644 ha of nonfederal land. The water category includes 4,293 ha of Lake Michigan extending 0.4 kilometers (km) from shore (NPS 1999b; NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., January 2009). SLBE consists of four mainland units (the Bow Lakes, Mainland-North, Mainland-Central, and Mainland-South Units) and two large islands (North and South Manitou). SLBE encompasses 104 km of Lake Michigan shoreline: 49.5 km on the mainland, 33.8 km on North Manitou Island, and 20.7 km on South Manitou Island.

SLBE lands are included in nine townships in Benzie and Leelanau Counties. A part of the 61,510 ha watershed upgradient from the park boundary extends eastward into Grand Traverse County in the Platte River basin. Approximately one-fourth of the watershed is managed by the state of Michigan, including 14,968 ha in the Pere Marquette State Forest (MDNR 2001). A Manitou Passage underwater preserve includes 730 km^2 of Lake Michigan bottomland and includes the wrecks of 16 ships (State of Michigan 1989; Michigan Underwater Preserve Council 2004).

Evidence of human use of the SLBE area dates back more than 10,000 years to when Paleo-Indian people hunted game during the retreat of the last glaciation (Lovis 1984). Today, SLBE has well over a million visitors each year. The highest number occurred in 1999, with 1,364,834 visitors; for 2007, the number was 1,134,314. For 2008, SLBE had forecasted 1,147,662 visitors, a 1.2% increase over 2007 (NPS 2008a); however, in November 2008 visitor numbers were expected to be down significantly from 2007 (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

The five-county region of northwest Michigan that includes Benzie and Leelanau Counties as well as Antrim, Charlevoix, and Grand Traverse Counties has experienced "phenomenal" population growth, growing by 66% from 1970-2000 and by 23% in the 1990s (NWMCOG 2004). It is expected to grow another 15% by 2010 and an additional 10% by 2020 (NWMCOG 2004). The highest densities are mostly found around large lakes, including Long Lake in Grand Traverse County, Platte Lake, and Glen Lake.

SLBE was established in 1970 by Public Law 91-479 (later amended by Public Law 97-361 in 1982) in recognition of "certain outstanding natural features, including forests, beaches, dune formations, and ancient glacial phenomena [that] exist along the mainland shore of Lake Michigan and on certain nearby islands…" that should be "preserved in their natural setting and protected from developments and uses which would destroy the scenic beauty and natural character of the area" (Karamanski 2000). SLBE's draft General Management Plan (NPS 2001a) describes the park as being significant for its "accessible and compactly grouped features of continental glaciation," location in "one of the most scenic portions of the Lake Michigan shoreline," "historic maritime, recreation and agricultural landscapes… of a size and quality that are unique on the Great Lakes," and "regionally important native flora and fauna."

SLBE takes its name from Sleeping Bear Dune, a sand-capped headland that rises as much as 135 m above the lake (Vana-Miller 2002). Other significant headlands occur at Empire Bluffs and Pyramid Point. SLBE's perched and lake-level dunes are a rare and protected habitat in the state of Michigan and are home to endangered birds and plants. SLBE's historic maritime landscapes include a lighthouse on South Manitou Island and US Life Saving Service complexes on North and South Manitou Islands and at Sleeping Bear Point (NPS 2006a).

SLBE's water resources include Lake Michigan, the largest lake entirely contained within the borders of the United States; 27 named lakes and ponds and 86 unnamed ponds (some of which are quite small and/or ephemeral), including 460 ha of inland water totally within the park; over 40 km of intermittent and perennial streams, including five named streams (MCGI 2006), and nearly 4,000 ha of wetlands (MDEQ 2006a, b). Upland features include over 16,000 ha of upland forest, the historic farming district of Port Oneida, other farms and orchards on the mainland and islands, the Glen Haven historic village, and the virgin white cedar grove called the Valley of the Giants on South Manitou Island. Forests are 73% of SLBE's land cover; 57% of the land cover is hardwood and upland deciduous forest, 3% is upland pines and conifers, 7% is mixed upland forest, and 6% is lowland forest. Openlands, including historic farmland, make up 12%, and an additional 9% is dunes, beaches, and other sand/soil areas. Inland waters make up 2%, and non-forested wetlands make up 3%. The remaining 1% consists of roads, parking lots, and other developed areas (MDNR 2003).

SLBE is home to two federal-endangered species, the piping plover (*Charadrius melodus*) and Michigan monkey-flower (*Mimulus glabratus* var. *michiganensis*), and one federal-threatened species, the Pitcher's thistle (*Cirsium pitcheri*). Five state-endangered birds (short-eared owl [*Asio flammeus*], king rail [*Rallus elegans*], bald eagle [*Haliaeetus leucocephalus*], common loon [*Gavia immer*], and prairie warbler [*Dendroica discolor*]), and the state-endangered American chestnut tree (*Castanea dentata*) are found in SLBE, as well as 23 state-threatened species and many more species of special concern. The chestnut trees were likely planted by early settlers and are north of the chestnut's natural range in Michigan (MNFI 2007).

Three grave threats to SLBE resources are climate change, the invasion of exotic species, and development pressures (Table i). Signs that climate change is already occurring in Michigan include increases in average annual temperatures, more frequent severe rainstorms, shorter winters, and decreases in the duration of lake ice cover. By the end of the 21st century, winter and summer temperatures may increase 3-6 ^{o}C and 4-7 ^{o}C, respectively (Kling et al. 2003).

The Great Lakes are forecast to have a reduced ice cover season, declining lake levels, and reduced groundwater levels and stream baseflows, but higher runoff during extreme precipitation events (IJC 2003). Thirty-seven percent of the mapped shoreline of SLBE was classified as having very high potential for physical change related to climate change, including Sleeping Bear Point, the Empire Bluffs, and the shoreline of Platte Bay (Pendleton et al. 2007). In coastal wetlands, lower water levels will change wetland vegetation, bird, and fish communities and create stresses that favor the spread of exotic species (Mortsch et al. 2006).

Biological productivity of aquatic ecosystems will likely increase with warmer temperatures, but existing natural communities may be greatly changed (IJC 2003). Lower oxygen levels and

Table i. Impact of stressors on aquatic and upland resources in Sleeping Bear Dunes National Lakeshore.

Stressor/Resource	Lake Michigan/ and coastal wetlands	Dunes	Inland lakes	Streams	Interior wetlands	Upland resources	Lowland forests
Land-Use Related Stressors							
Agriculture	potential problem; insufficient information	existing problem	potential problem; insufficient information	potential problem; insufficient information	not a known problem	not a known problem; insufficient information	not a known problem
Golf courses	potential problem; insufficient information	not a known problem	potential problem; insufficient information	potential problem; insufficient information	not a known problem	not a known problem	not a known problem
Atmospheric deposition	existing problem	existing problem; insufficient information	existing problem; insufficient information	existing problem; insufficient information	existing problem; insufficient information	potential problem; insufficient information	potential problem; insufficient information
Nutrient enrichment	existing problem	existing problem; insufficient information	potential problem	existing problem	potential problem	potential problem; insufficient information	--
Fire exclusion	--	--	--	--	--	existing problem	not a known problem
Mineral resource development (oil and gas, gravel)	potential problem	potential problem	potential problem	potential problem	potential problem	potential problem	potential problem
Soil and groundwater contamination	potential problem; insufficient information	not a known problem	existing problem; insufficient information	potential problem; insufficient information	existing problem; insufficient information	potential problem; insufficient information	potential problem; insufficient information
Physical alterations	existing problem	existing problem	not a known problem	existing problem; insufficient information	not a known problem	existing problem	potential problem
Habitat fragmentation	--	existing problem	--	--	not a known problem	existing problem	existing problem
Storm water	potential problem; insufficient information	not a known problem	existing problem	existing problem	potential problem	not a known problem	not a known problem

(red hexagon) =existing problem; (yellow hexagon) =potential problem; (green hexagon) =not a known problem; (grey shading) =insufficient information

Table i. Impact of stressors on aquatic and upland resources in Sleeping Bear Dunes National Lakeshore (continued).

Stressor/Resource	Lake Michigan/ and coastal wetlands	Dunes	Inland lakes	Streams	Interior wetlands	Upland resources	Lowland forests
Land Use Related Stressors (continued)							
Wastewater disposal	Yellow	Green	Yellow	Red	Yellow	Green	Green
Cultural landscapes	--	--	--	--	--	Red	--
Recreational and Commercial Use Stressors							
Great Lakes shipping	Yellow	Yellow	--	Yellow	Green	--	--
Commercial and recreational fishing	Yellow	Green	Yellow	Yellow	--	--	--
Recreational boating	Yellow	Yellow	Yellow	Red	--	--	--
Visitor use	Yellow	Red	Red	Red	Green	Green	Yellow
Water use and diversion	Yellow	--	Green	Green	Yellow	--	--
Climate Change	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Exotic Species	Red	Red	Red	Red	Red	Red	Red

Red =existing problem; Yellow =potential problem; Green =not a known problem warmer water temperatures in inland waters may change or eliminate fish populations, promote phosphorus release, and increase mercury release and uptake by biota (Kling et al. 2003).

SLBE's location on Lake Michigan may buffer it from temperature changes, at least temporarily, and allow it to serve as a refuge for plants and animals that cannot survive farther inland. However, that same location may jeopardize native plants and animals because it is more subject to precipitation extremes than inland sites (Davis et al. 2000), while invasive species may be more successful (Kling et al. 2003).

Climate change models suggest that many tree species associated with the northern hardwood forest type, or near the southern limit of their range, will almost certainly disappear from SLBE. SLBE may be out of the climatic range for white pine (*Pinus strobus*) and red oak (*Quercus rubra*) by 2025 (Walker 2002). Species currently found at SLBE that may lose 90% of their range within the US include both big-tooth and quaking aspen (*Populus grandidentata* and *P. tremuloides*), sugar maple (*Acer saccharum*), northern white cedar (*Thuja occidentalis*), balsam fir (*Abies balsamea*), red pine (*Pinus resinosa*), and white birch (*Betula papyrifera*) (Hansen et al. 2001). During roughly the same time period, an unknown (probably larger) number of novel plant species may expand northward and appear at SLBE, resulting in other ecosystem changes. Long-term forest health could also be compromised by increased concentrations of ground-level ozone, more frequent droughts and forest fires, and greater risks from insect pests (Kling et al. 2005).

Exotic (non-native) species are a second major threat to SLBE resources, both aquatic and terrestrial. The Lake Michigan ecosystem has been greatly changed by the introduction of sport fish such as salmon, in part to replace native fish populations that were decimated by the sea lamprey in the 1950s. A 'natural' ecosystem and food web will likely never return. However, the ecosystem is currently and constantly threatened by the continued introduction of new exotic species, mainly through the discharge of ballast water from commercial ships. Inland waters are also threatened, with some already affected, by the movement of these species up rivers and streams into inland lakes, and by their inadvertent transfer on recreational boats and equipment.

The NPSpecies (2007) database for SLBE contains four non-native mammals, seven non-native bird species, and 217 non-native plants (including both terrestrial and aquatic plants). Terrestrial herbaceous species of particular concern to park managers include baby's breath (*Gypsophila paniculata*), garlic mustard (*Alliaria petiolata*), spotted knapweed (*Centaurea* spp.), blue lyme grass (*Leymus arenarius*), and periwinkle (*Vinca minor*). Woody species of particular concern include tree of heaven (*Ailanthus altissima*), lombardy poplar (*Populus nigra*), black locust (*Robinia pseudoacacia*), Scots pine (*Pinus sylvestris*), autumn olive (*Elaeagnus umbellata*), and the bush honeysuckles (Morrow's honeysuckle [*Lonicera morrowii*], Tatarian honeysuckle [*L. taterica*], showy fly honeysuckle [*L.* x *bella*], and European fly honeysuckle [*L. xylosteum*]) (NPS 2006c). In addition, 149 non-native plants are considered to be encroaching on SLBE (NPSpecies 2007).

Exotic aquatic plants identified within SLBE by Hazlett (1986) are purple loosestrife (*Lythrum salicaria*), curly leaf pondweed (*Potamogeton crispus*), Eurasian water-milfoil (*Myriophyllum* *spicatum*), watercress (*Nasturtium officinale*), and brittle naiad (*Najas major*). The common reed (*Phragmites australis*) was also identified by Pavlovic et al. (2005).

At SLBE, known accidentally introduced exotic fish are the alewife (*Alosa pseudoharengus*), common carp (*Cyprinus carpio*), sea lamprey (*Petromyzon marinus*) (Kelly and Price 1979), and round goby (*Neogobius melanostomus*) (Michigan Sea Grant 2007a). Rusty crayfish (*Orconectes rusticus*) and zebra mussels (*Dreissena polymorpha*) (Murphy 2004a) and quagga mussels (*Dreissena rostriformis bugensis*) (Quinlan et al. 2007) have also been found.

Exotic aquatic animals considered to be encroaching on SLBE include the ruffe (*Gymnocephalus cernuus*), found in Lake Michigan in Little Bay de Noc and Big Bay de Noc (Czypinski et al. 2007), white perch (*Morone americana*) (NPSpecies 2007), and threespine stickleback (*Gasterosteus aculeatus*) (Quinlan et al. 2007). The spiny water flea (*Bythotrephes longimanus*) was documented by Dr. C. Kerfoot of Michigan Technological University in Big Platte Lake near SLBE in 2008 (NPS, Brenda Moraska Lafrancois, Aquatic Ecologist Great Lakes Area, pers. comm., November 2008), and its spines, but not eggs, have been found in Loon Lake in SLBE (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). The fishhook water flea (*Cercopagis pengoi*) has been found in Lake Michigan (Charlebois et al. 2001). VHS (viral hemorrhagic septicemia) and bloody red shrimp (*Hemimysis anomala*) are relatively new aquatic invasive species in Lake Michigan.

Exotic ‘pests’ represent the most important stressor for SLBE’s northern hardwood forests, including emerald ash borer, beech bark disease, and hemlock woolly adelgid. These have not yet begun to cause mortality in SLBE, but the impacts will be profound when they arrive. Emerald ash borer and beech bark disease are in the immediate vicinity of the park and will begin to affect plant communities containing ash and beech, respectively, very soon. On the other hand, hemlock woolly adelgid will not likely arrive in the next decade. The changes caused by these agents will be extensive, causing high levels of overstory mortality.

For Lake Michigan, other important concerns include atmospheric deposition of contaminants, including mercury, polychlorinated biphenyls, organochlorine pesticides, and polyaromatic hydrocarbons, which lead to fish consumption advisories; ecosystem health affected by factors including, but not limited to, the invasion of dreissenid mussels, round gobies, and other exotic species and severe losses of the small shrimp-like *Diporeia* that are a critical component of the lower levels of the food web; increases in nitrate loading from atmospheric deposition and runoff; nuisance blooms of the *Cladophora* alga that may have led to outbreaks of Type E botulism, killing thousands of birds, including federal-endangered piping plovers and state-threatened common loons; personal care products, pharmaceuticals, and other contaminants in Lake Michigan water; and accidental and deliberate discharges related to Great Lakes shipping.

SLBE’s dunes are inherently an unstable landscape feature and go through natural cycles of movement and replenishment. Climate change may speed these natural cycles. Visitor use contributes to dune erosion and destabilization of vegetation. Frequent human disturbance, along with the open nature of the dune system, make the dunes susceptible to continued invasion by exotic plants. Atmospheric deposition of nutrients may also contribute to changes in the dune flora.

SLBE surface waters are generally at the downgradient end of their watersheds (Murphy 2004a; see Figure 1), and as development pressures increase outside SLBE, its surface waters will be vulnerable to development effects. Effects of specific contaminants and contaminant sources, such as agricultural chemicals, soil and groundwater contamination sites, and onsite sewage disposal systems (OSDS) have not been evaluated; source data and better delineation of surface and groundwater subwatersheds would be necessary for such an evaluation.

Inland waters are generally thought to be of good quality, but some lakes exceed USEPA nutrient reference criteria for their ecoregion (Shell Lake and Lake Manitou for total nitrogen, and School Lake for both total nitrogen and total phosphorus); others did not meet the criteria for Secchi depth or dissolved oxygen. These exceedences of reference criteria do not necessarily indicate degradation, however; they indicate that some SLBE lakes are not typical for their region. Other recent studies showed generally healthy mussel (Nichols et al. 2004) and fish (Fessell 2007) populations. Consistency in data collection and comparison of data over time have been lacking, but may improve with the National Park Service's Great Lakes Inventory and Monitoring Network's oversight and management of the inland waters monitoring programs.

In addition to exotic plants and pests, important future secondary threats for the northern hardwood forest and upland deciduous association are white-tailed deer herbivory and exotic earthworms. For the upland conifer and pine-oak associations, alteration by past disturbance regimes is an additional primary stressor, with fire exclusion, acid deposition, and nutrient enrichment being important secondary stressors. For lowland forests, white-tailed deer herbivory has played a major role in preventing successful recruitment and continues to represent the most important ongoing stress, with the role of future altered hydrology being an important unknown.

Recommendations for future resource monitoring, management, and protection in SLBE include:

- developing strategies for evaluating, and mitigating, where possible, the impacts of climate change
- requesting the addition of nutrient monitoring capability to the IADP air monitoring station in SLBE
- establishing one or more nearshore sampling sites in Lake Michigan bays
- continuing monitoring beaches for fecal indicator bacteria and expanding to monitor shoreline biofouling and invasive species
- periodically examining the work of lakewide groups studying Lake Michigan
- monitoring population trends in the watershed and examining ways to track land use changes and their impacts
- continuing to sample SLBE index lakes after examining issues of timing and scope
- evaluating existing water quality data for its usefulness in examining long-term trends and standardizing future sampling
- establishing a long-term sampling program for the Crystal and Platte Rivers
- defining more precisely the watersheds and subwatersheds for some SLBE inland lakes
- investigating the effects of groundwater inputs on SLBE streams
- investigating the unique Aral Springs area
- continuing to monitor reports on the discharge of nutrients from the Platte River State Fish Hatchery

- systematically monitoring all surface waters for invasive species yearly and continuing and developing prevention and control plans
- evaluating erosion from the county roads that pass through the park
- documenting, ground-truthing, photographing, and mapping SLBE wetlands and ponds
- establishing permanent sampling quadrats in the northern hardwood community type
- discussing reduction in target density of the white-tailed deer herd
- cooperating with any ongoing efforts to monitor for hemlock woolly adelgid presence
- using nitrate and base cation concentrations of a small sample of streams and rivers to evaluate the nutrient depositional status of uplands
- using prescribed fire in mainland pine and pine-oak forests
- collecting baseline data on the understory of a combination of the pine and pine-oak community types
- monitoring old fields, trails, roads, campgrounds, and parking lots for the presence and spread of terrestrial exotic species
- allocating additional resources to controlling and monitoring exotic plants
- developing and implementing visitor use and capacity plans for the Crystal and Platte Rivers

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Introduction and Park Description

Size, Boundaries, Location, and Regional Setting

Sleeping Bear Dunes National Lakeshore (SLBE) is located on the eastern shore of Lake Michigan in the northwestern part of Michigan's Lower Peninsula (LP) (Figure 1). It was established in 1970 by Public Law 91-479 (later amended by Public Law 97-361 in 1982) in recognition of "certain outstanding natural features, including forests, beaches, dune formations, and ancient glacial phenomena [that] exist along the mainland shore of Lake Michigan and on certain nearby islands in Benzie and Leelanau Counties, Michigan" that should be "preserved in their natural setting and protected from developments and uses which would destroy the scenic beauty and natural character of the area" (Karamanski 2000).

SLBE is 28,851 hectares (ha); 24,067 ha of land and 4,784 ha of water. The land category consists of 23,206 ha of federal land and 5,644 ha of nonfederal land. The water category included 4,293 ha of Lake Michigan extending 0.4 kilometers (km) from shore (NPS 1999b; NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., January 2009). The federal and other public land category in Figure 2 includes 125.5 ha of non-federal public land, such as state of Michigan land and road rights-of-way in Glen Haven, among others. The "private/other" category includes 33 private tracts totaling 55.7 ha, 349 ha of land not classified in the NPS tracts coverage, and 700 ha of land not included in the NPS tracts coverage (in the Bow Lakes area, a small area northeast of Glen Lake, and the scenic corridor between Crystal Lake and Platte Lake) (Figure 2). By park unit, SLBE land areas include 16,090 ha of the mainland and all of North Manitou Island (5,830 ha) and South Manitou Island (2,147 ha) (NPS 1999b; NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., January 2009). SLBE encompasses 104 km of Lake Michigan shoreline: 49.5 km on the mainland, 33.8 km on North Manitou Island, and 20.7 km on South Manitou Island (MCGI 2006).

SLBE's mainland unit is entirely contained within the United States Geological Survey's (USGS) Betsie-Platte Hydrologic Unit (HUC 04060104); the Manitou Islands and Lake Michigan waters are in the Lake Michigan Hydrologic Unit (HUC 04060200) (Seaber et al. 1987). SLBE is also part of the Northern Lacustrine-Influenced Lower Michigan regional landscape ecosystem subsection that covers over 44,000 km^2 of the LP (Albert 1995). The United States Environmental Protection Agency (USEPA) includes SLBE in its nutrient ecoregion VII, level III ecoregion 51 (North Central Hardwood Forests) (USEPA 2000).

SLBE is located in Michigan's Benzie and Leelanau Counties, and a part of the 61,510 ha watershed upgradient from the park boundary extends eastward into Grand Traverse County in the Platte River basin (Figure 2). SLBE lands are included in nine townships in two counties (Lake, Benzonia, and Platte in Benzie County and Empire, Kasson, Glen Arbor, Leland, Cleveland, and Centerville in Leelanau County) (Figure 3). Approximately one-fourth of the SLBE watershed is managed by the state of Michigan, including 14,968 ha in the Pere Marquette State Forest and 446 ha under other state of Michigan management (MDNR 2001). The state of Michigan has designated a Manitou Passage underwater preserve that includes 730 km^2 of Lake Michigan bottomland and includes the wrecks of 16 ships (State of Michigan 1989; Michigan Underwater Preserve Council 2004).

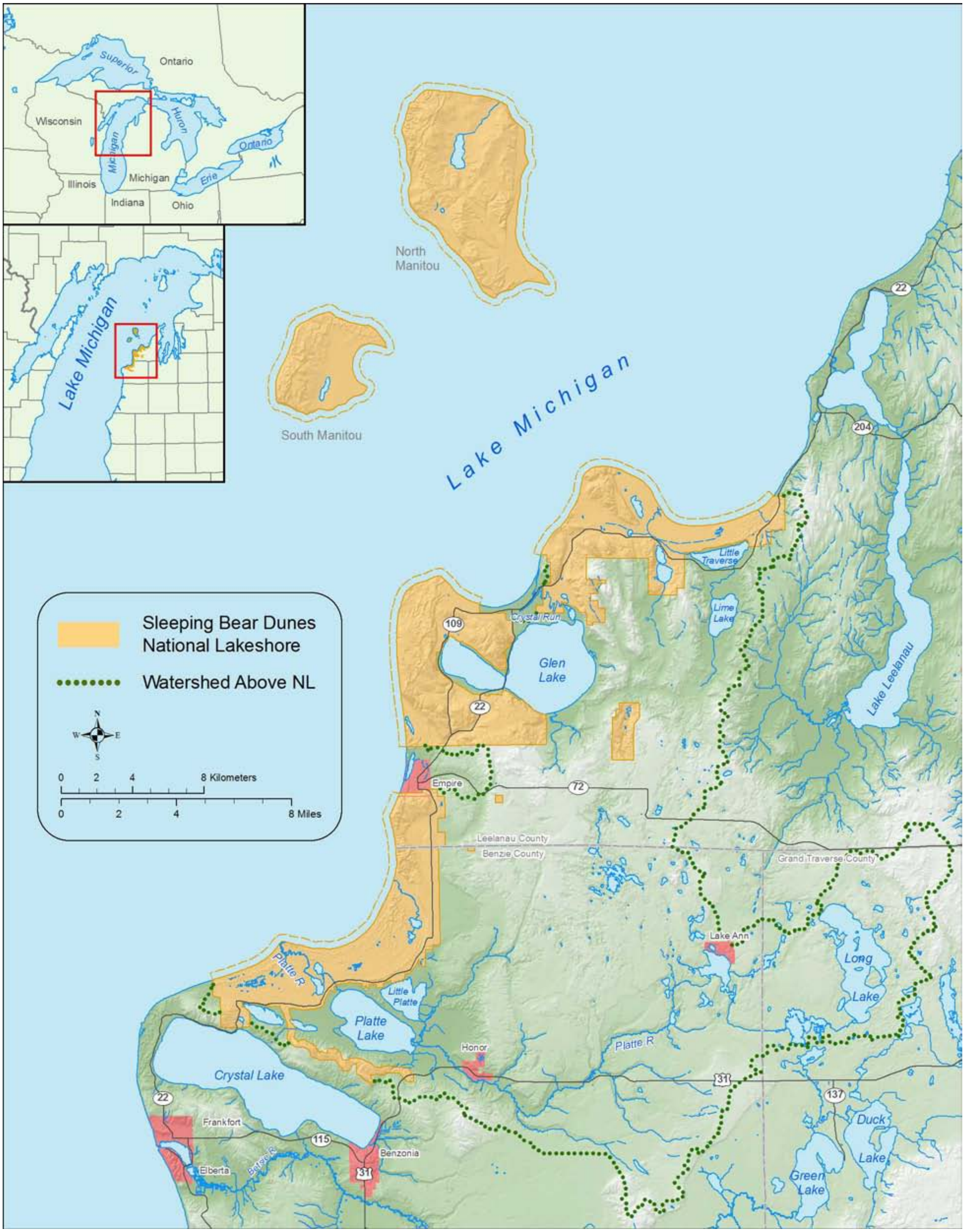

Figure 1. Location of Sleeping Bear Dunes National Lakeshore in the upper Great Lakes region of the United States (for sources, see Appendix A).

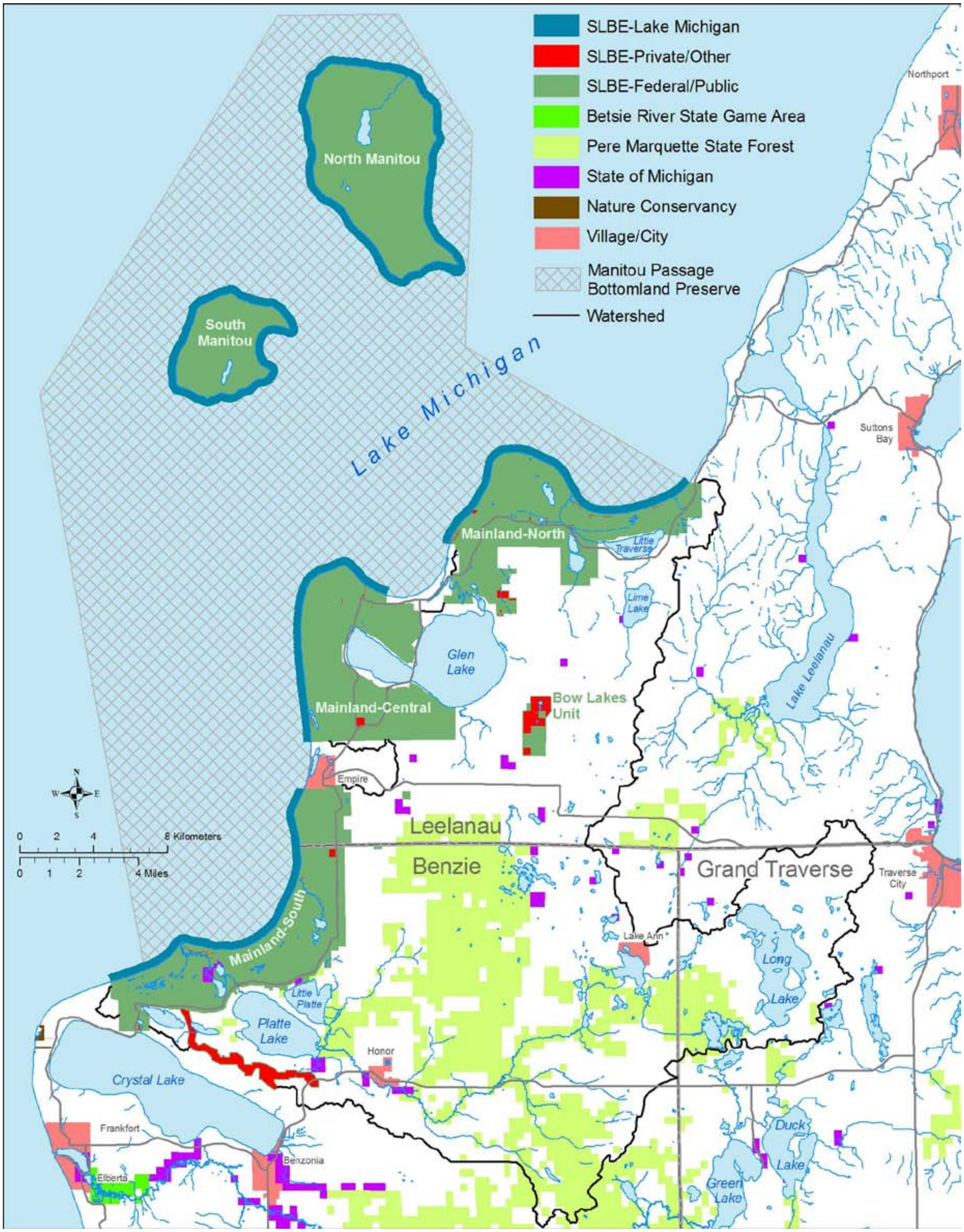

Figure 2. Land management, ownership, and political boundaries in the Sleeping Bear Dunes National Lakeshore watershed (areas not shaded are private lands; some inholdings are too small to see at this scale; approximately 10% of the Benzie Corridor is in NPS ownership) (State of Michigan 1989; NPS 1999b; MDNR 2001).

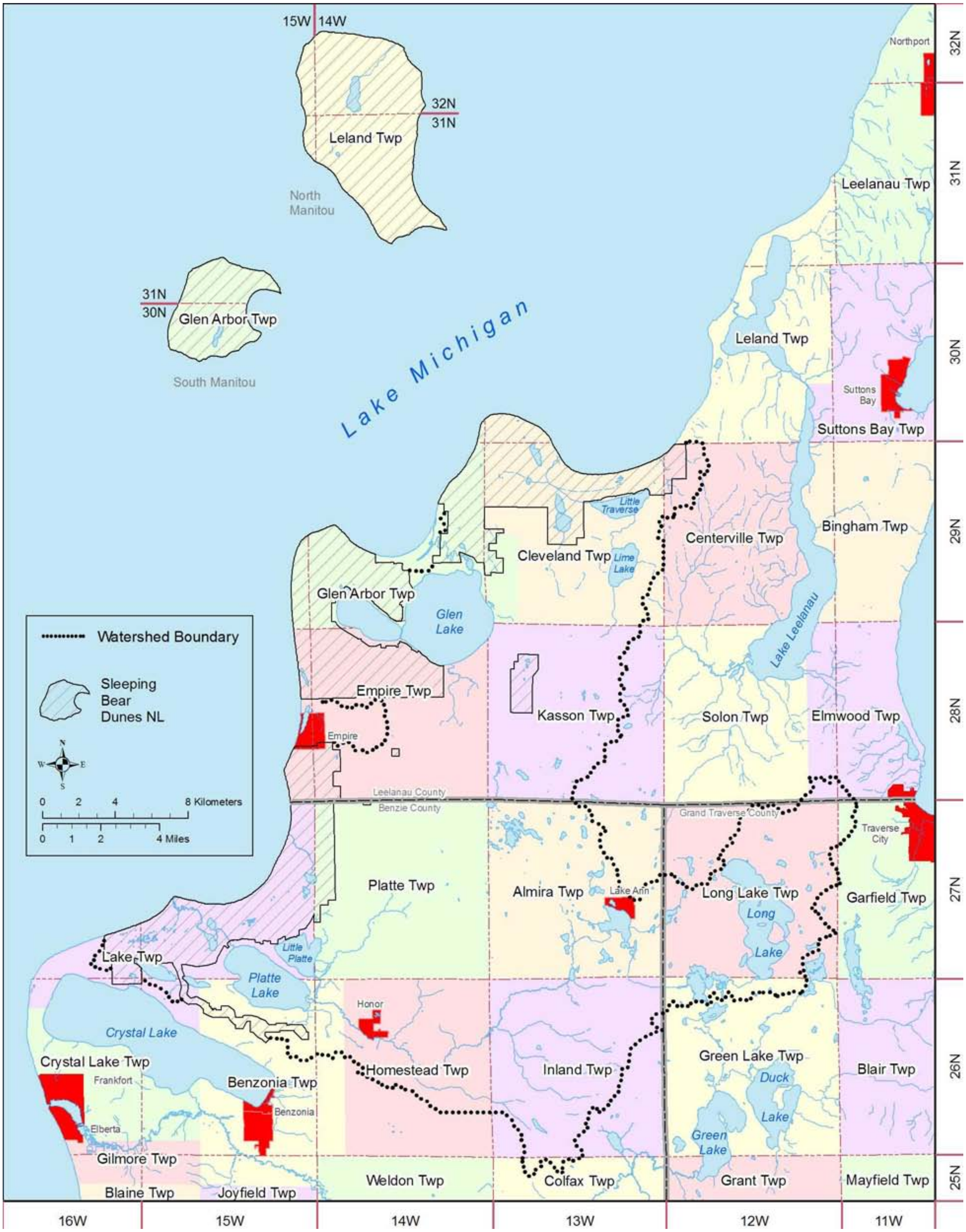

Figure 3. Local units of government in the vicinity of Sleeping Bear Dunes National Lakeshore (for sources, see Appendix A).

In total, over 36% of Benzie County is publicly owned. Over 4,000 ha are in SLBE, and nearly 24,000 ha are in the Pere Marquette State Forest, the Betsie River State Game Area and Fish Hatchery, and the abandoned Ann Arbor Railway right-of-way (now the Betsie Valley Trail) (Benzie County Planning Commission 2000). Leelanau County has only 11% of its land (about 9,000 ha) in public ownership (Leelanau County Board of Supervisors 2005).

For purposes of this report, SLBE is divided into the Bow Lakes Unit, the Mainland-North, Mainland-Central, and Mainland-South Units, North Manitou Island, and South Manitou Island (Figure 2). Two small inland areas totaling 26 ha just east and south of Empire will not be further discussed in this report.

Climate

In the Koppen climate classification system, SLBE is classified as Dfb, also known as the humid continental climate. Summers are moderately warm, winters are cold, and the climate is moist year round (de Blij and Muller 1993). At Frankfort, 8 km south of SLBE, temperatures for the period of record 1971-2000 ranged from -26^{o}C to 35^{o}C (NCDC 2004). The mean temperature ranged from -5^{o}C in the coldest month, January, to 20^{o}C in the warmest month, July, and the mean annual temperature was 7.8^{o}C during that time period. Lake Michigan has a significant local effect on climate; temperatures are cooler during the late spring and early summer and warmer during the late fall and early winter compared to locations at comparable latitudes inland (Haswell and Alanen 1994). SLBE has an average frost-free growing season of 130 days (Michigan State Climatologist's Office n.d.) to 150 days (NPS 2004a). The Lake also increases cloudiness in late fall and early winter, as cold air mixes with warmer, moist lake air and produces snow, rain, and fog near the Lake. The relatively temperate and humid climate of the nearshore environment strongly influences SLBE's plant communities (NPS 2008b).

The mean annual precipitation for the period of record from 1971 to 2000 was 89 cm (NCDC 2004). For the period of record from 1959 to 1980, precipitation was well distributed throughout the year, and approximately 53% of the annual precipitation at nearby Maple City occurred during the growing season, April to September (Michigan State Climatologist's Office n.d.). Annual snowfall totals average 241 cm on the SLBE shoreline and 305 to 330 cm inland (Vana-Miller 2002). The prevailing wind is from the southwest, averaging 17.4 km/hr through most of the year; however, prevailing wind direction switches to the northwest in fall and early winter and to northeast in late winter (Vana-Miller 2002).

Key Features and Significance

SLBE is located in and along the shore of Lake Michigan, which is the largest lake entirely contained within the United States borders. SLBE takes its name from Sleeping Bear Dune, a sand-capped headland that rises as much as 135 m above the lake (Vana-Miller 2002). Other significant headlands occur at Empire Bluffs and Pyramid Point. SLBE's historic maritime landscapes include a lighthouse on South Manitou Island and US Life Saving Service complexes on North and South Manitou Islands and at Sleeping Bear Point (Figure 4; NPS 2006a).

Inland water resources consist of 113 lakes and ponds (some of which are quite small and/or ephemeral) which together are 460 ha of inland water totally within the park; over 40 km of intermittent and perennial streams, including five named streams (MCGI 2006), and nearly 4,000

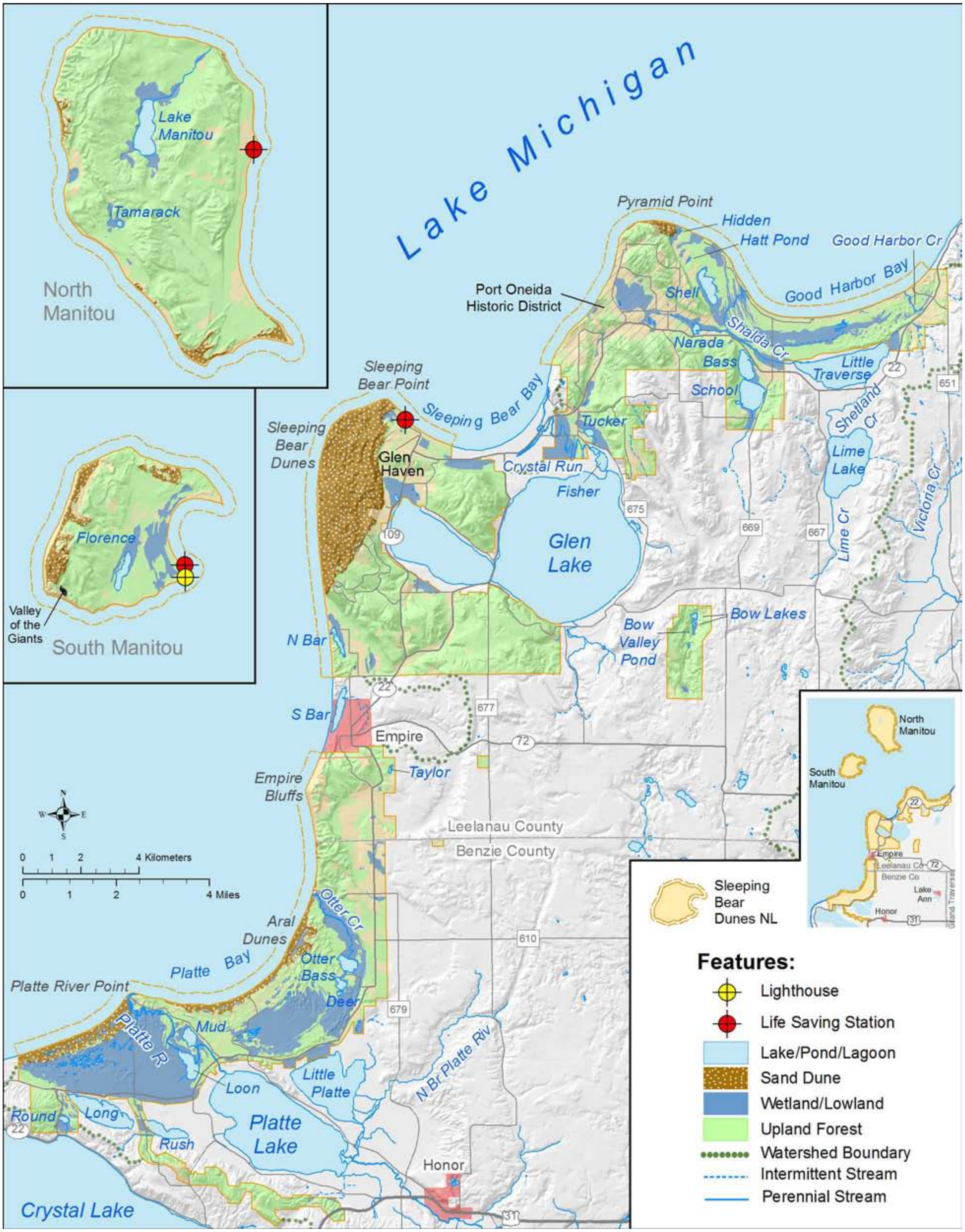

Figure 4. Key features of Sleeping Bear Dunes National Lakeshore (MDNR 1999, 2003; NPS 2001b; MDEQ 2006a, b).

ha of wetlands (see Table 17; MDEQ 2006a, b). Upland features include over 16,000 ha of upland forest, the historic farming district of Port Oneida, other farms and orchards on the mainland and islands, the Glen Haven historic village, and the virgin white cedar grove called the Valley of the Giants on South Manitou Island.

SLBE's draft General Management Plan (NPS 2001a) describes the park as being significant for its "accessible and compactly grouped features of continental glaciation," location in "one of the most scenic portions of the Lake Michigan shoreline," "historic maritime, recreation and agricultural landscapes… of a size and quality that are unique on the Great Lakes," and "regionally important native flora and fauna."

Historic and Current Human Uses

Evidence of human use of the SLBE area dates back more than 10,000 years to when Paleo-Indian people hunted game during the retreat of the last glaciation (Lovis 1984). However, most of the pre-European sites found in SLBE date from the Late Woodland period between 130 and 1620 A.D. (Haswell and Alanen 1994). Most of these sites within SLBE were probably short-term hunting camps, but larger agricultural villages have been found to the north, south, and east of SLBE (Lovis 1984).

In the 1700s and 1800s, Ottawa and Ojibwe people began settling in Michigan's LP, including the SLBE area. The Ottawa had been displaced from their lands in Ontario as the result of competition among Native American groups for furs to trade with French and Dutch traders (Haswell and Alanen 1994). Intensive human use of the SLBE area by Europeans began as early as the 1840s with logging for fuelwood to supply Great Lakes steamers using the Manitou Passage. Agricultural activities followed on the cleared land; subsistence farming was most common at first, but the foundations of the region's fruit-growing activities were laid by the 1870s (Haswell and Alanen 1994). However, by 1910 the forest resources of the area had been largely depleted, and farming declined to fairly low levels by the early 1920s (Vana-Miller 2002).

As the farming and logging industries declined, the government came into possession of hundreds of thousands of hectares of land through tax delinquency. Karamanski (2000) wrote: "In the 1920s and 1930s, northern Michigan was reconceived, from a raw resource frontier with ninety percent of the land in private hands, to a carefully managed landscape based on a sustainable forest products industry and tourism, with the bulk of the land controlled by public agencies." In 1923, a very small (73 ha) Benzie State Park was established at the mouth of the Platte River. By the 1940s, local people, concerned about development pressures and interested in capitalizing on the tourist trade, advocated for a larger state park that would include the Sleeping Bear Dunes, the D.H. Day Forest Estates, and a small part of the north shore of Glen Lake. However, the state lacked acquisition funds for the valuable land. During the late 1950s it consolidated the holdings it had acquired in the SLBE area as D.H. Day State Park. It was not until 1970 that Sleeping Bear Dunes National Lakeshore was created as part of the National Park Service (Karamanski 2000).

SLBE's boundaries included approximately 1,400 parcels of land that were held in private ownership at that time (Karamanski 2000). Those lands include "hundreds of dump sites, both residential and commercial; 11 gravel pits; two known gas stations; five or six areas suspected of prior use as gas stations; and over 100 underground storage tanks from commercial, farming, and residential use" (Vana-Miller 2002). Thus, the impact of past human land uses continues into the present day.

SLBE now has well over a million visitors each year. The highest number occurred in 1999, with 1,364,834 visitors; for 2006 and 2007, the numbers were 1,213,026 (Figure 5) and 1,134,314, respectively (NPS 2008a). For 2008, SLBE had forecasted 1,147,662 visitors, a 1.2% increase over 2007 (NPS 2008a); however, in November 2008 visitor numbers were expected to be down significantly from 2007 (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

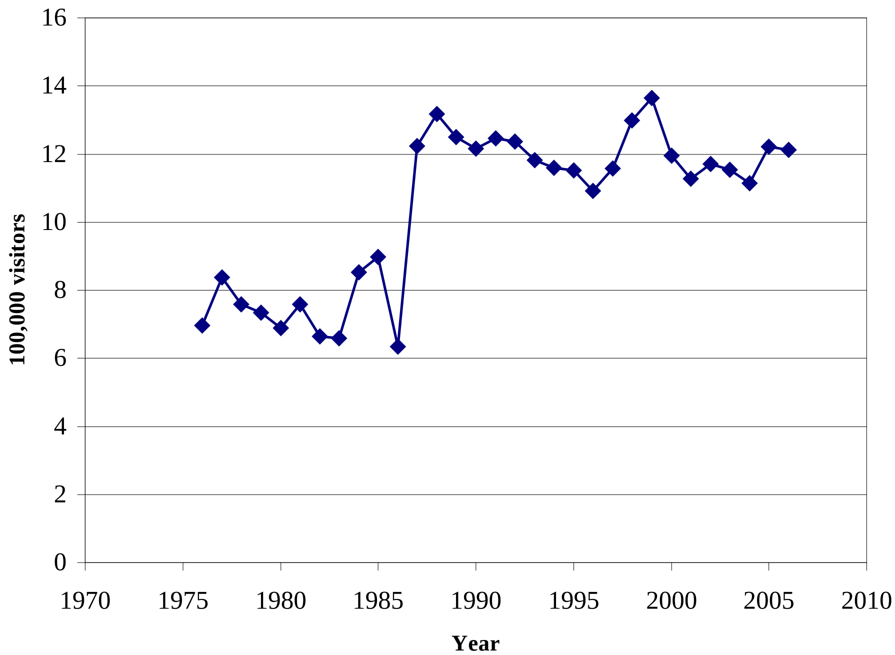

Figure 5. Annual visitors to Sleeping Bear Dunes National Lakeshore (NPS 2007).

The five-county region of northwest Michigan that includes Benzie and Leelanau Counties as well as Antrim, Charlevoix, and Grand Traverse Counties has experienced "phenomenal" population growth, unparalleled in the state, since 1970 (NWMCOG 2004). The region's population grew by 66% from 1970-2000 and by 23% in the 1990s. It is expected to grow another 15% by 2010 and an additional 10% by 2020 (Table 1). Approximately 80% of this growth has come not from births, but from in-migration from outside the region (NWMCOG 2004).

Similarly, population density has increased in Benzie and Leelanau Counties since the 1940s, with populations growing from 63 to 157 and from 64 to 129 persons/km^2, respectively (Table 2; Leelanau County Board of Supervisors 2005). By comparison, the average number of persons/km^2 for Michigan as a whole was 453 in 2000 (US Census Bureau 2000). The 2000 population of

Table 1. Population growth and projected growth for Benzie and Leelanau Counties, 1970-2020 (NWMCOG 2004).

County	Population (actual or projected*)					
	1970	1980	1990	2000	2010*	2020*
Benzie	8,593	11,205	12,200	15,998	19,418	21,782
Leelanau	10,872	14,007	16,257	21,119	23,419	25,977

Table 2. Population density in Benzie and Leelanau Counties, 1940-2000 (Leelanau County Board of Supervisors 2005).

County	Population (persons/km^2)						
	1940	1950	1960	1970	1980	1990	2000
Benzie	63	65	70	83	106	124	157
Leelanau	64	67	65	70	90	101	129

SLBE's watershed is 15,761 (US Census Bureau 2000), with an average density of 18.4 persons/km^2, but a very wide range of 0 to 1600 persons/km^2. The highest densities are mostly found around large lakes, including Long Lake in Grand Traverse County, Platte Lake, and Glen Lake (Figure 6).

The potential population of Leelanau County if all properties were developed under current zoning regulations (often referred to as the build-out scenario) is 153,550. This number, while very large, is lower than the 285,000 that would have been possible under 1990 zoning (Leelanau County Board of Supervisors 2005). The build-out scenario for Benzie County is 144,000 (Benzie County Planning Commission 2000).

Under the United States Department of Agriculture Economic Research Service's (USDA ERS) County Typology, Benzie and Leelanau Counties are both considered nonmetro recreation counties and retirement counties. Nonmetro recreation counties are classified using a combination of factors, including employment or earnings in recreation-related industries, seasonal or occasional use housing units, and per capita receipts from motels and hotels. Retirement counties are those in which the number of residents 60 and older grew by 15 percent or more between 1990 and 2000 due to in-migration (USDA ERS 2004).

In Benzie County, the largest category of employment is construction, with 1,153 workers, or 14% of the workforce. Other major employment categories include retail trade (13%), accommodations and food service (13%), and government and educational services (10%). Currently, Benzie County's largest employers are the Crystal Mountain Resort at Thompsonville, the Benzie County Central School District at Benzonia, and Graceland Fruit at Frankfort (MEDC 2007a). In Leelanau County, the largest employment category is government and educational services, with 2,153 workers (20%), followed by construction (11%); accommodations and food service (10%); and agriculture, forestry, fishing, and hunting (9%). Leelanau County's largest employers are the Grand Traverse Band's casino and resort at Peshawbestown, Memorial Health Center at Northport, and the Homestead Resort at Glen Arbor (MEDC 2007b). For both counties, the highest percentage employment growth over the next five years is projected to be in the

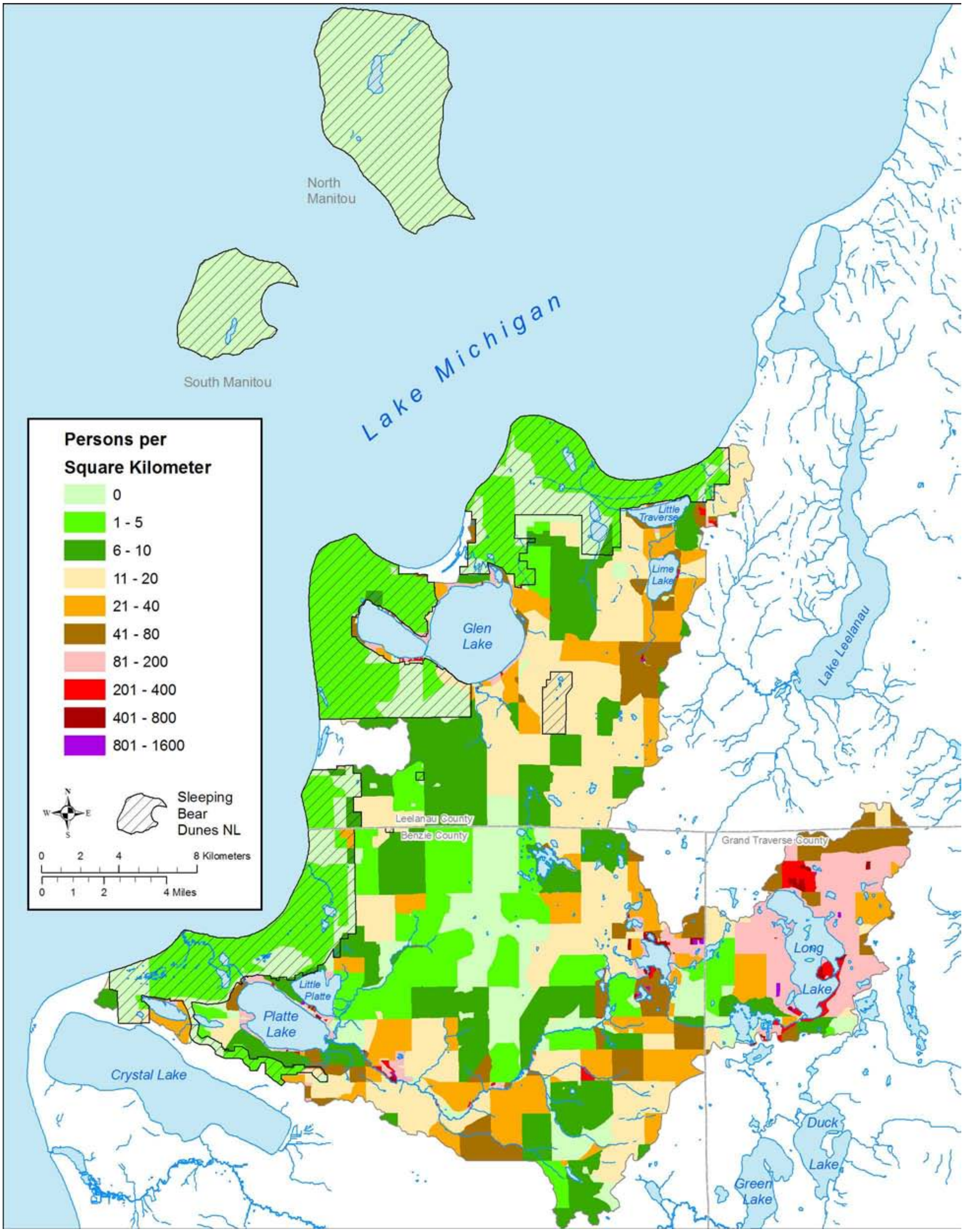

Figure 6. Population density (persons/km^2) in the Sleeping Bear Dunes National Lakeshore watershed (US Census Bureau 2001).

industry called “administrative and waste services,” which includes many clerical and service jobs in the private sector (NWMCOG 2006).

Land Use and Vegetative Cover

A general assessment of land use and vegetative cover for SLBE and its watershed was made using data from the State of Michigan Integrated Forest Monitoring Assessment and Prescription (IFMAP) program (MDNR 2003) (Table 3, Figure 7). These data were generated from Landsat Thematic Mapper imagery collected between 1997 and 2001. Forests are 73% of SLBE’s land cover (57% hardwood and upland deciduous forest, 3% upland pines and conifers, 7% mixed upland forest, and 6% lowland forest). Openlands, including historic farmland, make up 12%, and an additional 9% is dunes, beaches, and other sand/soil areas. Inland waters make up 2%, and non-forested wetlands make up 3%. The remaining 1% consists of roads, parking lots, and other developed areas (MDNR 2003).

Within SLBE’s watershed and including SLBE land, approximately 62% is forested, 15% is open and shrub land, and 7% is farmed and cultivated land. Open water covers nearly 9% of the land, including the Glen Lakes, Platte and Little Platte Lakes, and the many branches of the Platte River. Non-forested wetlands make up 2% of land, and sand/soil make up about 3%. Urban land uses, including roads and residential areas, make up 2.5% (MDNR 2003). However, most residential development in the watershed is located along inland lake shores; the importance of this will be discussed later in the report.

Soils

Eight soil associations (Figure 8, Table 4) have been mapped in and near SLBE. Most of the landscape is blanketed by coarse-textured, deep, and well-drained to excessively well-drained soils that developed in eolian, alluvial, and ice-contact parent materials. Some medium textured (loamy) soils occur on glacial features such as ground moraines, end moraines, and drumlins. Poorly drained (hydric) soils occur sporadically within most areas, and dominate in wetland areas such as the east end of Platte Lake (NRCS Soil Survey Staff 2007a).

Geology and Geomorphology

SLBE geology consists of up to 180 m of Quaternary deposits overlying sedimentary rocks. These sedimentary rocks are mainly Devonian age limestone of the Traverse Group, with a fringe of overlying Mississippian age Antrim shale along the area’s southeastern margin (Handy and Stark 1984; Lundstrom 2001). Little is known about the area’s geologic history for the period between the deposition of the ancient sedimentary rocks and the overlying Quaternary deposits (Handy and Stark 1984). SLBE’s Quaternary deposits consist of Pleistocene glacial deposits of a continental ice sheet, which give the landscape its main relief, modified by postglacial Holocene materials deposited by lakeshore, wind, river, and hillslope processes (Lundstrom 2001). Little has been reported about the character of the glacial deposits at depth, although some limited information might be gained from mapping of well construction reports mentioned in Handy and Stark (1984).

Recent surficial geology maps for SLBE and its vicinity recognize 15 deposits (Wallbom and Larson 1998, 1999; Larson et al. 2000). However, the work of Richmond and Fullerton (2001) is more useful here, as it generally describes landforms and their dominant grain sizes. SLBE’s

Table 3. IFMAP land classifications for Sleeping Bear Dunes National Lakeshore and its watershed (MDNR 2003).

IFMAP Code	Class	SLBE (ha and %)				SLBE and Watershed (ha and %)			
110	Low Intensity Urban	78.9	0.3%			630.0	0.7%		
123	High Intensity Urban	4.0	0.0%			58.6	0.1%		
122	Roads / Paved	190.5	0.8%			1,285.9	1.5%		
350	Parks / Golf Courses	0.0	0.0%			129.6	0.2%		
	Total Urban, Roads, Parks and Golf Courses			273.4	1.1%			2,104.2	2.5%
2111	Non-vegetated Farmland	0.0	0.0%			118.1	0.1%		
2112	Row Crops	3.6	0.0%			190.9	0.2%		
2113	Forage Crops / Non-tilled Herbaceous	177.7	0.7%			5,462.7	6.4%		
222	Orchards / Vineyards / Nursery	23.9	0.1%			459.5	0.5%		
	Total Farmed and Cultivated Lands			205.1	0.9%			6,231.1	7.3%
310	Herbaceous Openland	2,018.1	8.4%			9,814.5	11.5%		
320	Upland Shrub / Low-density trees	639.1	2.7%			3,051.6	3.6%		
	Total Open and Shrub Lands			2,657.2	11.0%			12,866.1	15.0%
411	Northern Hardwood Association	11,449.3	47.6%			31,305.4	36.6%		
412	Oak Association	14.0	0.1%			999.8	1.2%		
413	Aspen Association	1,809.9	7.5%			5,763.2	6.7%		
419	Mixed Upland Deciduous	413.8	1.7%			1,420.7	1.7%		
	Total Hardwood/Upland Deciduous			13,687.1	56.9%			39,489.2	46.2%
421	Pines	566.3	2.4%			3,733.0	4.4%		
423	Other Upland Conifers	5.0	0.0%			35.4	0.0%		
429	Mixed Upland Conifers	90.4	0.4%			342.1	0.4%		
	Total Upland Pines and Conifers			661.7	2.8%			4,110.4	4.8%
431	Upland Mixed Forest	1,661.6	6.9%	1,661.6	6.9%	5,265.7	6.2%	5,265.7	6.2%
	Total Upland Forest*			16,010.4	66.5%			48,865.3	57.1%

Table 3. IFMAP land classifications for Sleeping Bear Dunes National Lakeshore and its watershed (MDNR 2003) (continued).

IFMAP Code	Class	SLBE (ha and %)				SLBE and Watershed (ha and %)			
611	Lowland Deciduous Forest	672.0	2.8%			1,539.4	1.8%		
612	Lowland Coniferous Forest	722.4	3.0%			2,273.0	2.7%		
613	Lowland Mixed Forest	112.3	0.5%			392.1	0.5%		
	Total Lowland Forest			1,506.7	6.3%			4,204.5	4.9%
	Total Forest**			17,517.1	72.8%			53,069.8	62.0%
621	Floating Aquatic	29.4	0.1%			110.9	0.1%		
622	Lowland Shrub	341.2	1.4%			799.9	0.9%		
623	Emergent Wetland	104.5	0.4%			265.3	0.3%		
629	Mixed Non-Forest Wetland	141.6	0.6%			432.0	0.5%		
	Total Non-Forested Wetlands			616.6	2.6%			1,608.0	1.9%
	Total Lowland Forests and Wetlands***			2,123.3	8.9%			5,812.5	6.8%
500	Water	524.0	2.2%			7,307.5	8.5%		
710	Sand / Soil	2,266.8	9.4%			2,372.6	2.8%		
	Total	24,060.1	100.0%			85,559.3	100.0%		

*Total Upland Forest = Hardwood/Upland Deciduous+Upland Pines and Conifers+Upland Mixed Forest
**Total Forest=Total Upland Forest+Total Lowland Forest
***Total Lowland Forests and Wetlands=Total Lowland Forest+Total Non-Forested Wetlands

Figure 7. IFMAP land cover for the Sleeping Bear Dunes National Lakeshore area (MDNR 2003).

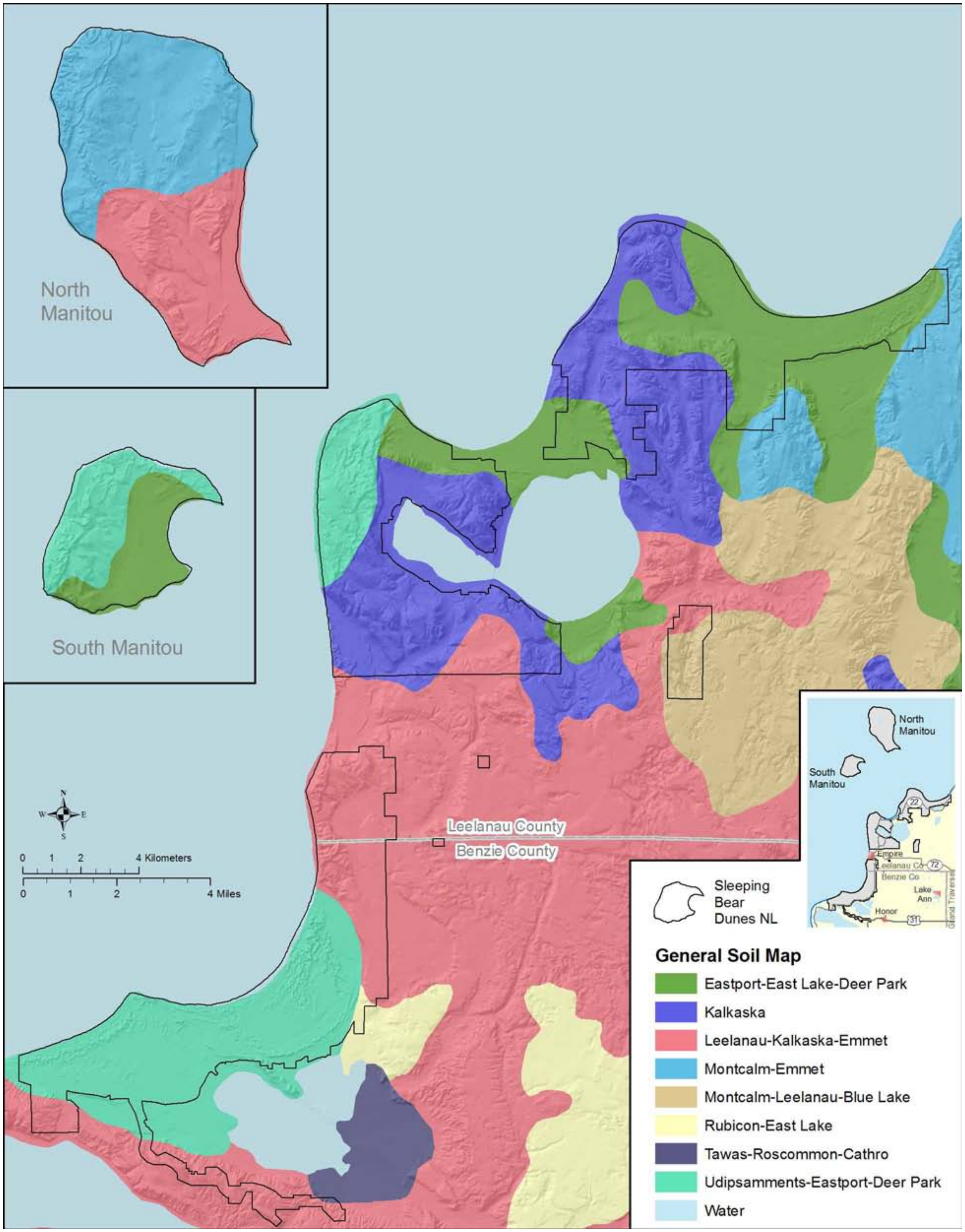

Figure 8. Soil associations in Sleeping Bear Dunes National Lakeshore and its watershed (NRCS 2006a).

Table 4. Descriptions of soil series in major soil associations for Sleeping Bear Dunes National Lakeshore (NRCS Soil Survey Staff 2007a).

Soil association	Location in SLBE	Major soil series	% of association	Slopes in SLBE	Series description
Eastport-East Lake-Deer Park	Mainland-North, Mainland-Central, South Manitou	Eastport	24%	1-12%	Very deep, excessively drained soils formed in sandy eolian deposits on vegetated beach ridges, plains near the Great Lakes or stabilized sand dunes.
		East Lake	20%	0-8%	Very deep, somewhat excessively drained soils formed in sandy and gravelly outwash deposits on outwash plains, stream terraces, lake terraces, lake basins, deltas, eskers, and beach ridges.
		Deer Park	15%	0-45%	Very deep, excessively drained soils formed in sandy deposits on beach ridges, level plains, and stabilized sand dunes along the Great Lakes.
Kalkaska	Mainland-North, Mainland-Central	Kalkaska	81%	0-45%	Very deep, somewhat excessively drained soils formed in sandy deposits on outwash plains, valley trains, moraines, and stream terraces.
Leelanau-Kalkaska-Emmet	South half North Manitou, Bow Lakes, Mainland-South	Kalkaska	53%	0-40%	(see above)
		Leelanau	17%	0-25%	Very deep, well drained soils formed in sandy and loamy deposits on moraines.
		Emmet	12%	3-25%	Very deep, well drained and moderately well drained soils formed in sandy loam till on end moraines, drumlins, and ground moraines.
Montcalm-Emmet	North half North Manitou, Mainland-North	Emmet	47%	2-40%	(see above)
		Montcalm	35%	2-40%	Very deep, well drained soils formed in sandy and loamy glacial drift material on ground moraines, end moraines, and outwash plains.
Montcalm-Leelanau-Blue Lake	Bow Lakes	Blue Lake	34%	0-50%	Very deep, well drained soils formed in deep sandy glacial drift deposits on moraines and outwash plains.
		Leelanau	24%	0-45%	(see above)
		Montcalm	21%	0-35%	(see above)

Table 4. Descriptions of soil series in major soil associations for Sleeping Bear Dunes National Lakeshore (NRCS Soil Survey Staff 2007a) (continued).

Soil association	Location in SLBE	Major soil series	% of association	Slopes in SLBE	Series description
Rubicon-East Lake	Mainland-South	Rubicon	68%	0-30%	Very deep, excessively drained soils formed in sandy deposits on disintegration, ground, end, and kame moraines; lake plains; outwash plains; stream terraces; beach ridges; and sand dunes.
		East Lake	14%	0-30%	(see above)
Tawas-Roscommon-Cathro	East of SLBE on east side of Platte Lake	Tawas	42%	0-2%	Very deep, very poorly drained organic soils that are moderately deep to sandy material. They formed in sapric material 41 to 130 centimeters thick overlying sandy drift. They are in depressions within outwash plains, lake plains, till floored lake plains, and moraines.
		Roscommon	17%	0-2%	Very deep, poorly drained and very poorly drained soils formed in sandy deposits on lake plains, outwash plains, lake basins and glacial drainageways.
		Cathro	15%	0-2%	Very deep, very poorly drained organic soils moderately deep to loamy materials. They formed in organic material 41 to 130 centimeters thick overlying loamy glacial deposits on ground moraines, end moraines, outwash plains, lake plains, stream terraces, and flood plains.
Udipsamments-Eastport-Deer Park	Mainland-Central, Mainland-South, South Manitou	Deer Park	47%	0-35%	(see above)
		Udipsamments (taxon above family)	27%	0-40%	Very sandy soils of recent origin.
		Eastport	10%	0-12%	(see above)

current surficial geology is dominated by deposits of fine to medium dune sand, fine to coarse outwash sand and gravel, fine to medium lake sand, and ground moraine of calcareous sandy loamy till (Figure 9; Richmond and Fullerton 2001).

SLBE's glacial and postglacial history is well summarized in Lundstrom (2001) and Vana-Miller (2002). The Greatlakean glacial advance of the Wisconsin stage is responsible for reshaping many landforms in the SLBE area into their current forms (Handy and Stark 1984). During this advance, ice is believed to have extended only into embayments in the pre-existing glacial headlands, creating the north-south end moraines near Glen Lake, Empire, and Platte Lake (Lundstrom 2001). These deposits have been alternatively described as crevasse-fill deposits by Wallbom and Larson (1998), although Larson has recently indicated that he is no longer certain of that interpretation (University of Michigan, Grahame Larson, email, 5/14/07). A broad outwash plain stretches south and east of the moraines, with only a small portion included in SLBE, and lake sands fill the old embayments and surround the larger lakes such as the Glen and Platte Lakes (Figure 9; Richmond and Fullerton 2001). Ice finally disappeared from the SLBE vicinity about 11,800 years BP (Drexler 1974).

Lake Michigan levels have since exerted a major influence on SLBE topography in the Holocene, controlled by changing outlets, isostatic rebound, and climate (Lundstrom 2001). Lake levels have varied from 70 m during the Lake Chippewa stage (7,500 years BP) to 185 m in the Lake Nipissing stage (3,500 years BP), and settled at the current level of 177 m around 3,000 years BP (Drexler 1974). Wave-cut bluffs, beach terraces, sand bars, ridge and swale formations, and old sandy lake plains were formed by these changes, as were many of SLBE's inland lakes (Lundstrom 2001).

For a more detailed discussion on dune geology, see the section on Dunes.

Landtype Associations

In 1999, the Michigan Natural Features Inventory worked with other state and federal agencies to prepare a report on landtype associations (LTAs) for the Northern Lower Michigan Ecosystem Management Project. LTA maps are based on the Michigan Quaternary Geology map (Farrand and Bell 1982) and USDA soil surveys and were verified by comparison to maps of presettlement vegetation. LTAs are landscape ecosystem units based largely on glacial landforms (Comer and Albert 1999).

SLBE is mainly (99.3%) in Landtype Association VII.4 (Northern Lacustrine-Influenced Lower Michigan-Manistee) (Albert 1995). Over 38% of SLBE consists of moraine ridges with few kettle lakes, especially in the Bow Lakes Unit (90%) and Mainland-Central Unit (48%) and on North Manitou Island (60%). The largest landtype in the Mainland-South Unit is dune or swale or traverse dunes in embayment (39%). The Mainland-North Unit consists of nearly equal amounts of moraine ridges with few kettle lakes (38%) and dune and swale complex (34%). South Manitou Island is almost half (46%) flat lake plain. Large, open dunes are most common in the Mainland-Central Unit and on North and South Manitou Islands (Comer and Albert 1999; Table 5, Figure 10).

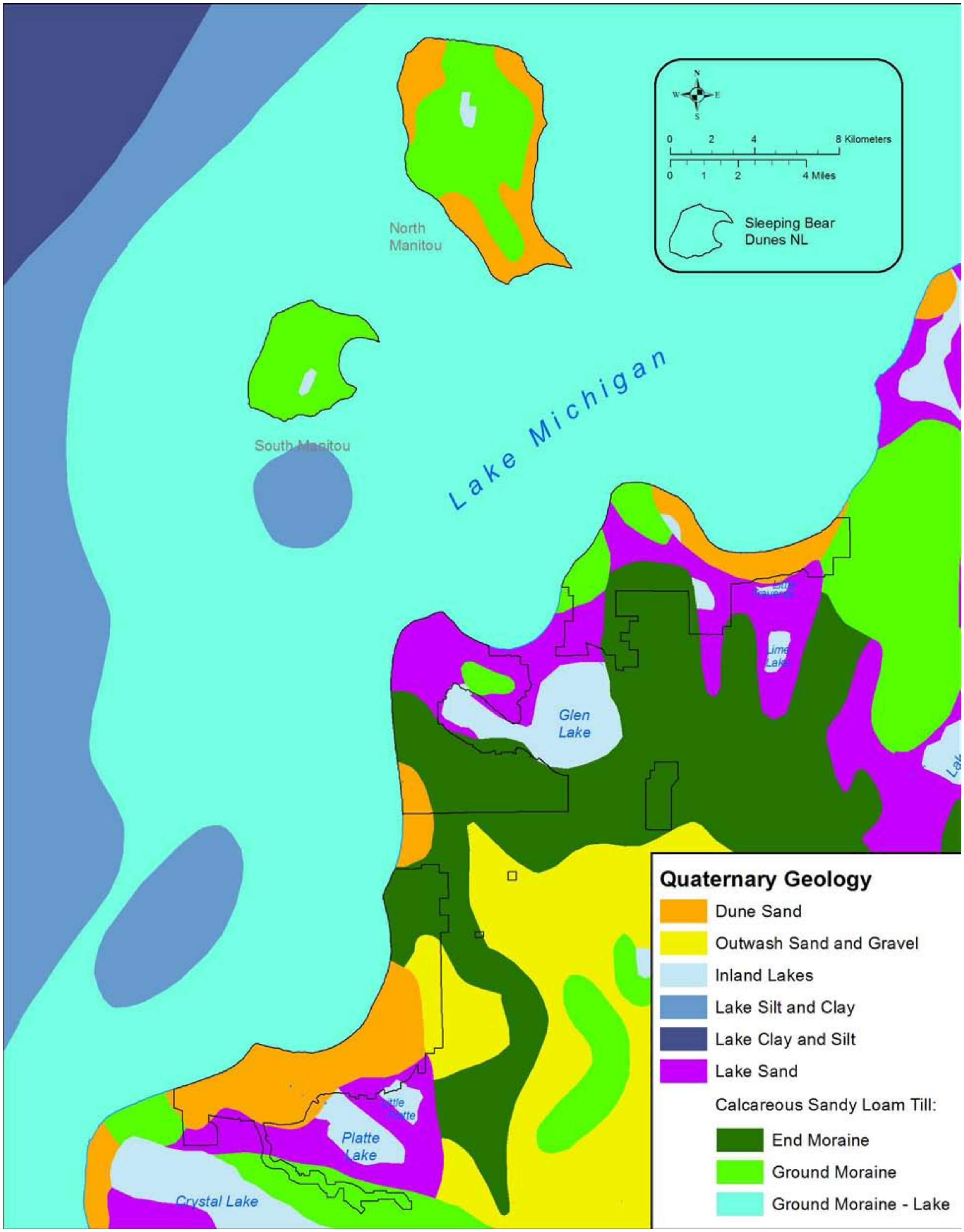

Figure 9. Surficial Quaternary geology of the Sleeping Bear Dunes National Lakeshore area (Richmond and Fullerton 2001).

Table 5. Number of hectares and percent of each landtype, based on Landtype Associations (Comer and Albert 1999).

	Bow Lakes Area	Inland-South and Central	Mainland-North	Mainland-Central	Mainland-South	North Manitou	South Manitou	Totals
Moraine ridges, few kettle lakes	355.7		1,845.5	2,305.1	553.8	3,467.9	698.7	9,226.8
	90.1%		37.7%	48.2%	9.2%	59.5%	32.3%	38.3%
Flat lake plain; sand, loamy sand, or sandy loam			1,281.8	10.5	230.6	1,064.2	998.3	3,585.3
			26.2%	0.2%	3.8%	18.3%	46.2%	14.9%
Large, open dunes				1,043.8	420.3	699.5	463.6	2,627.1
				21.8%	7.0%	12.0%	21.5%	10.9%
Dune and swale or transverse dunes in embayment					2,327.2			2,327.2
					38.7%			9.7%
Broad moraine ridges, till plain, or upland drumlin field; few lakes		10.0		1,106.4	948.8			2,065.2
		37.9%		23.1%	15.8%			8.6%
Dune and swale complex; very poorly drained peat or muck			1,666.6	318.3				1,984.8
			34.0%	6.7%				8.2%
Flat lake plain; very poorly drained peat or muck					915.9			915.9
					15.2%			3.8%
Flat moraine or till plain			104.4			598.7		703.2
			2.1%			10.3%		2.9%
Broad, flat outwash plain; few lakes or wetlands		16.4			615.9			632.3
		62.1%			10.2%			2.6%
Pitted outwash plain	39.0							39.0
	9.9%							0.2%
Lake				1.4				1.4
				<0.1%				<0.1%
Totals	394.7	26.4	4,898.3	4,785.4	6,012.4	5,830.2	2,160.6	24,108.1

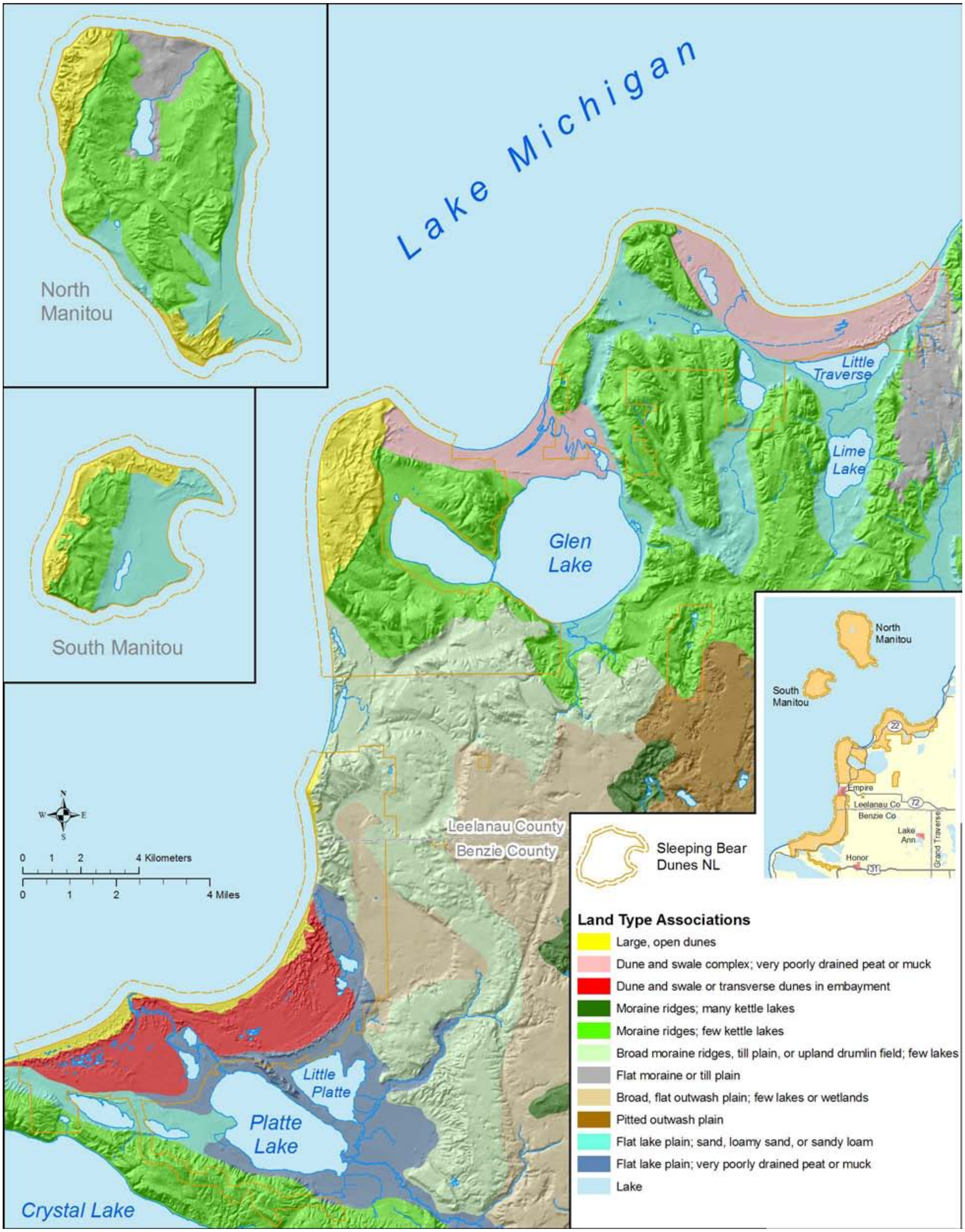

Figure 10. Landtype associations for Sleeping Bear Dunes National Lakeshore (Comer and Albert 1999General Hydrology and Water Budget

A water budget has not been completed specifically for SLBE, but a number of references provide general insight on the water budget and park hydrology. Annual precipitation at Frankfort, 8 km S of SLBE, is 89 cm (NCDC 2004). Measured pan evaporation rates at Frankfort and at Maple City are each 49 cm $year^{-1}$ (NRCS n.d.), and potential evapotranspiration rates for field crops for the period 2002-2006 were 75-79 cm (MSU n.d.). The annual groundwater recharge rate in the Betsie-Platte hydrologic unit area is 24 cm (Neff et al. 2005). Glen Lake and the Crystal River receive more than 50% of their water supply as direct groundwater input (Heiman and Woller 2003). For the entire Lake Michigan basin, groundwater contributes 79% of streamflow while surface runoff makes up the other 21%; no estimates were specifically made for SLBE streams (Holtschlag and Nicholas 1998).

Grannemann et al. (2000) have estimated that inputs to Lake Michigan consist of approximately 1,500 m^3sec^{-1} precipitation (52%), 250 m^3sec^{-1} direct surface runoff (9%), 900 m^3sec^{-1} indirect groundwater discharge (stream baseflow) (31%), 170 m^3sec^{-1} return flows to the lake from water users (6%) (reduced by a 90 m^3sec^{-1} diversion for the Chicago Ship and Sanitary Canal), 80 m^3sec^{-1} direct groundwater discharge (3%), and 1.4 m^3sec^{-1} diversions into the lake (<1%). Lake outputs consist of approximately 1,160 m^3sec^{-1} evaporation from the surface (40%), 1,470 m^3sec^{-1} outflow to Lake Huron (51%), 212 m^3sec^{-1} surface water withdrawals (7%), and 60 m^3sec^{-1} groundwater withdrawals in the watershed (2%).

Lake Michigan

Physical Limnology

SLBE is located in and along the shore of Lake Michigan, the third largest Laurentian Great Lake by surface area (Schwab et al. 2005) and the largest lake entirely within the borders of the United States. The low water datum for the lake is 175.8 m; based on this datum, the lake is 494 km long and 190 km wide and has a total shoreline length of 2,670 km (Schwab et al. 2005). Lake Michigan's watershed encompasses 118,000 km^2 of land, and the lake's surface is 58,000 km^2 (Beeton et al. 1999). The lake water residence time is approximately 69 years (Quinn 1977).

Lakes Michigan and Huron have the same water level because they are connected through the Straits of Mackinac and there is no hydrologic control between them (Beeton et al. 1999). The long-term mean lake level for Lake Michigan is 176.6 m (NOAA 2007a), with an overall range of approximately 2 m in annual average levels (Schwab et al. 2005). It reached record high levels of 177.5 m in 1886 and 1986; its record low of 175.6 m occurred as a result of the continental drought of 1964 (NOAA 2008). The lake has been below its long-term mean since 1998 (USACE 2006; NOAA 2007a).

SLBE is located in the eastern part of the northern basin of Lake Michigan, which is separated from the southern basin by a mid-lake sill extending from Milwaukee to Muskegon (Figure 11; MCGI n.d.; NGDC and GLERL 2006). This northeast part of the lake has an irregular bottom and is characterized by numerous north-south trending valleys and ridges (Schwab et al. 2005). Much of the offshore area out to the Manitou Islands is relatively shallow (15-20 m), but an area of 95 m depth occurs in the Manitou Straits, and water depths approximately 13 km west and northwest of the islands are 185 m (Figure 11).

Lake Michigan is monomictic, mixing freely from early winter through spring but then achieving thermal stratification in late May to early June and ending in late December to mid-January. Ice cover varies from open water to 70% or greater from mid-December to the end of April (Schwab et al. 2005), but averages a maximum of 45% in February (Beeton et al. 1999). Thermal variations are one source of water movement; other Great Lakes water movements are created by processes listed by Beeton et al. (1999) that include "free and forced lake oscillations, internal waves, wind-generated surface waves, and short and long-term lake level variations." Seiches are oscillations caused by atmospheric disturbances passing over the lake; small seiches of <0.3 m are a daily occurrence on the lake, while larger seiches associated with storm surges may cause flooding in low-lying areas (Keillor 1998).

Circulation is cyclonic (counterclockwise) in Lake Michigan's northern and southern basins (Beletsky et al. 1999), which means that currents move from the south to the north along the SLBE shoreline. Circulation is stronger in winter (averaging 2.4 cm/s from November-April) than in summer (averaging 1.3 cm/s from May-October) because of stronger winds. Along the mid-lake sill south of SLBE, currents are anticyclonic and stronger than in the basins, reaching a maximum speed of 4.5 cm/s (Figure 12; Beletsky et al. 1999).

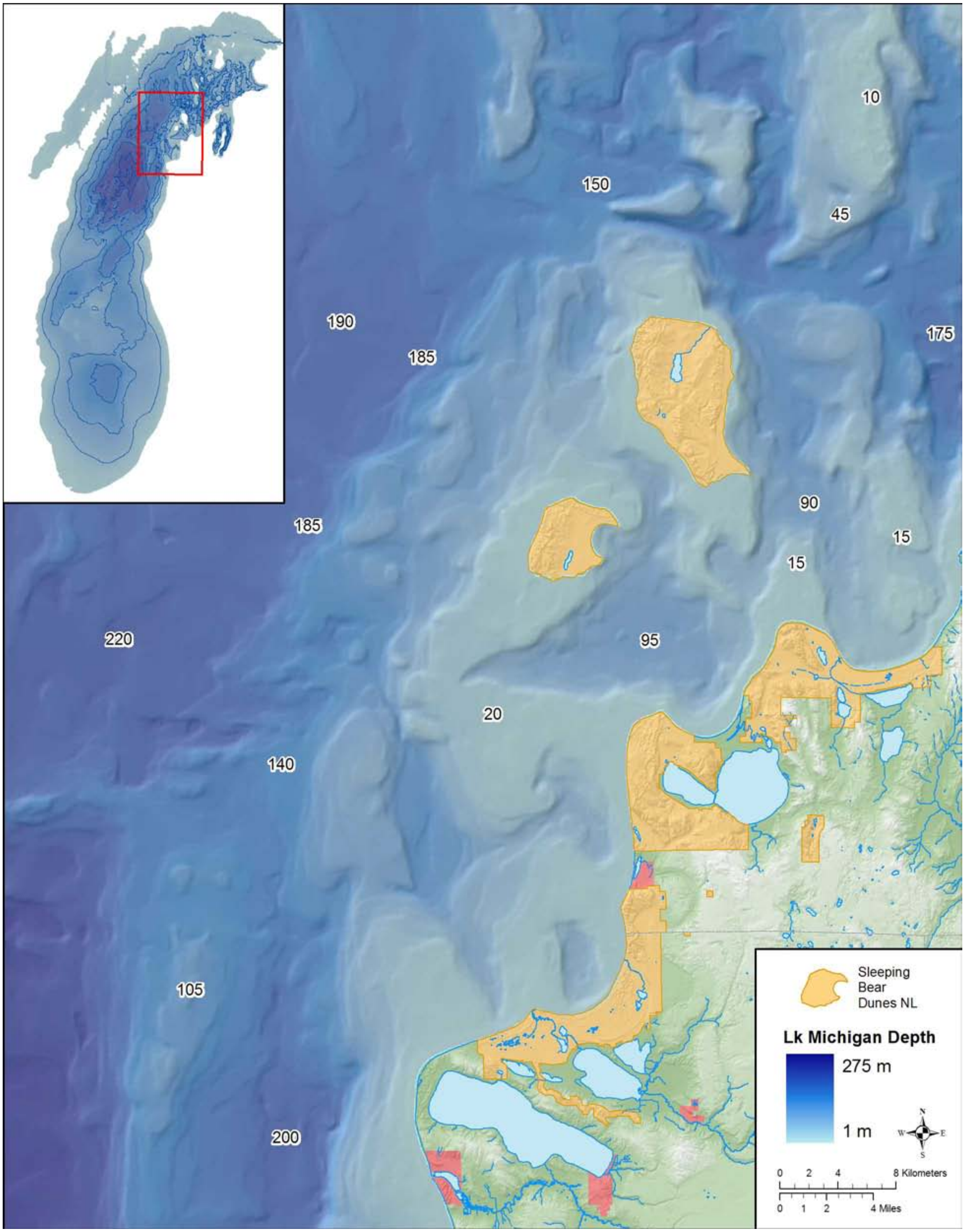

Figure 11. Lake Michigan bathymetry in the vicinity of Sleeping Bear Dunes National Lakeshore (MCGI n.d.; NGDC and GLERL 2006).

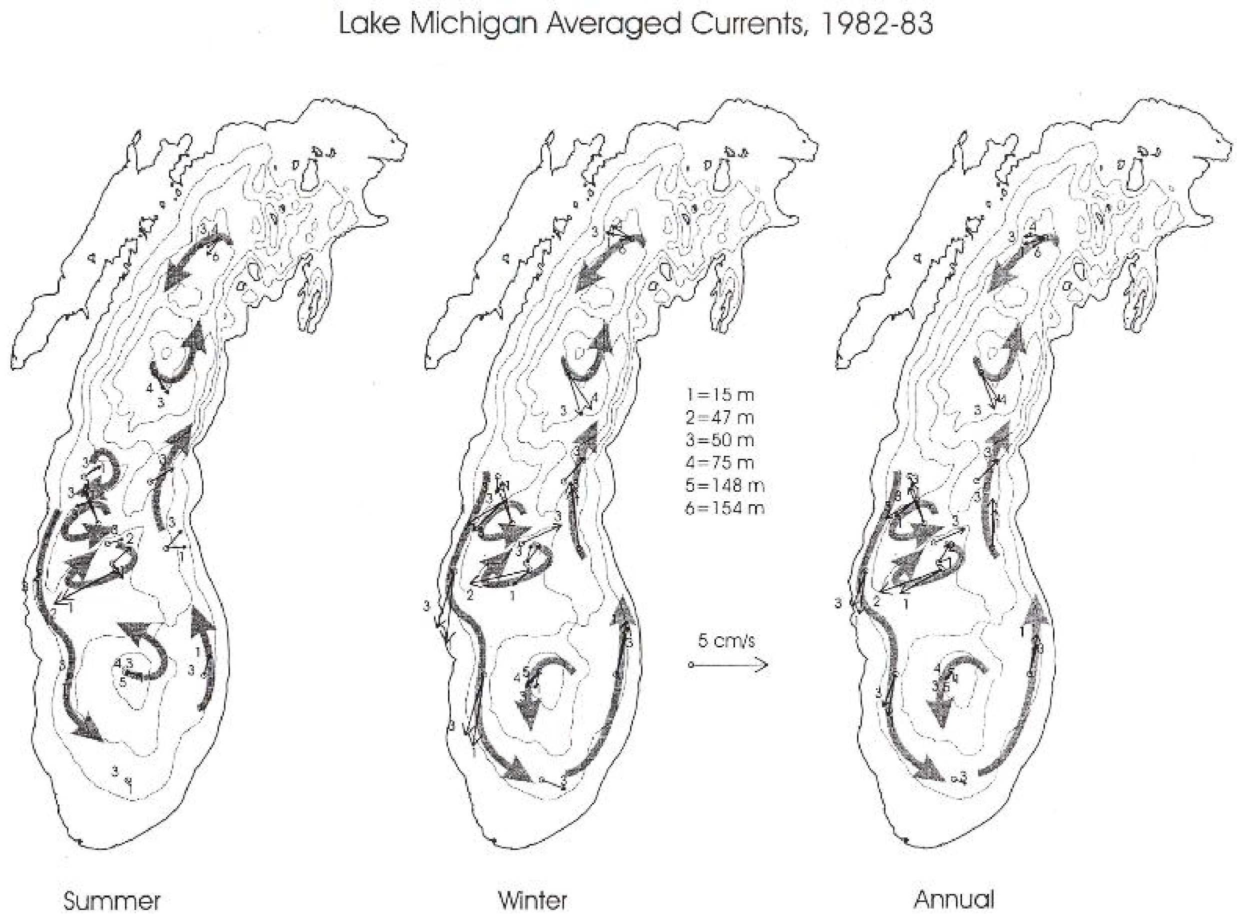

Figure 12. Lake Michigan averaged currents, 1982-1983 (Beletsky et al. 1999).

Trophic State

Lake Michigan's current trophic state is oligotrophic (USEPA 2006c). Based on diatom paleolimnology, northern Lake Michigan has experienced varied trophic conditions related to anthropogenic changes in the watershed from the time of European settlement (Table 6; Stoermer 2005).

Habitats

Coastal Wetlands

Coastal wetlands provide more food and shelter for wildlife than any other Great Lakes basin habitat (Jude et al. 2005a). They are substantial contributors to primary productivity and provide habitat for invertebrates, amphibians, reptiles, waterfowl, mammals, and fish (Herdendorf 1987). More than 90 percent of Great Lakes fish rely on coastal wetlands for at least a part of their life cycles (Albert 2003). Although approximately half of the wetlands that once existed in the state of Michigan had been destroyed by 1980, Lake Michigan still has 490 km^2 of coastal wetlands and 6,409 km^2 of littoral zone (Jude et al. 2005a). Lake Michigan has the largest number of coastal wetlands (460) on the US Great Lakes shoreline (Simon et al. 2005).

Table 6. Changes in northern Lake Michigan trophic state and population structure as evidenced by diatom paleolimnology since about 1470 (Stoermer 2005; MDEQ 2006e).

Time period	Trophic state and cause
1470-1885	Relatively stable prior to European settlement, except for a cold period around 1735.
1885	Modest but rapid eutrophication caused by land clearing.
After 1885	Modest recovery with landscape revegetation, but large-scale introductions of exotic species and extirpation of native species.
1925- early 1950s	Progressive eutrophication resulting from population growth and industrialization. Further exotic introductions and some extirpations.
1954-1964	Very rapid eutrophication from increased sewage discharges and use of phosphate-based detergents. Further introductions of exotics and extirpations.
1977	Partial decline in eutrophication caused by phosphate detergent ban and improved sewage management.
Present	Continued increase in water transparency related to introduction of zebra (*Dreissena polymorpha*) and quagga (*D. rostriformis bugensis*) mussels. Continuing changes in population structure caused by shifting dominance of native populations, exotic introductions, and extirpations of native species.

Various authors (Herdendorf et al. 1981; Albert 2003; Simon et al. 2005) have identified coastal wetlands in SLBE, generally in the areas of Good Harbor Bay, Point Oneida, North Manitou Island, and Platte Bay (Table 7). Simon et al. (2005) included Herdendorf's wetlands and added others based on a classification scheme for drowned river mouths suggested by Keough et al. (1999). Herdendorf et al. (1981) classified wetlands as lacustrine, palustrine or riverine, while Keough et al. (1999) classified them as open, protected, or drowned river mouth-flooded estuary wetlands. These differing classification schemes and naming conventions make it difficult to determine the exact number and sizes of unique wetlands at the locations inTable 7.

Table 7. Coastal wetlands in Sleeping Bear Dunes National Lakeshore (Herdendorf et al. 1981; Albert 2003; Simon et al. 2005).

Name	Reference	Size (ha)	Type
Good Harbor Bay Wetland #1	Herdendorf	35.6	Palustrine
Good Harbor Bay Wetland #2	Herdendorf	66.8	Palustrine/coastal beach ridges
Good Harbor Bay Wetland #2 (Shalda Creek)	Simon	66.8	Drowned river mouth
Good Harbor Bay Wetland #3	Herdendorf	15.8	Lacustrine
Port Oneida Wetland	Herdendorf	110.1	Palustrine
Point Oneida (Crystal Run)	Simon	110.1	Drowned river mouth
Leland Township Wetland (North Manitou Island)	Herdendorf	4.0	Palustrine
Tamarack Lake Wetland (North Manitou Island)	Herdendorf	23.4	Palustrine
Otter Creek	Simon	60.7	Drowned river mouth
Platte Bay	Albert	--	Dune and swale complex
Platte River	Simon	30.4	Drowned river mouth
Platte River Point	Albert	--	Dune and swale complex

Inshore Waters

The open waters of Lake Michigan are divided into inshore and offshore zones based on depth of the water column. In the Lake Michigan lakewide management plan (LaMP), the boundary between them is the depth at which vertical thermal stratification can be measured in summer, and may be as deep as 30 m by the end of summer (LMTC 2000). The LaMP also appears to use the term "nearshore" interchangeably with "inshore." An alternative fixed boundary designation at 10 m in depth is being used between inshore and offshore by agencies working on the Great Lakes regional aquatic gap analysis (USGS 2003). Clapp et al. (2005) describe inshore waters as those less than 45 m, and state that they account for 31% of the Lake's area. Munawar et al. (2005), in their assessment of the planktonic food web, separate the nearshore from the offshore zone at 20 m.

In any case, the inshore zone is the zone responsible for much of the biological productivity and richness of the lake (LMTC 2000). Organisms that use the inshore zone seasonally, or for parts of their life cycle, include insects, reptiles, amphibians, mammals, migrating birds, and fish. The inshore zone benefits from the energy inputs of water currents, waves, and wind; warm, well-oxygenated water; and inputs of dissolved nutrients, sediment, and organic matter from the land (LMTC 2000).

Offshore Waters

Offshore waters (those >45m in depth) make up 69% of the area of Lake Michigan (Clapp et al. 2005). Coldwater fish, including trout, salmon, and whitefish, are the dominant fauna in this zone (LMTC 2000). Light penetration extends to more than 60 m in some areas. Phytoplankton occupy the upper layers of the open lake, while zooplankton colonize the entire water column (LMTC 2000). The offshore zone serves as a sink for energy and material resources when they are stored in bottom deposits, but these resources may be recycled to shallower areas by fish (LMTC 2000).

Underwater Devonian limestone reefs were important spawning grounds for lake trout before the trout were extirpated in the 1950s. Dawson et al. (1997) used commercial lake trout fishing records to identify important historic spawning points and areas offshore adjacent to the Manitou Islands and onshore (defined as connected to the mainland by <40 m depths on at least three sides) at the south reef of Good Harbor Bay, Pyramid Point reef, the east side of Sleeping Bear Bay, and the Platte River reef (Figure 13). Today, these sites are in a primary management zone for lake trout stocking, second in significance only to two refuge zones where lake trout fishing is not allowed. One such zone is just north of North Manitou Island, extending northward to Beaver Island (Figure 13; MDNR 2006).

Rare species found in offshore waters include the state-threatened lake sturgeon (*Acipenser fulvescens*) and lake herring (*Coregonus artedi*) (Appendix C).

Sand and Gravel Beaches

SLBE has 25.3 km of sand beaches, 72.6 km of mixed sand and gravel beaches, and 5.5 km of gravel beaches (USEPA Region 5 2000; Pendleton et al. 2007). The Michigan Natural Features Inventory (MNFI) classifies the sand and gravel beach areas of the Great Lakes in Michigan as both "found in a restricted range at a global scale" (G3) and "rare or uncommon in the state of Michigan" (S3) (MNFI 2006). Sand and gravel beaches are characterized by both low levels of plant cover and a low diversity of plant species (Albert 2007). Michigan indicator species for sand and gravel beaches are the plants sea rocket (*Cakile edentula*), seaside spurge (*Chamaesyce polygonifolia*), Baltic rush (*Juncus balticus*), silverweed (*Argentina anserina*), marram grass (*Ammophila breviligulata*), sand reed grass (*Calamovilfa longifolia*), chair maker's rush (*Schoenoplectus americanus*), hard-stem bulrush (*Scirpus acutus*), sandbar willow (*Salix exigua*), Pitcher's thistle (*Cirsium pitcheri*), Lake Huron tansy (*Tanacetum huronense*), and sand cherry (*Prunus pumila*) (Albert 2007). Of these, all but Lake Huron tansy were reported in SLBE by Hazlett (1991).

SLBE's gravel beaches are home to rare plants and animals, including the federal-threatened Pitcher's thistle. Bird species associated with SLBE's gravel beaches include the federal-endangered piping plover (*Charadrius melodus*) and state-threatened Caspian tern (*Sterna caspia*) and common tern (*S. hirundo*) (Appendix C; Albert 2007).

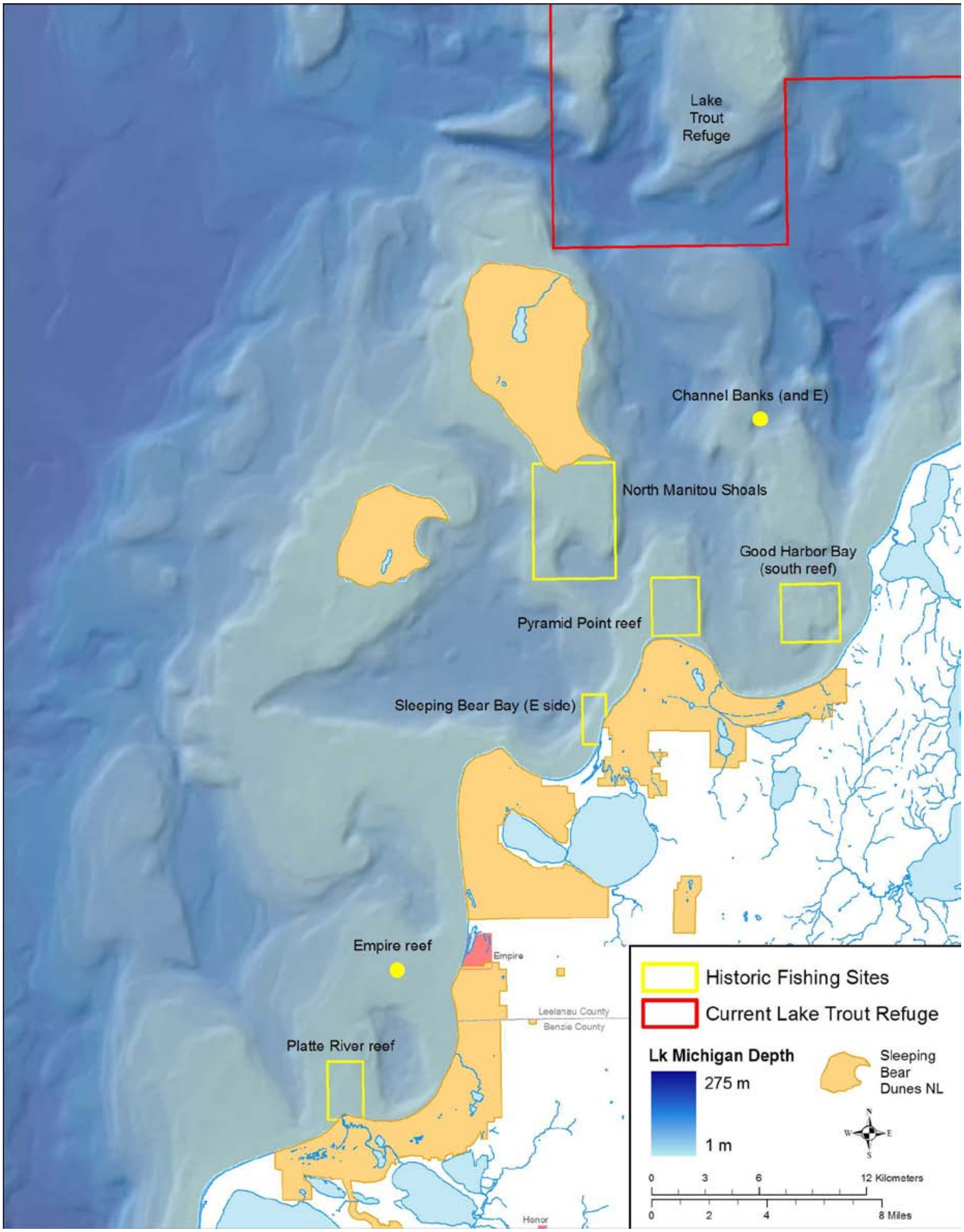

Figure 13. Historic lake trout spawning areas/commercial fishing sites (points and areas) and the current lake trout refuge in the vicinity of Sleeping Bear Dunes National Lakeshore (Dawson et al. 1997; MDNR 2006).

Dunes

A recent mapping effort indicates that 16% of the total land area of SLBE is covered with dunes (Larson et al. 2000; Pranger ca. 2005b). Two levels of dunes occur in SLBE: those at the level of Lake Michigan in lowland embayments along Platte Bay, Sleeping Bear Bay, Good Harbor Bay, and Empire, and those perched on morainal plateaus 100 m above lake level at Empire Bluffs, Sleeping Bear Plateau, and Pyramid Point (Handy and Stark 1984; Lundstrom 2001). The perched dunes around Sleeping Bear Point are still actively moving to the northeast (Handy and Stark 1984). The Manitou Islands also have significant areas of dunes (Figure 4). Dune forms in SLBE include parabolic, longitudinal, transverse, and foredune ridges, and others that do not neatly fit into these categories (Lundstrom 2001).

The age of the dunes has been the subject of some controversy in recent years (Harman and Arbogast 2004). The general view in Great Lakes literature has been that the dunes formed 4,000-6,000 years BP during the Nipissing high stand (Dorr and Eschman 1970; Buckler 1979; Harman and Arbogast 2004). However, current research indicates that SLBE's dune landscape is dominated by perched dunes that formed over the past 1,500 years in an approximately 150 year cycle (Loope and Arbogast 2000; Harman and Arbogast 2004).

Landslides have occurred three times in the last century (1914, 1971, and 1995) in a 500 m stretch of coastal dune along Sleeping Bear Point. One hypothesis for this instability is subterranean pipe erosion through a paleochannel between Glen Lake and Lake Michigan (Barnhardt et al. 2004).

Laurentian Great Lakes dunes are distinguished from other coastal dunes by a largely distinctive flora and fauna (MNFI 2004). The MNFI classifies the open dune areas of the Great Lakes in Michigan as both "found in a restricted range at a global scale" (G3) and "rare or uncommon in the state of Michigan" (S3) (MNFI 2006). Michigan indicator species for open dunes are the plants sea rocket, wormwood (*Artemesia campestris*), beach grass (marram grass), dune reed (sand reed grass), Pitcher's thistle, Lake Huron tansy, creeping juniper (*Juniperus horizontalis*), sand cherry, and Gillman's goldenrod (*Solidago simplex*) (MNFI 2004). Of these, all but Lake Huron tansy and Gillman's goldenrod were reported by Hazlett (1991) on SLBE dunes.

Pranger (ca. 2005b) determined dune vegetation types for SLBE and developed a dune sensitivity index with a scale of 1-10, with 10 being most sensitive to human disturbance. The factors considered in the index were based on vegetation categories and considered both carrying capacity (ability to withstand human passage) and recovery time. Northern hardwood forests, coastal forests, and northern conifer forests were the most susceptible dune vegetation in SLBE, with a sensitivity index value of 6.0; other values were dune grasses and shrubs, 3.75; fields, 2.5; and jack pine, 3.0 (Pranger ca. 2005b). Using this index, Pranger (ca. 2005b) determined that the most sensitive dunes are on North Manitou Island and in the Mainland-North, and the least sensitive were in the Mainland-Central (Table 8).

SLBE's dunes are home to rare plants and animals. The federal-endangered piping plover and federal-threatened Pitcher's thistle are associated with SLBE's dunes. The prairie warbler (*Dendroica discolor*) is a state-endangered species. State-threatened species in SLBE's dunes are the merlin (*Falco columbarius*), the Caspian and common terns, and the plant called fascicled or clustered broom-rape (*Orobanche fasciculata*) (Appendix C; MNFI 2006).

Table 8. Vegetative cover by park unit and dune type for dunes in Sleeping Bear Dunes National Lakeshore (Larson et al. 2000; Pranger ca. 2005b).

		Vegetation Type (ha)					
	Dune Sensitivity Index	Northern Hardwoods or Coastal Forest	Dune	Fields	Northern Conifer	Jack Pine	Total
Perched dunes (Sleeping Bear deposit)							
North Manitou	5.87	661.5	40.2	0.0	0.0	0.0	701.7
South Manitou	4.76	156.8	199.9	6.1	17.3	0.0	380.0
Mainland-North	5.62	52.2	0.0	6.3	0.0	0.0	58.5
Mainland-Central	3.75	0.0	553.5	0.0	0.0	0.0	553.5
Mainland-South	4.99	126.4	11.8	0.0	0.0	0.0	138.2
Total	5.05	996.9	805.4	12.3	17.3	0.0	1,831.9
Beach/dune complex							
North Manitou	3.38	0.6	34.4	16.5	0.0	0.0	51.5
South Manitou	4.90	125.3	59.1	36.0	15.1	0.0	235.5
Mainland-North	5.65	468.8	23.9	48.8	100.4	0.0	642.0
Mainland-Central	4.03	131.7	432.1	88.9	0.0	1.1	653.8
Mainland-South	4.99	944.0	265.1	2.9	0.0	22.6	1,234.6
Total	5.08	1,670.4	814.5	193.1	115.6	23.7	2,817.3

The state of Michigan has designated protected areas of “critical dunes” and described them as “a unique, irreplaceable, and fragile resource that provide significant recreational, economic, scientific, geological, scenic, botanical, educational, agricultural, and ecological benefits to the people of this state and to people from other states and countries who visit this resource” (State of Michigan 1994). Most of the dunes within SLBE have been designated as critical dunes (MDEQ 1996a, b; Figure 14).

For details on exotic species on dunes, see the Exotic Species-Terrestrial section below. For details on impacts of climate change and lake level changes on dunes, see the Climate Change section below.

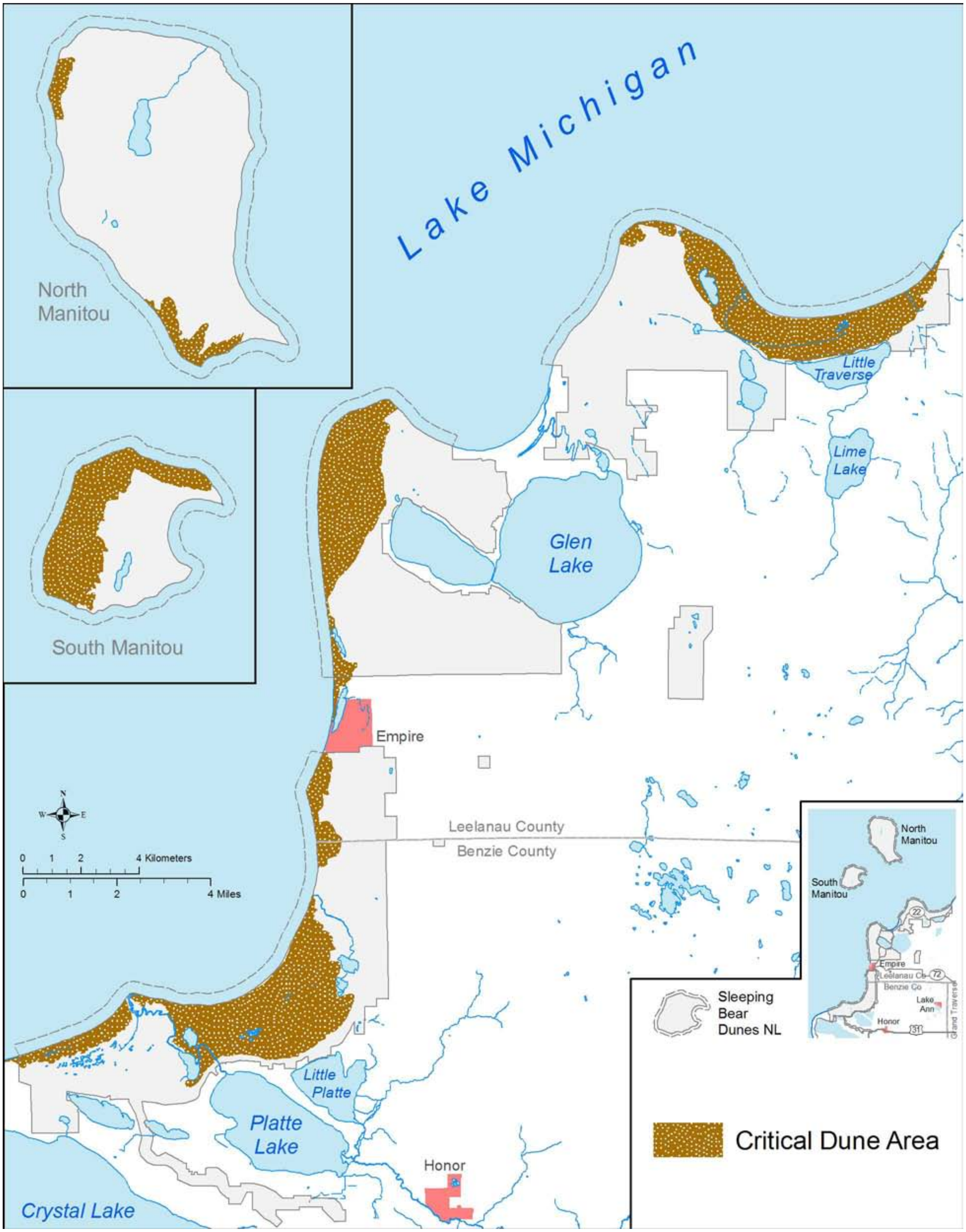

Figure 14. Dunes designated as "critical dunes" by the Michigan Department of Environmental Quality (MDEQ 1996a, b).

Biota

Phytoplankton

Historic reports indicate that Lake Michigan phytoplankton were dominated by diatoms at all times (Barbiero and Tuchman 2001). However, from the mid-1950s to the 1970s, dissolved silica concentrations needed for diatom production decreased in Lake Michigan. The cause was that increases in phosphorus loading caused increases in diatom production, which led to increased deposition of silica to sediments (and thus less silica availability) as the diatoms died (Barbiero et al. 2002). From the late 1960s through the 1970s, Cyanophyta (blue-green algae) and Chlorophyta (green algae) were the summer dominants. In the 1980s, summer phytoplankton communities shifted to phytoflagellate (Cryptophyta, Chrysophyta, and dinoflagellate) dominance, and these species were prevalent in summers from 1983-1999. However, diatoms still contributed the largest amount of phytoplankton biomass on an annual basis. Biomass volumes suggested that the pelagic waters were oligotrophic from 1983-1999 (Makarewicz 2005).

At 11 Lake Michigan sites, phytoplankton samples are collected annually during the spring isothermal period and the summer stratified period as part of USEPA's biological surveillance sampling program for the Great Lakes. A composite is made of water samples taken with a Niskin bottle at discrete depths (spring: surface, 5m, 10m, and 20m; summer: surface, 5m, 10m, and upper metalimnion) (Barbiero and Tuchman 2005). The most recent published reports on these samples cover the years 1998 (Barbiero and Tuchman 2001) and 1999 (Barbiero and Tuchman 2005). In spring 1998, the deep water sampling site approximately 24 km northwest of South Manitou Island (MI47) (Figure 15) had the greatest total phytoplankton population of the 11 sites, with over 75% of the phytoplankton biomass provided by diatoms. In summer 1998, approximately half the phytoplankton biomass at MI47 was composed of chrysophytes, and cryptophytes and cyanophytes together made up approximately another 25% (Barbiero and Tuchman 2001).

Results by site were not provided for 1999, but the filamentous centric diatoms *Aulacoseira islandica* and *A. subarctica* were the dominant spring species lakewide. In summer 1999 the "overwhelming" dominant lakewide was the dinoflagellate *Ceratium hirundinella* (Barbiero and Tuchman 2005). Chrysophytes and cyanobacteria increased in importance compared to spring. It is expected that as phosphorus loading continues to decrease, the lake's phytoplankton communities will be closer to their historic condition of year-round diatom dominance (Barbiero and Tuchman 2005).

The USEPA and Environment Canada (2007) have established a general objective that phytoplankton biomass size and structure should be indicative of oligotrophic conditions in Lake Michigan, but an index by which to evaluate the phytoplankton community has not yet been developed. The two most important future pressures on the community are changes in nutrient loading and the presence and expansions of non-native species populations, especially, but not limited to, zebra and quagga mussels (USEPA and Environment Canada 2007).

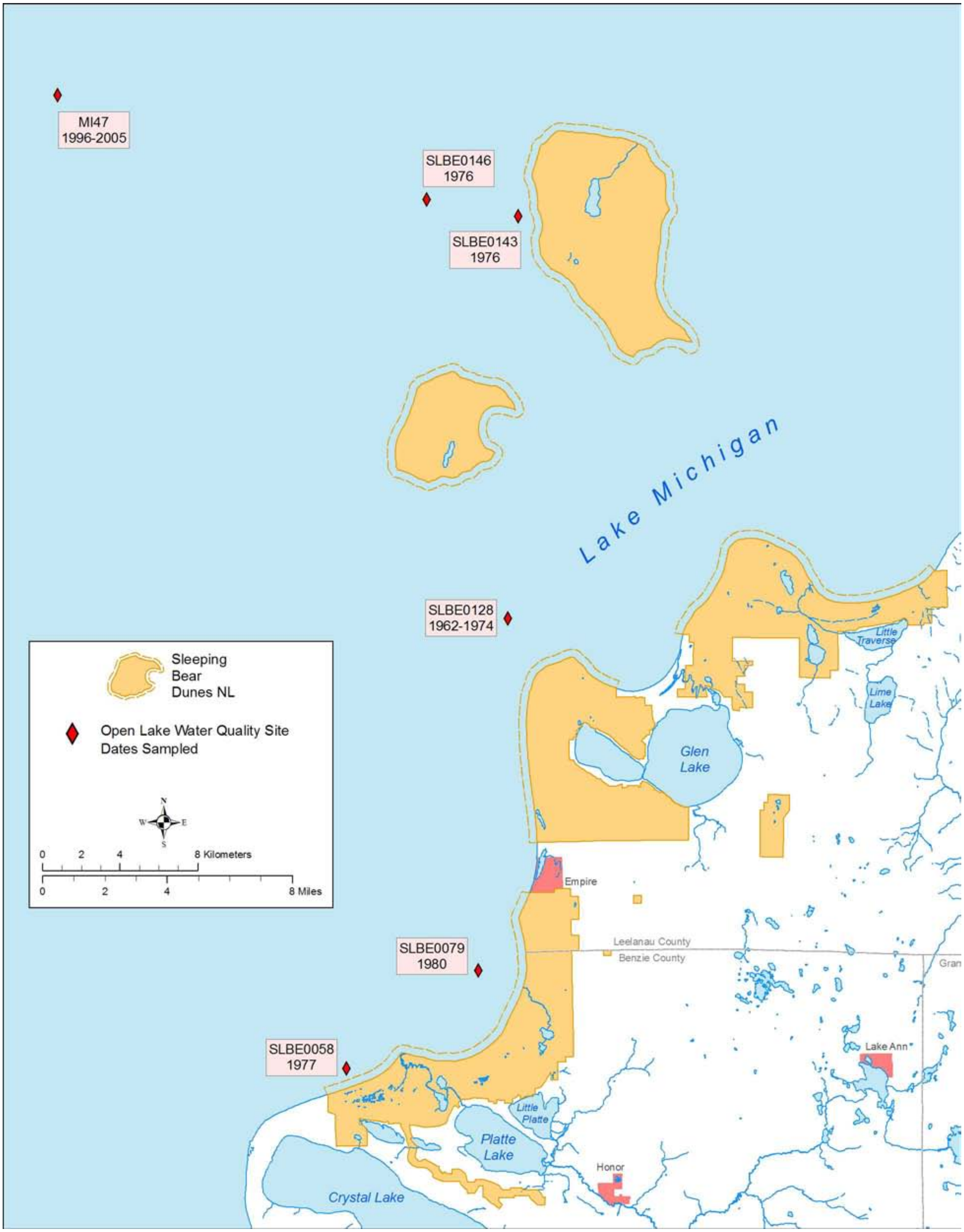

Figure 15. Locations of Lake Michigan open water sampling sites in the vicinity of Sleeping Bear Dunes National Lakeshore (NPS 1997b; Warren and Kreis 2005).

Zooplankton

The offshore crustacean zooplankton community in Lake Michigan is restricted to a relatively small number of taxa. Only 11 crustacean zooplankton taxa were found in offshore waters of Lake Michigan in spring of 1999 (the most recent year for which a species-specific published report was found); the most common of these were the cyclopoid *Diacyclops thomasi* and the calenoids *Limnocalanus macrurus*, *Leptodiaptomus ashlandi*, and *L. minutus.* The cladoceran *Daphnia mendotae* was the typical summer dominant. Other members of the offshore crustacean community included the calenoids *Leptodiaptomus sicilis*, *Skistodiaptomus oregonensis*, and *Epischura lacustris*; the cyclopoid *Tropocyclops extensus*; the cladoceran *Bosmina longirostris*; and the predators spiny water flea (*Bythotrephes longimanus*, an exotic species), *Leptodora kindti*, and *Polyphemus pediculus* (Barbiero and Tuchman 2005; Barbiero et al. 2005). "Profound differences" were noted in both species composition and abundance between inshore and offshore zooplankton communities in Lake Michigan in the 1970s, which presumably persist to this day (Beeton et al. 1999).

In the Great Lakes, calanoid copepods dominate oligotrophic communities, while cladocerans and cyclopoids are more indicative of nutrient-enriched waters (Gannon and Stemberger 1978). Offshore Lake Michigan summer zooplankton communities have increased their proportion of calanoid copepods in recent years, suggesting an improved trophic state (USEPA and Environment Canada 2007). However, overall offshore crustacean zooplankton biomass decreased in each annual survey of Lake Michigan between 2002 and 2005 (USEPA and Environment Canada 2007). The crustacean zooplankton community in Lake Michigan has experienced several shifts in the last fifty years that are not entirely understood; causes may include the expansion of alewife populations in the 1960s; the invasion of the spiny water flea, the fishhook water flea (*Cercopagis pengoi*), and dreissenid mussels; reduction in phosphorus inputs which has changed phytoplankton communities; and decimation of native lake trout and their replacement with stocked salmonines (Barbiero et al. 2005).

Aquatic and Shoreline Vegetation

No inventory of aquatic and shoreline vegetation in Lake Michigan wetlands was found for SLBE. However, Uzarski et al. (2004) suggest that typical wetlands in the SLBE vicinity would be northern Lake Michigan fringing coastal wetlands. These may have three zones: a wet meadow zone dominated by sedges (*Carex* spp.) and blue joint (*Calamagrostis canadensis*), an inner bulrush (*Scirpus* spp.) zone mixed with pickerel weed (*Pontederia* spp.) and submergents, and an outer bulrush zone. However, pickerel weed is not known in Benzie or Leelanau Counties.

Benthos

A literature review by Cook and Johnson (1974) found that benthos of the deeper waters of the southern basin of Lake Michigan were composed mainly of *Diporeia* (64-65%), Tubificidae (20-24%), and Sphaeriidae (5-15%) in surveys taken from the mid-1930s to the 1960s. Recent samples (summer 1999) collected at MI47 (Figure 15) were similarly dominated by *Diporeia* (>75%), followed by oligochaetes (Tubificidae) and sphaeriids (Sphaeriidae) (Barbiero and Tuchman 2002). The "concentration zone" for benthos was reported by various authors to be at depths of 35-50 m or 20-60 m (Cook and Johnson 1974).

The abundance of the three major benthic taxa (*Diporeia*, Tubificidae, and Sphaeriidae) increased from the 1930s to the early 1980s, mainly in shallow water (20-40 m) (Nalepa et al. 2005). Shifts in species composition (a decreased percentage of *Diporeia* and increased percentage of oligochaetes) were noted at shallow sites where nutrient enrichment was occurring (Cook and Johnson 1974). Abundances of *Diporeia* and sphaeriids declined at depths less than 50 m from the early 1980s to 1998-99; oligochaetes at these depths declined only from the early 1980s to 1992-93 and then stabilized (Nalepa et al. 2005).

Information on long-term trends in major macrobenthic taxa other than *Diporeia* was reported lacking for the lake's northern basin by Nalepa et al. (2005). Observed changes in the overall abundance and population composition of benthos in the lake's southern basin have been attributed to increased phosphorus loading, a trend that was reversed in the mid-1970s, and to invasive species (Nalepa et al. 2005). Perhaps of greatest concern to lake managers is the "dramatic" decline in *Diporeia* populations, most likely attributable to the population increase in dreissenid mussels (USEPA and Environment Canada 2007). *Diporeia* is a benthic amphipod that is particularly important as a food source for forage fish and is a key component of the food web in offshore regions. The status of *Diporeia* in Lake Michigan as a whole is considered to be poor and deteriorating (USEPA and Environment Canada 2007). In the northern part of the Lake Michigan basin, the population decline was 91% between 1994-95 and 2000 (Nalepa et al. 2006). A 2005 lakewide survey showed that abundances were lower by 84% compared to 2000. They are no longer found at depths <80 m (USEPA and Environment Canada 2007).

Fish

Ninety-eight species of fish, including native species, planned introductions, and accidental introductions, as well as extinct species, are known in Lake Michigan waters (Appendix E; Eshenroder et al. 1995). These include planktivores, benthivores, and piscivores, and are often divided by researchers into inshore and offshore communities.

Inshore Fish Community: Members of the Lake Michigan inshore fish community (<45 m depth) considered to have recreational and commercial significance by the Great Lakes Fishery Commission include the yellow perch (*Perca flavescens*), walleye (*Sander vitreus*), smallmouth bass (*Micropterus dolomieu*), northern pike (*Esox lucius*), muskellunge (*E. masquinongy*), catfish, and panfish (centrarchid sunfishes). Other nongame species include the spottail shiner (*Notropis hudsonius*), slimy sculpin (*Cottus cognatus*), mottled sculpin (*C. bairdi*), trout perch (*Percopsis omiscomaycus*), and Johnny darter (*Etheostoma nigrum*) (Clapp et al. 2005).

The status of Lake Michigan inshore fish communities is generally monitored by the Great Lakes Fishery Commission, which sets yield goals (Eshenroder et al. 1995). Information on inshore fish populations is also available from the USGS Great Lakes Science Center, which has conducted bottom trawls providing relative abundance and biomass estimates for prey fish species between the 5 m and 114 m depth contours of the lake each fall since 1973 (Bunnell et al. 2007). The 2005 year-class of yellow perch was the largest during the period of record 1973-2006 and was nearly three times the next-largest peak in the early 1980s (Bunnell et al. 2007). Target yields for walleye were met in only three years (1994-1996) between 1985 and 1998 (Clapp et al. 2005). Except for yellow perch and walleye, little long-term information is available on the yield (and by extension, the population) of the other inshore fishes (Clapp et al. 2005).

In 2006, Fessell (2007) made habitat observations and conducted fish seine hauls at Good Harbor Bay, Sleeping Bear Bay, the Bar Lakes shoreline, the Esch Road shoreline, and Platte Bay Lake Michigan Road. Good Harbor Bay had a largely sand substrate with large gravel and cobble deposits nearshore. Seven fish species were observed in a seine haul: spottail shiner, lake whitefish (*Coregonus clupeaformis*), emerald shiner (*Notropis atherinoides*), alewife (*Alosa pseudoharengus*), longnose dace (*Rhinichthys cataractae*), sand shiner (*Notropis stramineus*), and Chinook salmon (*Oncorhynchus tshawytscha*), in order of numeric abundance. Kelly and Price (1979) additionally observed rainbow smelt (*Osmerus mordax*) and smallmouth bass in Good Harbor Bay.

Sleeping Bear Bay's substrate is similar to that of Good Harbor Bay, with gravel and cobble likely more abundant (Fessell 2007). A seine haul yielded round goby (*Neogobius melanostomus*), Johnny darter, alewife, and longnose dace. Kelly and Price (1979) observed alewife, lake herring, spottail shiner, and longnose dace in Sleeping Bear Bay.

Fessell (2007) described the shoreline near North Bar Lake as "featureless sand with scattered gravel and stone," and observed large amounts of filamentous algae in June 2006. A seine haul yielded alewife, spottail shiner, lake whitefish, sand shiner, and emerald shiner (listed in order of numeric abundance). At another exposed beach at Esch Road, Fessell (2007) observed sparse habitat dominated by sand with some gravel and stone. Fish collected here by seine haul were spottail shiner, sand shiner, lake whitefish, alewife, Chinook salmon, and banded killifish (*Fundulus diaphanus*), in order of numeric abundance.

At Fessell's (2007) final Lake Michigan sampling site in 2006 on Platte Bay near Lake Michigan Road, the nearshore habitat was predominantly sand, with significant deposits of gravel and stone at the shore's edge. Two seine hauls yielded ten fish species: round goby, alewife, Chinook salmon, spottail shiner, lake whitefish, common shiner (*Notropis cornutus*), yellow perch, Johnny darter, sand shiner, and longnose dace, in order of numeric abundance.

Offshore Fish Community

Planktivores: The most important native planktivores historically were the deepwater ciscoes, lake herring, and emerald shiner; these have been replaced by naturalized exotic species such as the alewife and rainbow smelt. Other planktivores of significance in Lake Michigan include the bloater (*Coregonus hoyi*) and the ninespine stickleback (*Pungitius pungitius*) (Eshenroder et al. 1995; Fleischer et al. 2005).

Planktivores are significant as prey fish in the Lake Michigan food web (Fleischer et al. 2005). The biomass of four planktivores that are significant as prey fish (lake herring, bloater, alewife, and rainbow smelt) has been declining in the Great Lakes since 1990 (O'Gorman et al. 2007).

Benthivores: Important native benthivores in the Lake Michigan ecosystem include the lake whitefish, round whitefish (*Prosopium cylindraceum*), lake sturgeon, deepwater sculpin (*Myoxocephalus thompsoni*), burbot (*Lota lota*), and ninespine stickleback (Schneeberger et al. 2005; Bunnell et al. 2007). The lake whitefish is the most important commercial species harvested in Lake Michigan, yielding $11.1 million of the total $15.4 million value of fish commercially harvested in Michigan from 2000-2005 (National Marine Fisheries Service, Fisheries Statistics Division, Silver Spring, MD, pers. comm. [website], 11/6/07). Its population declined in the late 1950s because of sea lamprey (*Petromyzon marinus*) predation and an increase in the rainbow smelt population, but it rebounded during the 1960s. In northern Lake Michigan management units, its condition factors (weight vs. length) declined from 1992-1997 (Schneeberger et al. 2005). Little is known about the ecology of the round whitefish, or its size and age population structures, but it appears to be self-sustaining (Schneeberger et al. 2005). It has been of some importance as a commercial species, usually sold as 'menominee' in fish markets.

Lake sturgeon historically spawned along the shorelines of North and South Fox Islands, north of SLBE in Leelanau County (MNFI 2000). They were historically abundant and were the dominant benthivore, but are currently listed as threatened in Michigan (MNFI 2000; Schneeberger et al. 2005). Their populations appear to be once again increasing because of habitat improvements and protection from harvest (Schneeberger et al. 2005).

Burbot are an important predator in the Lake Michigan ecosystem. They are currently abundant in the Great Lakes, and their population density in Lake Michigan is high relative to other systems in the world (Schneeberger et al. 2005). Deepwater sculpin, an important diet item for burbot, made up about 38% of the total preyfish biomass in Lake Michigan in 2006 (Bunnell et al. 2007). Ninespine stickleback were the most abundant species in the USGS bottom trawls from 2003-2006 but make up only about 7% of total preyfish biomass (Bunnell et al. 2007).

Piscivores: Before the 1900s, the top offshore predators in the Lake Michigan ecosystem were burbot and lake trout (*Salvelinus namaycush*). By the 1950s, lake trout were extirpated and burbot populations were greatly reduced. Seven species of exotic trout and salmon have been introduced to Lake Michigan. Chinook salmon, steelhead (*Oncorhynchus mykiss*), coho salmon (*O. kisutch*), and brown trout (*Salmo trutta*) are considered to be the key species (Jonas et al. 2005). Their populations, as well as the populations of lake trout, are currently sustained in large part by stocking (Jonas et al. 2005). The other three introduced trout and salmon species are Atlantic salmon (*Salmo salar*), pink salmon (*Oncorhynchus gorbuscha*), and splake (hybrid between brook and lake trout, *Salvelinus fontinalis* x *namaycush*).

Exotic Species
The Aquatic Nonindigenous Species (AIS) List for the Great Lakes (NOAA 2006a) contains 187 species, beginning with the introduction of bitter dock (*Rumex obtusifolius*) in 1840, continuing through bloody red shrimp (*Hemimysis anomala*), introduced in 2006, but not including VHS (viral hemorrhagic septicemia), found in Lake Michigan in 2007 (WDNR 2007). The vector for 75 of these AIS was shipping; 74 more were released either deliberately or accidentally, 14 entered through canals, and one was attributed to railroads and highways. The source of 21 species is unknown (NOAA 2006a). Seventy-nine exotic aquatic species are known for Lake Michigan; 11 species of algae, two oligochaetes, one arthropod, two bacterial diseases, one hydrozoan, 14 crustacean species, one bryozoan, 30 fish, 11 mollusks, four plants, one protozoan parasite, and one viral disease (USGS 2007a). Nineteen exotic aquatic species are known for the Betsie-Platte watershed (HUC 4060104); one hydrozoan, two crustaceans, 11 fish, one mollusk, and four plants (USGS 2007a). Except for the hydrozoan and the four plants, all the Betsie-Platte

watershed species are also found in Lake Michigan (USGS 2007a). Both lists include salmonids that were deliberately introduced to Lake Michigan (Appendix F). Details on specific exotic species are found in the Stressor section below.

Cladophora

The green alga *Cladophora* is found in fresh and marine waters worldwide, but it becomes a nuisance by forming unsightly, malodorous mats (made up mainly of *Cladophora glomerata*) on Lake Michigan beaches. *Cladophora* grows on hard substrates such as rock, cobble, and dreissenids, sloughs off these substrates, and then washes up on shore. Sites where *Cladophora* has been found in SLBE include Good Harbor Bay, Sleeping Bear Bay, Platte Bay, South Manitou Island (Whitman et al. 2003), and North Manitou Island (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). Various environmental conditions are known to influence *Cladophora* growth, but “the most commonly published observation is that excessive *Cladophora* biomass or production in freshwaters is stimulated by phosphorus additions” (Dodds and Gudder 1992). More recently, it has been suggested that increases in *Cladophora* production in Lake Michigan are stimulated by increased light penetration, increased substrate availability, and changes in nutrient cycling caused by the invasion of zebra and quagga mussels (dreissenids) (Harris 2004; Higgins et al. 2008).

Cladophora can provide a suitable habitat for *E. coli* bacteria. Since *E. coli* are used as an indicator of recreational water sanitation, *Cladophora* may contribute to beach closures in summer (Whitman et al. 2003). However, this problem has not been noted in testing to date at SLBE (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). *Cladophora* may also provide a niche for pathogenic bacteria (Whitman et al. 2003). As *Cladophora* mats decay, they may also lead to anaerobic conditions needed for the production of botulism (*Clostridium botulinum*) toxin (Zuccarino-Crowe 2007)

Type E Botulism

Type E botulism is a neuromuscular disease caused by the bacterium *Clostridium botulinum.* In 2006, it killed nearly 3,000 birds, including loons, ring-billed gulls, grebes, and red-breasted mergansers, along a 19-km stretch of SLBE beaches (Zuccarino-Crowe 2007). In 2007, it resulted in at least 1,100 bird deaths in SLBE, including four endangered piping plovers, but bird death numbers appear to be lower for 2008 (USGS 2007b; NPS, Ken Hyde, Biologist-Wildlife, SLBE, pers. comm., November 2008).

Type E botulism was first documented on Lake Michigan in 1963, and has been a regular problem on Lakes Erie and Ontario since 1999 (Michigan Sea Grant 2007b). Ecologic factors related to botulism outbreaks include warm water temperatures, anoxic conditions, and adequate levels of bacterial substrate (Zuccarino-Crowe 2007). The toxin produced by the bacteria is passed up the food chain as fish eat organic material and birds consume the infected, vulnerable fish or eat maggots in the decaying carcasses of botulism victims.

Aquatic invasive species may also be contributing to botulism outbreaks in a complex cycle that includes *Cladophora* algae blooms, dreissenid mussels, and round gobies (USGS 2007b). The dreissenids clarify the water, which promotes the growth of benthic algae like *Cladophora* that may harbor *Clostridium* (Stankovich 2004; Jude et al. 2005a). Dreissenids may also provide habitat for the *Clostridium* bacteria. They may harbor the bacteria internally without being affected by it and pass it up the food chain when they are eaten by the exotic round goby, which prefers dreissenids as a food (Jude et al. 2005b; Zuccharino-Crowe 2007). Getchell and Bowser (2006) have recently summarized current research on mechanisms that support the expansion of type E botulism in dreissenid mussel beds and identified the need for a better understanding of the role of food chain organisms in the movement of type E botulism into fish and waterfowl.

Lake Michigan Food Web

The native Lake Michigan food web has two separate but overlapping parts: a pelagic food web associated with offshore, open water, and a benthic, or bottom, food web (Eshenroder et al. 1995). Both parts are based on planktonic algae and photosynthetic bacteria produced in upper water layers with adequate light penetration. In the pelagic food web, algae are consumed by small invertebrates, mainly cladocerans and copepods, which are then consumed by larval and juvenile fish including deepwater ciscoes, lake whitefish, lake herring, deepwater sculpin, and burbot. In the benthic food web, two macrobenthic genera are especially important: the opossum shrimp (*Mysis relicta*) and the closely related amphipods (*Diporeia* spp.). Common native adult fish species are either benthivores (including deepwater ciscoes and whitefish) or piscivores (including lake trout and burbot) that feed primarily on other fish. Piscivores use both the pelagic and benthic food webs (Eshenroder et al. 1995).

Human activities have influenced the Lake Michigan food web to a significant degree ever since the 1800s (Schneeberger et al. 2005), but perhaps the most dramatic changes occurred from the 1930s to 1960s, precipitated by the invasion of the exotic sea lamprey. Sea lamprey predation and overfishing led to the extirpation of the lake trout and large declines in the burbot population. Lack of top piscivores led to an explosion in the introduced alewife and drastic declines in the populations of emerald shiner, yellow perch, and deepwater sculpin. Coho and Chinook salmon were introduced to control the alewife as well as to establish a sport fishery (Madenjian 2005).

Madenjian et al. (2002) have documented changes in the food web that occurred from 1970-2000. These include the recoveries of lake whitefish and burbot populations, and an increase in salmonines, with sea lamprey control; a resulting reduction in alewife populations; and a subsequent recovery of deepwater sculpin, yellow perch, and burbot. Decreases in phosphorus loading led to a decrease in primary production, which decreased the abundance of the three dominant macroinvertebrate groups (*Diporeia*, oligochaetes, and sphaeriids) during the 1980s. *Diporeia* continued to decrease during the 1990s concomitant with the invasion of zebra mussels.

Fishery managers are concerned about a possible “collapse” of the salmon fishery in Lake Michigan similar to Lake Huron’s since 2003 (O’Keefe 2008). Salmon size and condition declined drastically in Lake Huron as dreissenids diverted nutrients and energy away from forage fish such as older alewife, which disappeared early in the “collapse.” However, Lake Michigan salmon currently appear to be in better condition than those in Lake Huron, older alewife (up to age 9) are still being found, and although forage fish biomass decreased dramatically from 2006-2007, alewife biomass actually increased. Currently, the MDNR is considering raising the bag limit for Chinook and coho salmon in Lake Michigan to increase forage fish biomass and ecosystem stability (O’Keefe 2008).

Water Quality

Lake Michigan sampling has not been a consistent component of SLBE water quality monitoring programs. However, the Baseline Water Quality Data Inventory and Analysis Report for SLBE (often referred to as the Horizon report after its contractor) (NPS 1997b) and the USEPA's Great Lakes Environmental Database (GLENDA) (USEPA 2006d) provide some Lake Michigan water quality data in the SLBE vicinity. The Horizon report includes data for five Lake Michigan open water sites in the SLBE vicinity (Figure 15). Sites SLBE0058 and SLBE0079, offshore from the Mainland-South Unit, were each sampled once, in July 1977 and May 1980, respectively. Site SLBE0128, off Sleeping Bear Point, was sampled three times a year from 1962-1974. Sites SLBE0143 and SLBE0146, near North Manitou Island, were sampled from April-October, 1976.

The USEPA has monitored 11 Lake Michigan stations twice annually since 1983 for phosphorus (total and total dissolved), nitrogen (as nitrate plus nitrite), soluble reactive silicon, chloride, total alkalinity, specific conductance, and turbidity (Warren and Kreis 2005). Lakewide averages are calculated from the simple mean of values at 1 m, mid-water column, 10 m above bottom, and 2 m above bottom for samples collected in spring (USEPA, Glenn Warren, Environmental Monitoring and Indicators Team Leader, email, 10/9/07). GLENDA includes a deep water sampling site in Lake Michigan (MI47) that is approximately 24 km northwest of South Manitou Island. It has been sampled generally twice a year, in March-April and in August-September, since 1996.

Core Water Quality Parameters

The core water quality parameters for freshwater bodies in the Great Lakes region, as defined by the NPS Great Lakes Inventory and Monitoring Network (GLKN), are water clarity, temperature, specific conductance, dissolved oxygen (DO), and pH (Route and Elias 2007). Data for these parameters were collected for open water site MI47 from the GLENDA database (USEPA 2006d). As a measure of water clarity, Secchi depth readings were collected annually at MI47 on dates ranging from August 1-September 1. For the period 1998-2004, Secchi depth varied from 6 m in 1999 to 13.5 m in 2004 (Figure 16). Bottom temperatures normally ranged from 1.3-3.9^{o}C in both March-April and August-September. Surface temperatures were often similar to bottom temperatures in April, but reached 16-22^{o}C in August-September. Intermediate temperatures occurred in the thermocline (from 15-23 m depending on the year) when stratification was present (Figure 17).

Specific conductance values are a measure of the total mineral content of water, but do not indicate which specific minerals are present. Individual values at site MI47 for the period 1996-2005 at depths ranging from near-surface (1-2 m) to near-bottom (approximately 188 m) ranged from 277-303 µS/cm with the exception of higher values in April 1998, when values ranged from 362-367 µS/cm throughout the profile, and April 1999, when values from 2-20 m were 295 µS/cm, but increased to 375-378 µS/cm at the 95, 180, and 188 m depths. Values in August and September varied more with depth than did March and April values (Figure 18). Lakewide specific conductance values, measured in spring from 1993-2001, had a statistically significant ($p<0.001$) increase of 0.8 µS/cm year^{-1} (Warren and Kreis 2005). A similar trend was not noted in the data from MI47, whether the April 1998 and 1999 data were included or considered outliers and excluded. However, 26 specific conductance samples collected from SLBE0128 for

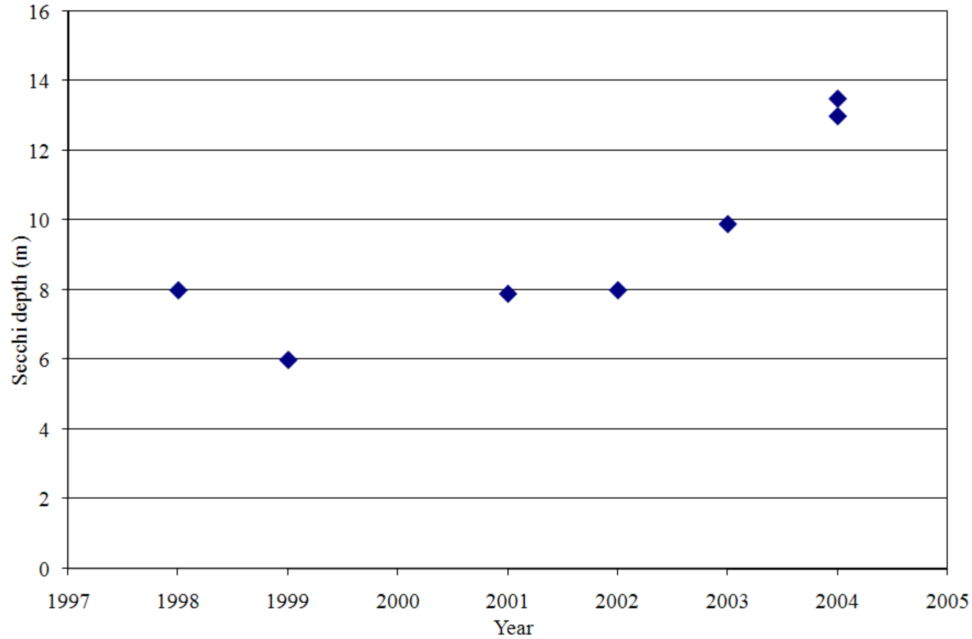

Figure 16. August-September Secchi depth readings at Lake Michigan deep water site MI47, 1998-2004.

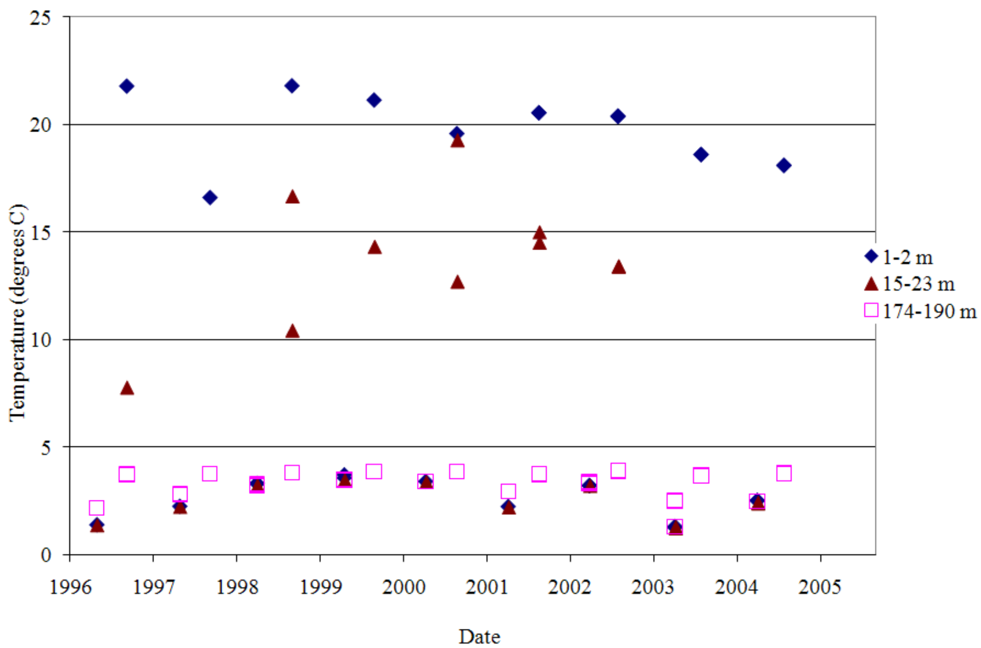

Figure 17. Spring (March-April) and summer (August-September) individual temperature measurements at Lake Michigan deep water site MI47, 1996-2005.

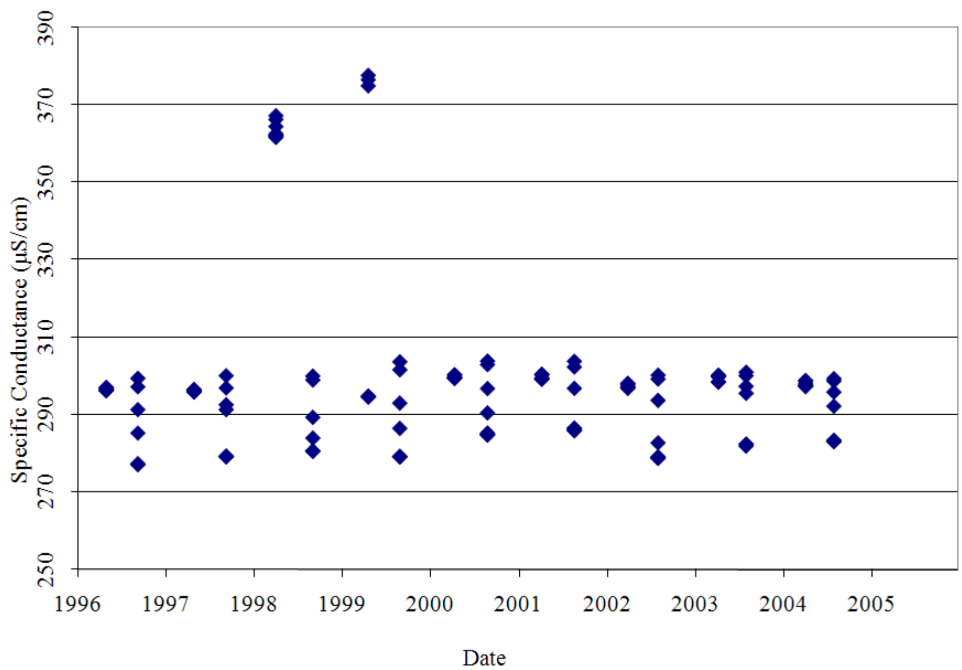

Figure 18. Spring (March-April) and summer (August-September) individual specific conductance values at depths from 1-188 m at Lake Michigan deep water site MI47, 1996-2005.

an earlier period (June 1962-October 1974) did have a lower range of 266-288 µS/cm (NPS 1997b).

Site MI47 is well oxygenated at all depths and times of year, with a low for the period of 6.9 mg/L recorded at 1 m in August 2001 and a high of 13.4 mg/L at the 30 m depth in August 2004 (Figure 19). (Negative values listed in the database for the entire profile on April 1, 1998 were excluded from the analysis.) Twenty-six oxygen samples collected from SLBE0128 for an earlier period (June 1962-October 1974) had a higher minimum value (8.6 mg/L) but a lower maximum value (13.1 mg/L) (NPS 1997b). Site MI47 pH values for the period varied from 7.8 at 185 m depth in April 2003 to 8.7 at 2 m depth in August 1999 (USEPA 2006d).

Advanced Water Quality Parameters

In addition to the core water quality parameters, NPS monitors major ions, dissolved silica, alkalinity, dissolved organic carbon (DOC), chlorophyll-*a*, and nutrients for freshwater lakes in the Great Lakes region (Route and Elias 2007). Of these, data are available at MI47 for alkalinity, chloride, nitrate and nitrite-nitrogen, total phosphorus (TP), silica, and chlorophyll-*a*; these will be discussed below.

Alkalinity: Alkalinity is a measure of water's buffering capacity and ability to resist a change in pH (USEPA 1986). Twenty-six samples collected at four sites near SLBE (Figure 15) during the open water season from 1962-1980 had alkalinity values in the range of 100-120 mg $CaCO_3$/L, with a mean of 112 mg/L at SLBE0128 for the period 1962-1974 (NPS 1997b). Spring means (averaged over the profile from 1-188 m for each date) for MI47 from 1997-2004 ranged from 102-111 mg/L as $CaCO_3$ (Figure 20; USEPA 2006d).

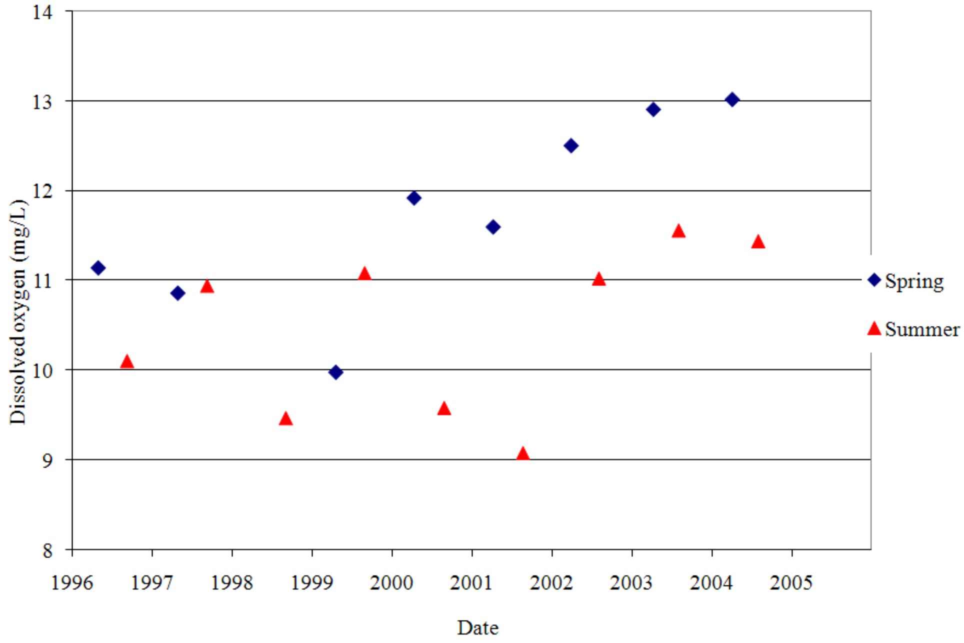

Figure 19. Spring (March-April) and summer (August-September) mean dissolved oxygen values at Lake Michigan deep water site MI47, 1996-2004.

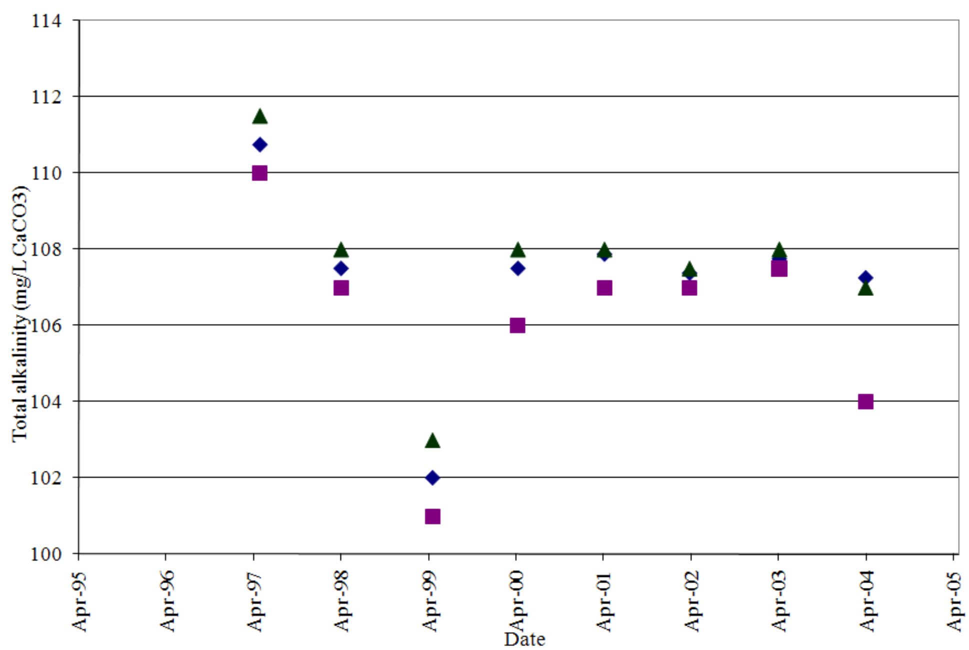

Figure 20. Total alkalinity for Lake Michigan deep water site MI47, mean (♦), minimum (■), and maximum (▲) for profile ranging from 1-188 m, spring 1996-2004 (USEPA 2006d).

Because its alkalinity is greater than 25 mg/L, Lake Michigan is not considered susceptible to acid rain (Sheffy 1984; Shaw et al. 1996). However, Warren and Kreis (2005) noted that alkalinity values for Lake Michigan appear to be trending downward slightly from 1983-2001, but that the trend was not statistically significant.

Chloride: Chloride levels in Lake Michigan are an indicator of human impacts (Warren 2005), including wastewater, storm water, and agricultural runoff. Rising chloride concentrations are linked to rising sodium concentrations in Lake Michigan, which may give undesirable sodium-requiring cyanobacteria a competitive advantage over other phytoplankton (Warren 2005). Spring chloride concentrations in both the northern and southern basins of Lake Michigan rose from 8.68 mg/L in 1983 to 10.86 mg/L in 1999 (Warren and Kreis 2005). The statistically significant ($p<0.001$) lakewide rate of increase was 0.13 mg/L $year^{-1}$ from 1983-2001 (Warren and Kreis 2005).

Mean chloride concentrations were 8 mg/L for 62 samples collected during the open water season near SLBE (Figure 15) from 1962-1980, with a range of 5-13 mg/L (NPS 1997b). Spring means for MI47 (averaged over the profile from 1-188 m for each date) from 1996-2004 ranged from 9.6-11.5 mg/L (USEPA 2006d) with an apparent upward trend that is not statistically significant (Figure 21).

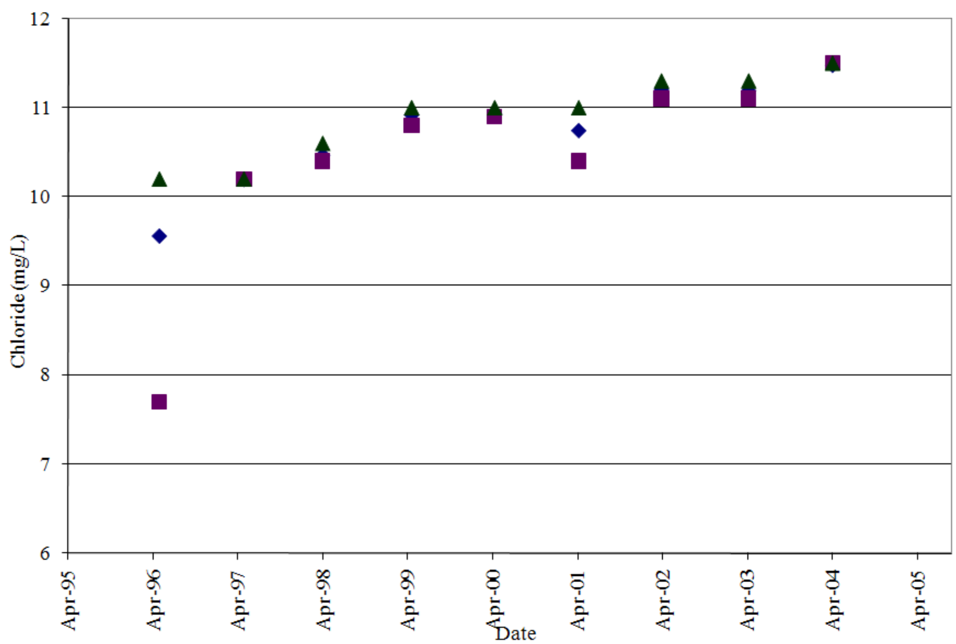

Figure 21. Chloride for Lake Michigan deep water site MI47, mean (♦), minimum (■), and maximum (▲) for profile ranging from 1-188 m, spring 1996-2004 (USEPA 2006d).

Nitrate/Nitrite Nitrogen: Nitrogen (N), although an essential plant nutrient, is not of immediate eutrophication concern for Lake Michigan, which is generally phosphorus limited (Warren 2005). The springtime lakewide average nitrate/nitrite-N concentration increased from 0.262 mg/L in 1983 to 0.311 mg/L in 1999. The trend, although inconsistent, is highly significant ($p<0.001$), with an increase of 0.0022 mg/L $year^{-1}$ (Warren and Kreis 2005). The increase reflects continuing loading, with about half attributable to tributaries and half to the atmosphere (Warren and Kreis 2005).

Seventeen samples collected during the open water season at SLBE0128 (Figure 15) from 1962-1970 had nitrate-N concentrations ranging from 0.07-0.38 mg/L (mean 0.165 mg/L) (NPS 1997b). Forty-two samples collected at SLBE0143 and SLBE0146 in 1976 and one sample from 1980 at SLBE0079 had nitrate/nitrite-N concentrations of 0.1-0.3 mg/L (NPS 1997b). Spring nitrate/nitrite-N means for MI47 (averaged over the profile from 1-188 m for each date) from 1996-2004 ranged from 0.309-0.354 mg/L (USEPA 2006d) without a consistent upward trend (Figure 22). Four sites near SLBE's South Manitou Island and Platte Point were sampled at 7-8 m depth as part of a botulism investigation in 2007. Dissolved nitrogen concentrations (likely comprised mainly of nitrate/nitrite-N) were similar to previous observations, averaging 0.314 mg/L at these sites from July through October (NPS, Brenda Moraska Lafrancois, Aquatic Ecologist Great Lakes Area, pers. comm., November 2008).

Total Phosphorus: Phosphorus is often the limiting nutrient for aquatic plants in the Great Lakes (USEPA 2006c). The International Joint Commission (IJC 1980) has set a water quality guideline for TP in Lake Michigan open waters at 7 µg/L to maintain the lake's oligotrophic to mesotrophic status. From 1983 to 2001 there was a statistically significant decline ($p<0.001$) in TP concentrations lakewide, even though there was an increase between 1992 and 1996 (Warren and Kreis 2005). A recent springtime lakewide phosphorus low of 4.09 µg/L was observed in 2001 (Warren and Kreis 2005). However, recent data (USEPA and Environment Canada 2008) indicate that along Lake Michigan's eastern shore, phosphorus concentrations may exceed 7 µg/L for at least part of the growing season, and that *Cladophora* blooms are common in such areas. At the same time, a phosphorus deficit may be occurring in deeper waters (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

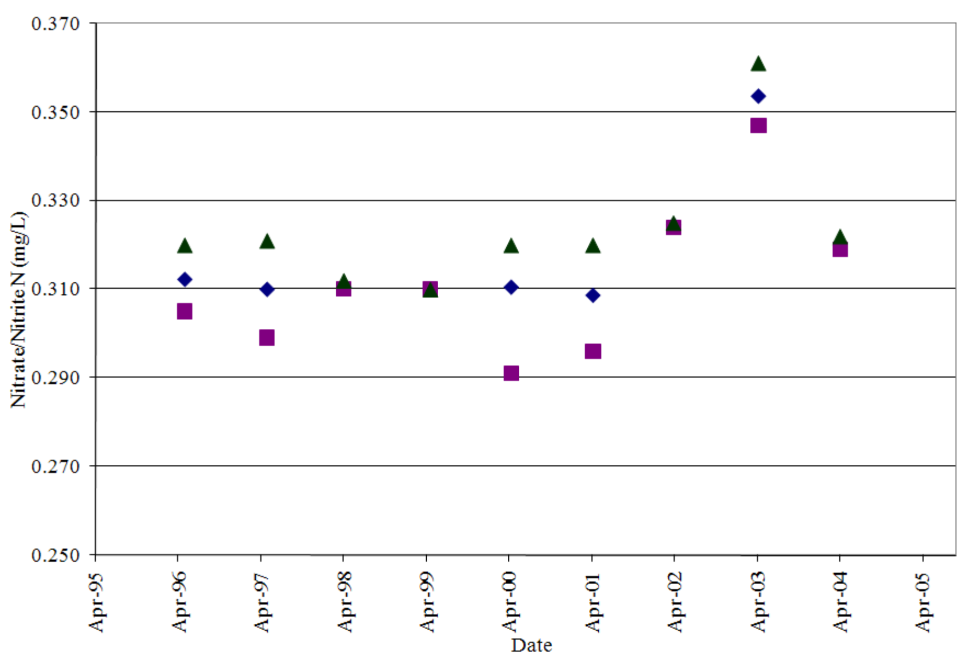

Figure 22. Nitrate/nitrite nitrogen for Lake Michigan deep water site MI47, mean (♦), minimum (■), and maximum (▲) for profile ranging from 1-188 m, spring 1996-2004 (USEPA 2006d).

TP concentrations at SLBE0128 ranged from 3-13 µg/L in 10 samples from 1970-1974 (mean 6 µg/L), and from 4-21 µg/L in 41 samples at SLBE0143 and SLBE0146 in 1976 (mean 7 µg/L) (NPS 1997b). Spring TP means for MI47 from 1996-2004 (averaged over the profile from 1-188 m for each date) ranged from 3.244-8.000 µg/L (USEPA 2006d) with an apparent downward trend that was not statistically significant (Figure 23). TP concentrations at the four sites in the 2007 SLBE botulism study fell within this range, averaging 7 µg/L from July through October (NPS, Brenda Moraska Lafrancois, Aquatic Ecologist Great Lakes Area, pers. comm., November 2008).

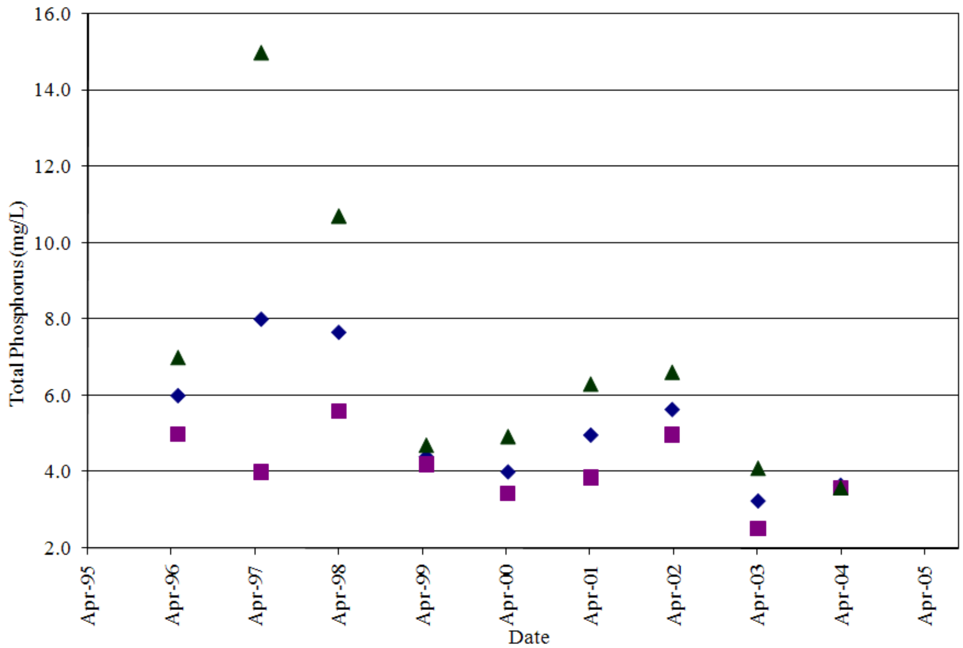

Figure 23. Total phosphorus for Lake Michigan deep water site MI47, mean (♦), minimum (■), and maximum (▲) for profile ranging from 1-188 m, spring 1996-2004 (USEPA 2006d).

Dissolved Reactive Silica: Dissolved reactive silica is a nutrient essential to diatom growth (Warren 2005). As previously noted, phosphorus loading has been credited for increased diatom growth and decreased silica availability from the mid-1950s to the 1970s (Barbiero and Tuchman 2005). However, the phosphorus loading trend has reversed, and spring lakewide dissolved reactive silica concentrations increased significantly ($p<0.001$) from 1.21 mg/L as SiO_2 in 1983 to 1.63 mg/L in 2001 (0.56-0.76 mg/L as Si), at a rate of 0.0246 (0.0115 as Si) mg/L year^{-1} (Warren and Kreis 2005).

At site SLBE0128, dissolved reactive silica concentrations ranged between 0.8-3.6 mg/L as SiO_2 (mean 1.8 mg/L, n=11) during the open water season from 1962-1970. Concentrations during the 1976 open water season averaged 0.46 mg/L and 0.81 mg/L at sites SLBE0143 and SLBE0146, respectively (NPS 1997b). Spring dissolved reactive silica means for MI47 from 1996-2004 (averaged over the profile from 1-188 m for each date) ranged from 1.43-1.88 mg/L as SiO_2 (0.669-0.875 mg/L as Si) (USEPA 2006d), higher than the lakewide averages, and without a clear trend (Figure 24).

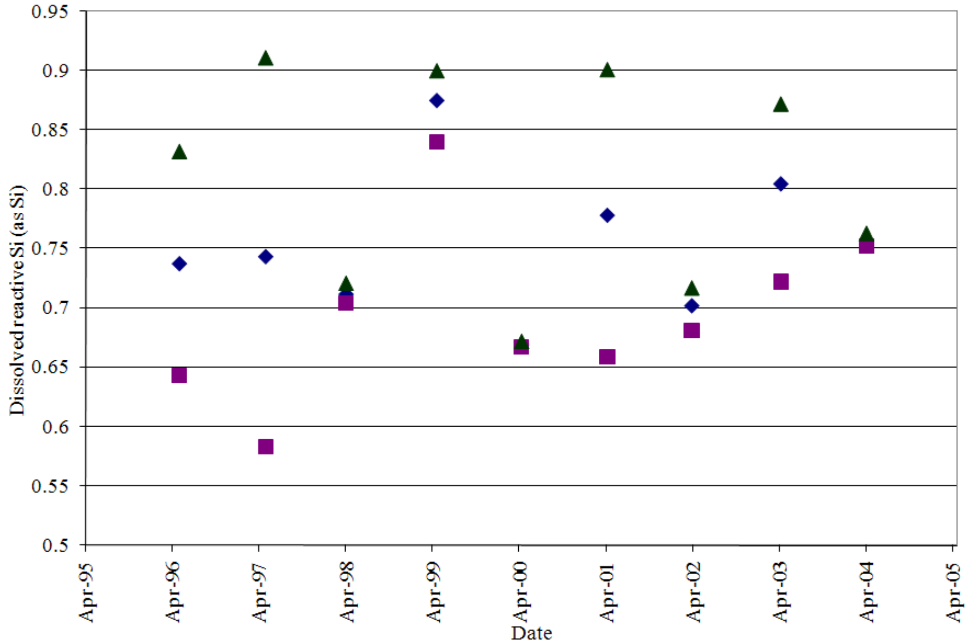

Figure 24. Dissolved reactive silica as Si for Lake Michigan deep water site MI47, mean (♦), minimum (■) and maximum(▲), spring 1996-2004 (USEPA 2006d).

Chlorophyll-*a*: Spring lakewide average chlorophyll-*a* concentrations were highly variable over a range of 0.54-2.69 µg/L and did not trend for the period 1983-1997. The southern basin has been consistently higher in chlorophyll-*a* than the northern basin (Warren 2005). At site MI47, spring averages varied from 0.53-0.95 µg/L for the period 2001-2004 (USEPA 2006d).

Critical Pollutants for Lake Michigan: In the 2006 revision of the Lake Michigan Lakewide Management Plan (LMTC 2006), the following pollutants were considered to be of critical importance: polychlorinated biphenyls (PCBs), mercury, the organochlorine pesticides chlordane and DDT and its metabolites, dioxin, and pathogens, including *Escherichia coli, Cryptosporidium, Giardia*, and *Salmonella*. Additional chemicals and categories of chemicals (including metals and nutrients) were placed on a list of pollutants of concern, and a watch list (including organic compounds and pesticides in current use) was created to be reevaluated at a future date.

Pharmaceuticals and personal care products (PPCPs) are an emerging concern in wastewater, surface water, groundwater, and drinking water supplies around the nation. In 2000, sites in Lake Ontario relatively remote from sewage treatment plant discharges were found to contain detectable amounts of clofibric acid (a pesticide and cancer drug), ketoprofen and fenoprofen (painkillers), and carbamazepine (an antiepileptic drug) (Metcalfe et al. 2003). In 2002 and 2003, contaminants in surface waters in the Clinton River watershed in Michigan, which drains to Lake St. Clair, included benzophenone (a fixative in perfumes and soaps), caffeine, fluoranthene (found in coal tar and asphalt), HHCB1 and AHTN2 (musk fragrances), phenanthrene (a disinfectant), and tributyl phosphate (a flame retardant) (Fogarty 2007). The status of PPCP contaminants in Lake Michigan and especially around SLBE is largely unknown, and the effect on ecosystems where these chemicals are found is just beginning to be studied.

Escherichia Coli and Beach Water Quality

The federal BEACH (Beaches Environmental Assessment and Coastal Health) Act of 2000 requires coastal and Great Lakes states to report beach monitoring results and closures to USEPA, which is in turn required to create and make available a public database for the protection of public health. SLBE's beaches are not officially designated for swimming (NPS 2005a), so the USEPA and state of Michigan beach information databases do not include results for samples within SLBE. However, SLBE beaches have been monitored since 1997, and most recently, weekly samples are collected by SLBE staff from early May until early September within the park at Platte Point, Platte River outlet, Peterson Road, Otter Creek, the Otter Creek (Esch Road) vernal pond and the associated Lake Michigan beach, North Bar Lake and the associated Lake Michigan beach, Little Glen Lake, Glen Haven, D.H. Day Campground, the Shalda Creek outlet (not since 2005) and the ends of County Roads (CR) 651 and 669 on Good Harbor Bay (Figure 25; Murphy 2004a; McMahon 2007).

The MDEQ guidelines for beach water quality indicate that waters of the state used for total body contact recreation must not contain more than 130 *Escherichia coli* colonies/100 ml water as a 30-day geometric mean, or more than 300/100 ml water as a daily geometric mean. The daily geometric mean requires a minimum of three samples; the 30-day geometric mean requires at least five daily sampling events (MDEQ 2007a).

Murphy (2004a) reported that *E.coli* levels at Little Glen Lake seemed to have a direct relationship with the wind direction. However, wind direction seems to have little effect on North Bar Lake, and *E.coli* levels there were almost nonexistent. Otter Creek had consistently exceeded the daily and monthly geometric mean limits. In previous years Shalda Creek had also exceeded both limits. It was not completely understood why both streams regularly exceeded the limits, but the most accepted theory was the active beaver colonies on each stream. Further monitoring such as DNA testing could be used to determine whether the high *E.coli* levels are from beaver or another source. Otter Creek also created an oxbow or vernal pond between the entrance from Esch Road and the Lake Michigan Beach. This vernal pond regularly exceeded the daily geometric mean through the sampling season.

More recently, the coastal waters of SLBE have generally met the standards for total body contact recreation. In 2006, daily geometric mean advisory limits were exceeded once each at CR 651, Lake Michigan near North Bar Lake, and Peterson Road (NPS, Steve Yancho, Chief of Natural Resources, SLBE, spreadsheet, November 2007). These exceedences did not occur at the same time and were preceded and followed by low counts (<50). In 2007, a daily mean was exceeded at the Esch Road beach (McMahon 2007). The Otter Creek pond had three exceedences of the daily mean and two of the 30-day mean in 2006, one exceedence of the daily mean in 2007, and two in 2008. Otter Creek also exceeded the daily mean during one of the 2008 events (NPS, Chris Otto, Biological Technician-Water Quality, SLBE, pers. comm., November 2008). The Otter Creek pond is not always present, but when it is, it often has high coliform counts. These may be naturally occurring or caused by the high number of visitors who allow

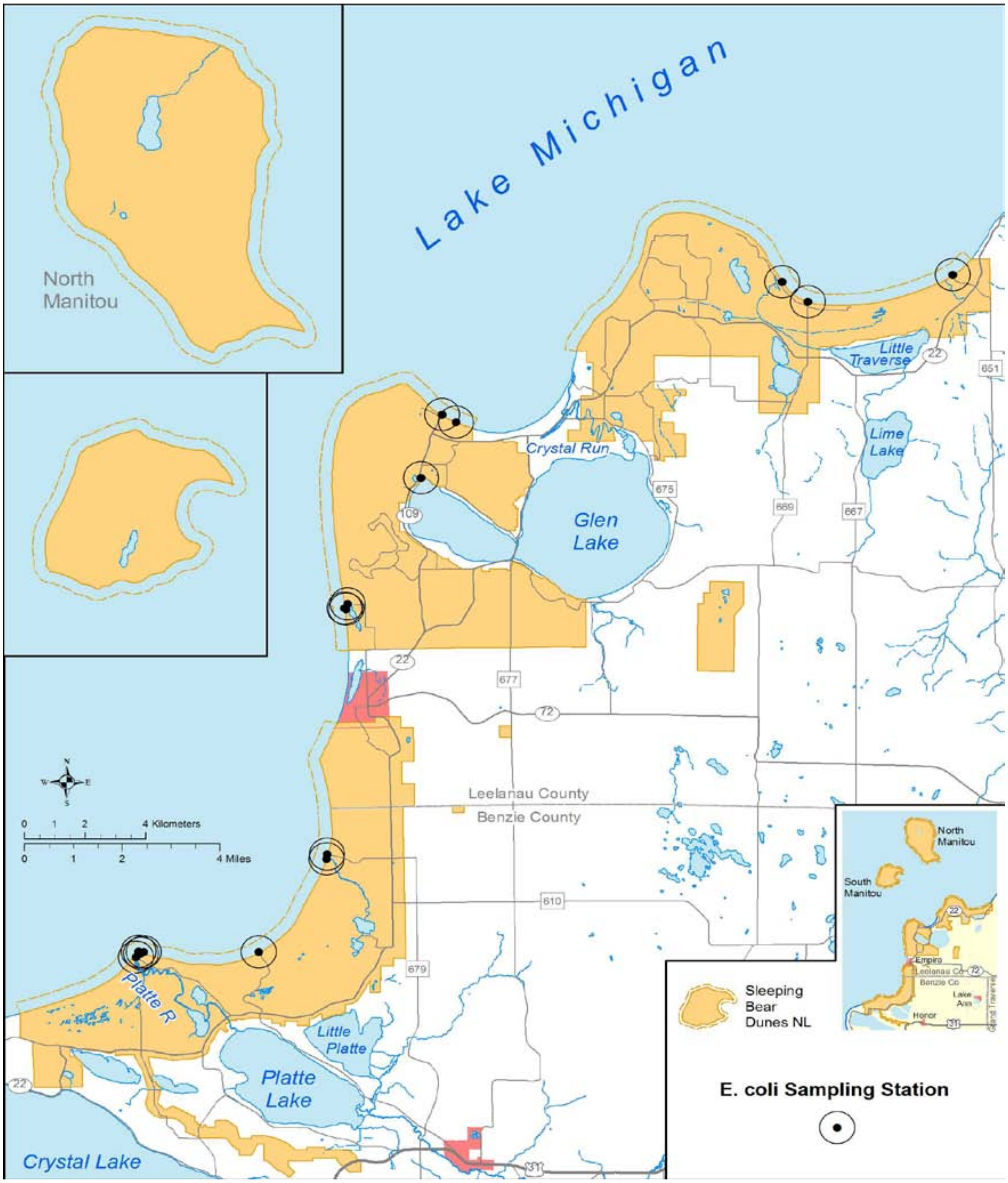

Figure 25. Locations of beach sampling sites for *E. coli* in Sleeping Bear Dunes National Lakeshore (Murphy 2004a, b; McMahon 2007).

young children, some in diapers, to play in the warm, shallow water (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., June 2007).

Inland Waters and Wetlands

SLBE has 460 ha of inland lakes completely within its boundaries. It includes all or part of 27 named lakes (Table 9) and 86 smaller unnamed lakes and ponds (some of which may be ephemeral), 40.5 km of streams, including five named streams (Table 10; MCGI 2006), and many bogs, springs, and interdunal wetlands (Lafrancois and Glase 2005). Most surface waters are groundwater fed and thus fairly stable (Lafrancois and Glase 2005). Natural SLBE lakes formed from glacial scouring, post-glacial declines in Lake Michigan levels, and post-glacial uplift (Calver 1946; Handy and Stark 1984). SLBE surface waters are generally at the downgradient end of many watersheds (Murphy 2004a; see Figure 1 and Figure 42), and thus are susceptible to impacts from increasing development.

Table 9. Morphometric features of lakes wholly or partially within Sleeping Bear Dunes National Lakeshore (modified from Vana-Miller 2002; surface areas from MCGI 2006)

Lake	Surface Area (ha)	Maximum Depth (m)	Mixing Pattern	Inlet	Outlet
Florence	31.4	8.0	Polymictic	--	--
Manitou	104	14	Dimictic	--	X
Bow Lakes (2)	4.7	--	Dimictic	--	--
Bow Valley Pond	0.1	--	--		
Tamarack	3.7	2.7	Polymictic	X	X
School	70.7	<2.0	Polymictic	X	X
Bass (Leelanau)	37.5	9.0	Dimictic	X	--
Narada	6.6	9.4	Dimictic	X	X
Shell	41.3	4.0	Polymictic	--	X
Hidden	0.5	0.6	Polymictic	--	--
Tucker	7.1	3.0	Polymictic	X	X
Long	132	6.0	Polymictic	--	--
Hatt Pond	0.7	<1.0	Polymictic	--	--
Rush	48.0	<1.0	Polymictic	--	--
Little Glen	573	4.3	Polymictic	--	X
Glen	1,973	40	Dimictic	X	X
Taylor	1.3	--	Polymictic	--	--
North Bar	12.5	10	Dimictic	X	X
Deer	1.9	6.7	Dimictic	X	X
Bass (Benzie)	10.9	8.0	Dimictic	X	X
Otter	25.9	6.4	Polymictic	X	X
Loon	37.9	19	Dimictic	X	X
Little Platte	325	2.4	--	X	X
Day Mill Pond	2.3	<1.0	Polymictic	--	X
Mud	21.8	<1.0	Polymictic	X	X
Round	6.2	8.0	Polymictic	--	X

Table 10. Characteristics of streams in Sleeping Bear Dunes National Lakeshore (MCGI 2006).

Stream Name	Length within SLBE (km)	Order
Crystal River	4.1	3
Shalda Creek	4.3	2
Good Harbor Creek	1.2	1
Otter Creek	3.7	2
Platte River	7.5	3

Historic Overview of Inland Waters Studies and Management Plans

Brown and Funk (1940) conducted one of the first studies of the Platte River system, including Loon Lake. They concluded that oxygen was sufficient to allow fish populations to survive below the thermocline in Loon Lake (called Round Lake at that time). Rodeheffer and Day (1950) later studied Glen and Little Glen Lakes.

Stockwell and Gannon (1975) provided some baseline water quality information for SLBE lakes, concentrating on Loon Lake and the Platte River system and Florence Lake on South Manitou Island. This information included nutrients, DO, pH, alkalinity, specific conductance, and chlorophyll-*a*. Oxygen concentrations were at saturation except for some depletion in the lower hypolimnion. Loon Lake was found to be a nutrient sink; Boyle and Hoefs (1993a) agreed some years later.

Kelly and Price (1979) did the first intensive comprehensive fisheries study within SLBE, using 40 sampling stations and examining all habitats. Combining their results with studies conducted by the USFWS and the Michigan Museum of Zoology, they reported a total of 76 fish species for SLBE. Details are provided in the Fish section below.

Hazlett and Vande Kopple (1983) studied the aquatic macrophytes of North and South Manitou Islands, and Hazlett (1988) later studied the aquatic vegetation of the aquatic and wetland habitats within the mainland units of SLBE. In 1986 and 1987, Round Lake had the greatest number of emergent and shoreline species. Loon Lake had the lowest number of plant species of all types.

Handy and Stark (1984) measured water quality in eight SLBE lakes (Loon, Bass, South Bar, Shell, Round, Rush, Manitou, and Florence Lakes), concluding that the water quality was "excellent" and met the USEPA criteria for all chemical parameters measured (arsenic, barium, cadmium, chloride, chromium, color, fluoride, iron, lead, manganese, mercury, nitrate, pH, selenium, silver, sulfate, zinc, and total dissolved solids). The four streams and rivers they studied (Platte River, Otter Creek, Crystal River, and Shalda Creek) also had excellent water quality relative to 1977 USEPA drinking water standards (USEPA 1977a, b). Pesticides were not detected, and suspended sediment was low. Total dissolved solids ranged from 35-180 mg/L in lakes and 145-214 mg/L in streams.

A biological study undertaken by NPS staff in 1988 showed that all SLBE rivers and streams had pollution-sensitive invertebrates present, indicating good water quality (NPS 2004a). Albert

(1992) studied the vegetation of five SLBE lakes (Bass [Benzie], Bass [Leelanau], Otter, School, and Tucker Lakes), the four major rivers, and dune swales.

Boyle and Hoefs provided an aquatic natural resource inventory (1993a) and a long-term aquatic resource monitoring program (1993b). Water quality was measured in 21 lakes (Bass [Benzie], Bass [Leelanau], Bow Lake Valley Pond, Bow Lakes [2], Deer Lake, Florence Lake, Glen Lake, Little Glen Lake, Lime Lake, Little Traverse Lake, Lake Manitou, Loon Lake, Narada Lake, North Bar Lake, South Bar Lake, Otter Lake, Round Lake, School Lake, Shell Lake, and Tucker Lake) and four streams (Platte River, Otter Creek, Shalda Creek, and the Crystal River) within SLBE. Parameters for lakes were temperature, discharge, pH, alkalinity, DO, Kjeldahl nitrogen, nitrate/nitrite, TP, organic carbon, chlorophyll-*a*, Secchi depth, and benthic macroinvertebrates.

Nine SLBE lakes (Glen Lake, Loon Lake, Platte Lake, Narada Lake, North Bar Lake, Manitou Lake, Bow Lake North, Deer Lake, and Bass Lake [Benzie]) typically were dimictic (stratified from spring to late fall) (Boyle and Hoefs 1993a). Elias (2007) later listed Bass (Leelanau) among dimictic lakes. Oxygen deficits may occur in dimictic lakes. The other SLBE lakes were polymictic (circulated frequently throughout the summer). Polymictic lakes may exhibit short term summer stratification and/or stratification under the ice. All the study lakes had high alkalinities, ranging from 77 mg/L $CaCO_3$ in School Lake to 178 mg/L $CaCO_3$ in Narada Lake, and alkaline pH values, ranging from 7.2 in Narada Lake to 9.1 in School Lake. Secchi depths varied from 2.0 m in North Bar Lake to 7.3 m in Bow Lake North (except where it was visible resting on the bottom); the authors noted phytoplankton density, suspended sediments, and marl formation as variables that influenced Secchi depth variability. TN to TP ratios in all SLBE lakes were above 14, indicating that phosphorus was the limiting nutrient. Chlorophyll-*a* values suggested that all SLBE lakes were in the mesotrophic to oligotrophic range. The one exception was a deep water sample (9.60 µg/l chl *a*) from Narada Lake which ranked it as slightly eutrophic (Boyle and Hoefs 1993a).

The Boyle and Hoefs (1993a) study streams (Platte and Crystal Rivers and Otter and Shalda Creeks) all originate as lake outflows. The Platte River had the greatest discharge, and the discharge of both the Platte River and Shalda Creek was greater in lower reaches due to groundwater inflows through springs. Boyle and Hoefs (1993a) measured 31 chemical parameters, including many metals of concern, and found that all variables were within the range defined as tolerable for aquatic life. An exception was a single sample for aluminum (140 µg/L) from Shalda Creek taken in December 1990, which was attributed to the anoxia in Little Traverse Lake at the headwaters of Shalda Creek. Nitrogen was greatest in Otter Creek and attributed to groundwater inputs. TP in all streams was low, and organic carbon was dominantly in the fine particulate organic matter (FPOM) fraction. FPOM was greater in Otter Creek and the Platte River than in the Crystal River or the headwaters of Shalda Creek. Coarse particulate organic matter (CPOM) was highly variable within and between the study streams, reflecting changes in the riparian vegetation cover. Overall, the lowest concentrations of CPOM were found in the Platte River, and greatest in the lower reaches of Otter Creek. The authors attributed this somewhat unusual finding to the fact that the lower portion of Otter Creek passes through a marsh. CPOM levels were typical of upper Midwestern streams. Macroinvertebrate densities were highly variable at a given site over multiple sampling dates, which was attributed to the great heterogeneity of stream substrates at sampling sites. The lower reaches of Shalda Creek had the highest densities of macroinvertebrates, and the Platte River had medium to low densities. Species richness was more stable than density, as would be expected. In the Platte River the upstream site had higher richness than the downstream site; however, the opposite was true in Otter Creek. The downstream site in Shalda Creek had the highest richness of all the study sites, but the difference between streams was not great.

Boyle and Hoefs (1993b) studied the characteristics of six SLBE watersheds: the Platte, Otter Creek, North Bar, Crystal River, and Shalda Creek watersheds, and a Lakes watershed which included School, Bass (Leelanau), Narada, and Shell Lakes. The Platte River watershed is 465 km^2. Main branches of the Platte River are the North Branch (draining Little Platte Lake), Carter Creek, and Brundage Creek. The Platte River flows through Platte and Loon Lakes and receives outflow from Mud Lake before draining into Lake Michigan. The authors stated that nutrient loading and high recreational use are potential threats to this watershed. The Otter Creek watershed north of the Platte River watershed is a groundwater-dominated system, and there are many springs and seeps within the watershed. Deer Lake forms the headwaters of Otter Creek, which then flows through Bass (Benzie) and Otter Lakes and into Lake Michigan. Surface water in the North Bar watershed north of the Otter Creek watershed includes only North Bar Lake, which is close to Lake Michigan and occasionally connected to it. There is no development on the lake. The Crystal River watershed northeast of the North Bar watershed has significant groundwater flow and also includes surface water inflow from Little Glen Lake through Glen Lake, Fisher Lake, and a small stream from Tucker Lake. Glen and Little Glen Lakes have little area within SLBE and are influenced greatly by non-park land use. Drainage through the watershed is through the Crystal River to Lake Michigan. Big and Little Glen Lakes are highly developed, and Tucker Lake is the only lake in the watershed that is entirely within SLBE's boundaries. The Lakes watershed northeast of the Crystal River watershed is fed primarily by groundwater. School Lake is the only lake in the watershed that was surveyed prior to 1993; Handy and Stark (1984) found it to be primarily groundwater fed with excellent water quality. The Shalda Creek watershed northeast of the Lakes watershed includes Lime and Little Traverse Lakes, which are outside SLBE's boundaries.

Last and Whitman (1996) summarized the water quality work in SLBE from 1990-1995. SLBE staff monitored 21 lakes in 1990; 12 lakes were monitored thereafter until 1995. Whitman et al. (1994) collected the water quality and macroinvertebrate data in 1994 with the help of SLBE staff. DO and temperature vertical profiles, Secchi depth, surface pH, chlorophyll-*a*, nitrate-N, ammonia-N, and TP levels were measured in the deepest part of the lakes. Additionally, ten sites on the Platte and Crystal Rivers and Otter and Shalda Creek were monitored from 1990-1995. Lotic variables measured included temperature, DO, pH, specific conductance (1994-1995), and benthic macroinvertebrate community structure. Results for 1994 were reported both by Whitman et al. (1994) and Last et al. (1995).

All lakes examined by Whitman et al. (1994) were stratified except for Little Glen, Tucker, School, Bass (Leelanau), and Shell Lakes. Loon, Deer, Otter, North Bar, and Narada Lakes were dimictic and had clinograde oxygen curves, although Loon and Narada Lakes were the only ones with great changes from surface to bottom. Bass (Benzie) and Glen Lakes had metalimnetic oxygen maxima. Secchi depth varied among the lakes from 1.9-4.6 m. Chlorophyll data ranked the lakes as either oligotrophic or mesotrophic, and all lakes were alkaline, with pH values ranging from 8.0-9.2 and specific conductance values ranging from 137-238 µS/cm. Tucker Lake had the highest concentrations of ammonia, and nitrate levels were the highest in Otter, North Bar, and Glen Lakes. Lakes in the Lakes watershed had lower specific conductance values than the other lakes; the authors suggested groundwater inflow as the cause (Whitman et al. 1994). Last et al. (1995) further reported that Loon Lake had the lowest nitrate-N levels of all the study lakes, and North Bar Lake had the lowest Secchi disk readings, lowest surface pH, and highest ammonia-N, nitrate-N, and specific conductance values of the study lakes.

In streams examined by Whitman et al. (1994), temperature and DO ranged from 21-24^{o}C and 8.0-15.0 mg/L respectively. The pH values ranged from 8.3-8.8, and specific conductance values ranged from 214-276 µS/cm. Macroinvertebrate data were variable within and between sites. Greatest macroinvertebrate density occurred on Otter Creek at the upstream site. Most streams had greater densities and richness at upstream sites. Greatest richness occurred at the upstream sites of Otter Creek and the Crystal River (Whitman et al. 1994).

Whitman et al. (1994) concluded that SLBE water resources are generally of good quality. Small, highly-used lakes such as North Bar Lake, lakes with highly developed shorelines, such as Little Glen and Glen Lakes, and lakes and streams that are affected by inputs from outside SLBE, such as Loon Lake and the Platte River, are susceptible to impairment. Tucker Lake, located near an old dump site, is also vulnerable. The authors suggested studying water quality on a larger scale outside SLBE and continuing existing water quality monitoring programs in the future.

In 1998 and 1999, 18 lakes in SLBE were monitored by SLBE staff (11 thoroughly and seven sporadically), but no streams. Some of the 1998 results were reported in concurrent studies conducted by Whitman (2000) and Whitman et al. (2002a, b). Water quality parameters in 1998 were temperature, pH, total dissolved solids, DO, sulfate, nitrate, ammonia-N, alkalinity, calcium hardness, total hardness, and chloride. SLBE staff installed staff gauges on North Bar Lake in 1998 and on the Crystal River and Loon Lake in 1999. In 2000, 13 lakes were monitored bi-monthly (June-September). Specific conductance, chlorophyll-*a*, and TP were added to the 1998-1999 parameter list, and chloride was deleted. Five sites on the Platte River, two each on the Crystal River, Shalda Creek, and Otter Creek, and 12 springs in the Otter Creek drainage also were monitored monthly for the same parameters. In 2001, the same sites and parameters were measured, except that the Shalda Creek sites were omitted and a site on the Platte River was added (Vana-Miller 2002). Lakes less than 7 m maximum depth generally did not stratify, and lakes with lower surface to volume ratios generally were more strongly stratified than lakes with higher ratios (Vana-Miller 2002). Whitman et al. (2002b) stated that SLBE surface waters, especially those that lie only partly within the park, are highly susceptible to numerous anthropogenic influences. There is no buffer zone between SLBE and private and other public land.

In an overview of Great Lakes parks, Ledder (2003) stated that SLBE appears to have good water quality, with the greatest threats arising from “septic leakage, wastewater, runoff, and recreational use.” No documented problem parameters were noted, although past exceedences noted at least once in SLBE include DO, pH, aluminum, cadmium, copper, zinc, lead, and indicator bacteria (Boyle and Hoefs 1993a; NPS 1997b).

Two recently developed water resources management plans have provided much needed information about the resources and needs of SLBE (Vana-Miller 2002; Heiman and Woller 2003). Vana-Miller's (2002) report detailed the current condition of the resources and discussed planning and high priority issues. His recommendations included conducting wetland and amphibian and reptile inventories and monitoring, developing a water quality monitoring plan, conducting more detailed bacterial surveys, and studying the recreational use of the Crystal River and its condition during low flow periods. Heiman and Woller (2003) reported on management concerns with the Glen Lake/Crystal River watershed. They identified the major watershed stressors as nutrient enrichment, exotic species, habitat loss, bacterial and thermal pollution, and contaminants.

The Platte River has been the subject of a number of studies addressing water quality, physical processes and integrity, and visitor perception (Lafrancois and Glase 2005). The Platte River is affected by a number of activities. Increased phosphorus levels have been attributed to the Platte River State Fish Hatchery, both from feeds provided for the salmon and the decay of returning salmon. Steps have been and continue to be taken to reduce this impact (Vana-Miller 2002). Bank erosion and degradation of water quality occurs on the Platte River due to high visitor use. The occasional use of motorboats increases erosion issues and, at times, conflicts with other visitors using the river (Kemezis 1983 in Lafrancois and Glase 2005).

The biological diversity of the Crystal River is relatively high, with 15 macrophyte species and 35 fish species documented in several studies (Lafrancois and Glase 2005). The Crystal River has the highest number of riffles (four) of any stream reach in SLBE and receives high use from canoers, kayakers, and tubers. Though the Crystal River was called "pristine" in a 2002 grant proposal, concern exists that increased use will degrade habitat and negatively affect the aquatic community (Vana-Miller 2002). This river is the second largest stream in the park and drains the Glen Lake watershed to Lake Michigan. The water level is controlled by a small low-head dam that regulates discharges from Glen Lake and Fisher Lake.

Elias (2007) sampled nine lakes as part of a diatom biomonitoring and calibration and water quality study. Samples were collected from Manitou, Florence, Shell, Bass (Leelanau), School, Tucker, North Bar, Loon, and Round Lakes from May 23-26, June 27-July 5, August 8-11, and September 26-30, 2005. All lakes except Florence Lake were well-buffered and generally hard. Mean pH levels ranged from 8.3 for Tucker Lake to 8.8 for School Lake. Round and School Lakes had high levels of sodium and chloride compared to other lakes in SLBE, possibly due to salt from nearby roads. Except in Florence Lake, calcium levels were sufficient to support zebra mussels, and several lakes already host this exotic species. All the SLBE lakes in this study had surface water connections except for Shell, North Bar, and Florence Lakes. Several lakes also had relatively high sulfate concentrations, not unusual in calcareous regions. Dissolved organic carbon differed widely among lakes from 3.3 mg/L (Loon Lake) to 13.4 mg/L (School Lake). Several lakes on multiple occasions did not meet the USEPA ecoregional reference criteria for chlorophyll-*a* and Secchi depth (5 μg/L and 3.2 m respectively). These exceedences are interesting because one might expect waters in a national lakeshore to typify reference conditions, but they are not detrimental at the levels observed in SLBE (GLKN, Joan Elias, Aquatic Ecologist, letter, 11/17/08). Dissolved silica levels were generally below detection limits in the early part of the season, which may limit diatom populations, except in North Bar and Loon Lakes.

Elias (2007) found that Carlson Trophic State Indexes (TSI) (Carlson 1977) based on average chlorophyll-*a* levels varied from 38 (Shell Lake) to 49 (Florence Lake). Generally lakes with TSI values <30 are ranked as oligotrophic, and lakes with values >50 are ranked as eutrophic (Wetzel 2001). Elias (2007) thus classified all nine study lakes as mesotrophic. Shell, School, and Tucker Lakes, all of which are shallow, had TSIs based on TP and Secchi depth that exceeded the TSI value based on chlorophyll-*a*, suggesting that non-algae factors such as other particulates and color are reducing transparency. Elias (2007) found that all nine study lakes were phosphorus limited, using the TN:TP ratio >15 of Shaw et al. (1996).

Elias (2007) found that temperature profiles exhibited a weak thermocline in all the sampled lakes during May 2005. (School Lake was omitted because it is too shallow, at <2 m, to collect profile data). Except for Shell and Tucker Lakes, which are shallow, all lakes had begun to develop a weak oxycline in May. During the late June/early July and August sampling periods, most lakes had a clearly recognizable thermocline. Shell and Tucker Lakes remained fairly well mixed throughout the season. Loon and Round Lakes had an increase in DO slightly below the Secchi depth in early July, suggesting a deeper layer of photosynthetic activity. Several lakes had DO concentrations below the USEPA criterion of 4 mg/L for fresh water in a substantial portion of the lake. For example, in Loon Lake, the bottom 9-10 m, or nearly half of the total depth, was below the USEPA criterion in July, August, and September. Most lakes had turned over by the time of the September sampling, with the exceptions of Lake Manitou and Loon Lake, both of which are relatively deep and maintained an anoxic layer below the thermocline (Elias 2007).

Elias and VanderMeulen (2008) monitored six SLBE ‘index’ lakes (Manitou, Shell, Otter, Tucker, Loon, and Round Lakes) in 2007. All had good buffering (mean alkalinity 117-142 mg/L), high specific conductance (253-320 µS/cm), and high cations. Calcium was generally high enough (>20 mg/L) to support zebra mussels. Round Lake had greater chloride and sodium levels than the other lakes, and the authors indicated this might be due to runoff of de-icing chemicals used on Hwy M-22. All six lakes were alkaline, with the pH ranging from 8.2-8.8. Dissolved organic carbon levels ranged from 3.5 mg/L (Loon Lake) to 9.7 mg/L (Tucker Lake). Mean Secchi depths ranged from 1.6 m (Manitou Lake) to 4.2 m (Loon Lake). Shallower lakes (Shell, Tucker and Otter Lakes) exhibited either weak or no stratification during the course of the study. Lake Manitou and Round Lake were stratified through most of the sampling period; Loon Lake was stratified on all three sampling dates. Stratified lakes often exhibited DO concentrations <4 mg/L in the hypolimnion. The authors recommended sampling other lakes in addition to the index lakes in the future. Benchmarks were installed at the six index lakes and School Lake for measuring water levels. The authors planned to install benchmarks at Florence and Bass Lake (Leelanau) in 2008 and evaluate the feasibility of installing them on other lakes.

These studies generally indicated that all SLBE streams and lakes had high water quality and minimal impairments. It is obvious from the above data retrieval that many SLBE surface waters do not have much more than short term monitoring assessments, and there is a great need for a long-term monitoring strategy that will include the important surface water resources of SLBE for future management decisions.

Plankton

Historic plankton data on SLBE surface waters are limited and have usually been collected as part of larger broad-based limnologic studies. Stevenson (1992) studied the phytoplankton in Big and Little Glen Lakes, and found that the communities differed between the two lakes and diatom abundance was low in both. The phytoplankton communities of Round, Loon, and North Bar Lakes were investigated by Nevers and Whitman (2004), who found that green algae (Chrysophyta) dominated the flora in all three.

Whitman et al. (2002a) studied the potential use of limnetic zooplankton community structure as a bioassessment tool for SLBE lakes and found that this community was able to describe lake trophic status, but that cost would probably limit the broad use of this approach. They studied the Shalda Creek, Crystal River, Otter Creek, Platte River, and Betsie River watersheds as well as isolated SLBE lakes. The Shalda Creek watershed study included Narada, School, and Shell Lakes. The Crystal River watershed study included Big Glen and Tucker Lakes. The Otter Creek watershed included Otter Lake, and the Platte River watershed included Loon Lake. The isolated lakes in their study were North Bar and South Bar Lakes. Round and Crystal Lakes, in the Betsie River watershed which lies mostly outside the SLBE boundaries, were also studied. A total of 85 taxa of zooplankton were found in their study lakes. Only 32 taxa comprised 1% or more of the average abundance of any lake. Immature copepods were common in most lakes. The cladoceran *Bosmina longirostris* made up 2-13% of average total zooplankton abundance in all study lakes. The rotifer *Kellicottia* sp. was also common and comprised more than 1% of the total abundance in all lakes. The authors also used Carlson's (1977) TSI and Kratzer and Brezonik (1981) to determine the trophic status of each study lake.

Aquatic Macrophytes

Quantitative aquatic macrophyte data are limited for the SLBE islands prior to 1983 and the SLBE mainland prior to 1988. Coulter (1904), Waterman (1922), Thompson (1967), Stockwell and Gannon (1975), and Linton (1987) all provided information on the aquatic macrophytes of SLBE; however, most of these studies were qualitative or descriptive in nature. Recent studies on aquatic macrophytes (Hazlett 1988, 1991; Albert 1992) provide much more detailed information on the mainland aquatic macrophytes of SLBE. Hazlett's (1988) quantitative study involved 18 lakes and three watersheds. Albert (1992) provided quantitative information on the aquatic macrophytes of four SLBE watersheds, four lakes, and the dune swales near the Platte River and Shalda Creek. Hazlett and Vande Kopple (1983) studied the aquatic vegetation of North and South Manitou Island lakes.

Forty-two species of floating or submerged (not emergent) aquatic macrophytes have been reported for SLBE, with richness varying from one (Tamarack Lake) to 23 species (Platte River). Lakes with high diversity are Otter Lake (20 species), Bass Lake (Benzie) (19 species), Otter Creek (18 species), and Tucker Lake, School Lake, and Crystal River (15 species each). Lakes with low diversity are Hidden and Florence Lakes (4 species each), Bow Lakes (5 species), and Mud and Loon Lakes (6 species each) (Vana-Miller 2002). Extensive macrophyte beds were generally present in all lake outlets (White 1987). Albert (1992) reported 10 species of aquatic macrophytes in the dune and swale habitats of the Platte River and Shalda Creek, and in both Bass Lakes, School Lake, and Tucker Pond. Hazlett (1986) and Albert (1992) provided some information on the riparian plant vegetation, but this zone of SLBE is basically unstudied in detail.

Hazlett's (1988) aquatic vegetation study sampled the following by canoe during 1986: Round, Loon, Deer, Bass, Otter, and Narada Lakes and the Platte River (four times), North Bar Lake, Day Mill Pond, Bass Lake (Leelanau), School Lake, Shell Lake, and Otter Creek (twice), and Lake Florence, Mud Lake, and Big Glen Lake (once). All the mainland lakes and streams except Taylor Lake and Day Mill Pond were resampled at least once during 1987. SLBE lakes, streams, and associated wetlands contained 69 families, 164 genera, 338 species, and two hybrids of aquatic macrophytes and vascular plants. Hazlett recommended continued preservation of the Otter Creek drainage from Otter Lake to Lake Michigan, Taylor Lake, Round Lake, the M-22 bog, and the lakes and bog in the lower Bow Lakes based on their floristic diversity. He also recommended that the water quality of lakes and streams be evaluated by the composition of the aquatic vegetation due to the fact that several studies (Volker and Smith 1965; Lind and Cottam 1969; Stuckey 1971; Steggal and Judd 1983) have indicated that a decline or disappearance of northern clear-water species such as largeleaf pondweed (*Potamogeton amplifolius*), Fries' pondweed (*P. friessi*), variableleaf pondweed (*P. gramineus*), floating pondweed (*P. natans*), whitestem pondweed (*P. praelongus*), flatstem pondweed (*P. zosteriformis*), and water-marigold (*Megalodonta beckii*), and an increase in "alien species" such as curly leaf pondweed (*Potamogeton crispus*) and Eurasian water-milfoil (*Myriophyllum spicatum*) might indicate a decline in water quality. He also stated that the invasive species purple loosestrife (*Lythrum salicaria)* potentially poses the greatest threat to shoreline vegetation in SLBE and should be monitored, and he even suggested that removal should begin immediately.

Hazlett (1991), in his study of Day Mill Pond, found star duckweed (*Lemna trisulca*), greater duckweed (*Spirodela polyrhiza*), Robbins' pondweed (*Potamogeton robbinsii*), and Hill's pondweed (*P. hillii*), all relatively rare in SLBE. He also found the rare species mare's-tail (*Hippuris vulgaris*) and white water crowfoot (*Ranunculus longirostris*) in Otter Creek and the state-threatened species cutleaf waterparsnip (*Berula erecta*) in the marl springs area near Otter Lake and in Otter Creek. The latter has been reported to prefer cold calcareous streams (Voss 1985) and is known from only eight counties in Michigan. Hazlett (1988) found the rare Oakes' pondweed (*Potamogeton oaksianus*) in the Port Oneida Bog.

Aquatic Macroinvertebrates

A biological study undertaken by NPS staff in 1988 showed that all SLBE rivers and streams had pollution-sensitive invertebrates present, indicating good water quality (NPS 2004a).

Hildebrand (1971) quantitatively sampled the aquatic macroinvertebrates of the Platte River above Platte Lake and provided important baseline data. The Chironomidae of the Crystal River were studied by Curry (1977), who also included Big and Little Glen Lakes. He found that the lakes and stream had from 9-28 and 9-26 species respectively on various dates. White (1987) found 50 macroinvertebrate taxa from 19 sites on four SLBE streams and indicated that the streams were probably autotrophic. The taxa were typical of warm water streams in Michigan. Linton (1987) identified macroinvertebrate habitat types in SLBE streams and indicated that the most common types were lotic depositional runs and marshes.

Boyle and Hoefs (1993a) conducted a three year quantitative study of SLBE aquatic macroinvertebrates and found the highest and lowest density in Otter Creek and the Platte River, respectively, although the Platte River had the highest taxa richness. In most instances, taxa richness increased in downstream reaches. Filter feeding and gathering guilds were dominant near lake outlets. Fine sediments dominated all streams. Whitman et al. (1994) studied aquatic macroinvertebrates in SLBE streams and lakes and found high variability in richness and density. Flower and Walker (1999a, b) conducted a bioassessment study of the Crystal River and found low nutrient and metal concentrations.

Heuschele (2000) found freshwater sponges in Narada, Bass (Benzie), and Deer Lakes, with the highest populations in Narada Lake. Sponges were not found in School, Glen, North Bar, Shell, and Bass (Leelanau) Lakes.

Edsall and Phillips (2004) studied the use of burrowing mayflies (*Hexagenia*) to assess the health and cultural eutrophication of Loon Lake and the lower Platte River ecosystem compared to two reference lakes, Crystal Lake and Frankfort Harbor (Betsie Lake). The study followed legal action initiated by property owners on Platte Lake to require nutrient loading from the MDNR's Platte River State Fish Hatchery to be reduced. The effects of the nutrient loading included excess algae blooms and reduced water clarity.

Edsall and Phillips (2004) found that the DO concentration in Loon and Platte Lakes was 7.3 and 7.5 mg/L at the surface and 0.6 and 2.8 mg/L at the bottom of the thermocline, respectively. In Crystal Lake, the DO was 7.9 mg/L at the surface and increased to 11.5 mg/L at 13.7 m, and in Frankfort Harbor, the DO increased from 8.5 mg/L at the surface to 11.8 mg/L at 6.1 m. *Hexagenia* nymphs were not found at depths of 9.2-12.8 m in Loon Lake and 7.6-14.9 m in Platte Lake; the authors attributed this to *Hexagenia*'s requirement for DO levels of 7.5 mg/L or higher. Nymphs were found only in mud and fine sand substrates to a depth of 37.3 m in Crystal Lake, but not greater than 6.1 m in Loon Lake and 7.6 m in Platte Lake.

Freeman (2004) listed 67 species of Odonata in SLBE and 98 for Benzie County; 160 are known for Michigan. The wandering glider (*Pantala flavescens*), spot-winged glider (*Pantala hymenaea*), black saddlebags (*Tramea lacerata*), and variegated meadowhawk (*Sympetrum corruptum*) collected in SLBE were new species records for western Michigan. They are migratory, and Freeman stated the larvae probably do not occur in SLBE surface waters. The common sanddragon (*Progomphus obscurus*) and the splendid clubtail (*Gomphus lineatifrons*) were found only within the park. The Platte River between Big Platte Lake and Loon Lake was the only site where the Illinois River cruiser (*Macromia illinoiensis*) was found. The Crystal River had very rich populations of gomphid dragonflies, which generally require high water quality.

Nichols et al. (2004) studied the unionid mussel populations in SLBE from 2000-2003. Samples were collected once from Bass (Leelanau), Loon, Manitou, North Bar, Otter, School, and Shell Lakes and Otter Creek, and twice from the Crystal and Platte Rivers, in the three year period. Sixteen species were found, but not all species were found at all sites. The highest mussel richness occurred in the Platte River (12 in 2001 and 9 in 2003) with a richness of 13 mussel species for both years combined. The Crystal River had the second highest diversity (eight species) of the sites sampled, with the highest densities just below the dam where host fish species congregate. Otter Creek was devoid of mussels; although a few individuals were found near the river mouth, no individuals were collected upstream. Only one species was found in School Lake in 2000. Only large numbers of dead mussels were found in Bass Lake (Leelanau), and the researchers estimated that these mussels had died within the last 10-15 years. They suspected that the lake had been treated to control swimmers itch, and the treatment may have caused the mussels' demise.

The most common mussels collected in the Nichols et al. (2004) study were the giant floater (*Pyganodon grandis*) and the fat mucket (*Lampsilis siliquoidea*), which dominated the unionid fauna in lakes where they occurred. Wavyrayed lampmussel (*Lampsilis fasciola*), a state-threatened species, was found in the tailrace of the Crystal River Dam but nowhere else. Unionid species richness, density, and distribution were not correlated with any measured environmental variable, including fish species present. This is surprising, since mussels depend on fish as hosts for successful reproduction. The authors also did not find a correlation between trophic status and mussel density. Calcium, DO, and pH levels were all at known acceptable levels at all sites they sampled. The mussel populations at SLBE contained very low levels of all the organic and metals contaminants tested and were well below the state and federal action limits.

Unionid distributions in the Nichols et al. (2004) study lakes appeared to be random except in Lake Manitou, Shell, and Otter Lakes, where distributions appeared to be related to water depth and occurred above the thermocline. In the Platte River, distributions were also random with respect to environmental factors but appeared somewhat clumped. Most species were habitat tolerant and have a fairly wide distribution in the Midwest. Numbers of mussels were higher than those found in other northern areas of lower Michigan (Badra and Goforth 2003). Generally, river habitats had higher numbers of mussels than lakes, apparently typical for North America. Nichols et al. (2004) concluded that mussels should be found in most SLBE streams and lakes if the body of water does not freeze solid, summer temperatures are above 13^{o} C, and the pH is >5.5.

Nichols et al. (2004) concluded that the species composition of unionids in SLBE is typical for the Great Lakes region but may be influenced in the future by human interactions and invasive species. The greatest threat to the existing unionid populations in SLBE appears to be the exotic invasive zebra mussel. These mussels became established in SLBE by 1997 and appear to be spreading rapidly. Schloesser and Nalepa (1994), Baker and Hornback (1996), and Schloesser et al. (1996) have shown high mortality rates of native mussels when there is interaction with zebra mussels; it is reasonable to assume that a similar situation will occur with quagga mussels.

Fish

The fish composition of SLBE lakes and streams has not been systematically sampled through time. Kelly and Price (1979) did the first intensive comprehensive fisheries study within SLBE, using 40 sampling stations and examining all habitats. Combining their results with studies conducted by the USFWS and the Michigan Museum of Zoology, they reported a total of 76 species for SLBE. Historic fish distribution maps (Lee et al. 1980) indicated the potential for another six species, bringing the total for SLBE to 82. Kelly and Price found eight exotic species (sea lamprey, alewife, carp [*Cyprinus carpio*], rainbow smelt, coho salmon, Chinook salmon, rainbow trout, and brown trout) and one hybrid fish species (splake) in SLBE. Big Glen Lake was the only location of splake in SLBE. The authors ranked four SLBE watersheds according to fish species richness and found the Platte River watershed had the highest number of species (53 species), followed by the Shalda Creek watershed (45 species), Crystal River watershed (35 species), and Otter Creek watershed (27 species). A total of 34 fish species were found along the shoreline of Lake Michigan. Species richness was generally related to watershed size. The nine common game fish occurring in SLBE were largemouth bass (*Micropterus salmoides*), smallmouth bass, trout, salmon, lake trout, yellow perch, bluegill (*Lepomis macrochirus*), rock bass (*Ambloplites rupestris*), and northern pike (Kelly and Price 1979). Taube (1974) reported that arctic grayling (*Thymallus arcticus*) historically occurred in the Platte River (prior to 1895) (Appendix D).

The Natural Resources Department of the Grand Traverse Band Ottawa and Chippewa Indians surveyed 35 waterbodies in a collaborative project with SLBE from 2003-2006 (Murphy 2004a; Fessell 2007). Waterbodies sampled were Good Harbor Creek, Shalda Creek, Narada Lake, School Lake, Bass Lake (Leelanau), Shell Lake, Tucker Lake, Tucker Creek, Day Mill Pond, Otter Creek, Otter Lake, Upper Otter Creek, Bass Lake (Benzie), Hidden Pond, Hatt Pond, North Bar Lake, Lake Manitou, Florence Lake, Aral Springs, Taylor Lake, Beck Pond, Esch Road Pond, Deer Lake, Peterson Road Pond, Mud Lake, Loon Lake, Round Lake, Long Lake, Little Traverse Lake, Boekeloo Road Ponds, and Lake Michigan sites including Good Harbor Bay, Sleeping Bear Bay, Bar Lakes shoreline, Esch Road shoreline, and Platte Bay at Lake Michigan Road. Methods used were similar to those of Kelly and Price (1979).

Fessell (2007) used gillnets, fyke nets, boom style electro-shocking, backpack electro-shocking, minnow traps, and seining methods to sample the fish populations, and his sampling sites represented approximately 99% of the waterbodies within SLBE. He found 46 fish species from 2003-2006. He noted that the tables in the Kelly and Price (1979) report include only 62 species, not the 76 that they had indicated, and gave a revised total of 65 species that have been documented for SLBE. He found three species (lake whitefish, brook silverside [*Labidesthes sicculus*], and round goby) that were not previously reported by Kelly and Price (1979). He found much higher diversity in inland streams than lakes and increased species diversity for the Lake Michigan sites from north to south. Lakes that had some connection to Lake Michigan had higher fish diversity than the smaller isolated lakes. The Crystal River had the highest (31 species) and Good Harbor Creek had the lowest (7 species) fish diversity of streams. Loon Lake had the highest (23 species) and Hatt and Day Mill Ponds had the lowest (1 species) fish diversity in lakes he sampled. Lakes surveyed where no fish were found were Taylor Lake, Esch Road Pond, and Peterson Road Pond. Taylor Lake is a shallow lake with low pH and alkalinity. Esch and Peterson Road Ponds are also very shallow and probably experience winterkill (Murphy 2004a). Fessell (2007) found eight exotic species within SLBE (brown trout, Chinook salmon, coho salmon, rainbow trout, alewife, common carp, round goby, and sea lamprey). He did not find the exotic rainbow smelt reported by Kelly and Price (1979), and he observed the common carp in Loon Lake but did not collect it.

Water quality variables measured by Murphy (2004a) with the fisheries surveys were DO, pH, temperature, depth, total dissolved solids, Secchi depth, and specific conductance. A vertical profile of these variables was constructed for each water body. In addition sulfate, nitrate-N, ammonia-N, alkalinity, total hardness, calcium hardness, chloride, TP, and true color were measured in the epilimnion, one meter below the lake surface, and one meter above the lake bottom in the hypolimnion.

Amphibians and Reptiles

GLKN Vital Signs protocols include amphibian monitoring for numerous reasons, including that amphibians are sensitive to numerous environmental factors and are highly linked in food webs, declines of amphibian populations are a prominent global issue, and many types of amphibians live in both terrestrial and aquatic habitats (Route and Elias 2007). Up to 35 species of amphibians occur in the Great Lakes basin, and about two-thirds of those have conservation concerns at least somewhere in the basin (Hecnar 2004). The Lake Michigan basin is known to be home to 21 species of amphibians, 16 of which have been found in SLBE (Table 11) (Bowen and Gillingham 2004; Hecnar 2004; Anton 2007; NPSpecies 2007; Bowen and Beever 2008). Seventeen reptile species are also known for SLBE: one lizard, five turtles, and 11 snakes (Table 12; Bowen and Gillingham 2004; Bowen et al. 2007; NPSpecies 2007).

Most amphibians depend on wetlands for at least part of their life cycles (Hecnar 2004). A 2007 survey of amphibians on North and South Manitou Islands focused on areas of hydric soils (Bowen and Beever 2008;Figure 26); the wetlands base map provided by MDEQ includes only hydric soil complexes that have 15% or more hydric soils. Only four species (spotted salamander, eastern American toad, eastern red-backed salamander, and northern spring peeper) were found in this survey, and this result may be related to low precipitation which led to the disappearance of some wetlands (NPS, Ken Bowen, email, April 10, 2008).

Near the time of publication of this report, we received Casper and Anton's (2008) reptile and amphibian inventory for SLBE documenting the presence of 14 amphibians (five salamanders and nine anurans) and 15 reptiles (four turtles, ten snakes, and one lizard). Two salamanders, two anurans, three turtles, and two snakes were listed as unconfirmed. The authors recommended removing the Blanchard's cricket frog (*Acris crepitans blanchardi*) from the SLBE species list. Table 11 and Table 12 have been modified to reflect these recent changes.

Species within SLBE's range limits, but unconfirmed at SLBE in 2007 field work, include blue-spotted salamander (*Ambystoma laterale*), Cope's gray treefrog (*Hyla chrysoscelis*), wood turtle (*Glyptemys insculpta*), Blanding's turtle (*Emydoidea blandingii*), northern red-bellied snake (*Storeria occiptomaculata occiptomaculata*), and eastern massasauga (*Sistrurus catenatus catenatus*). Their absence could indicate ecological factors or simply insufficient inventory effort (Casper and Anton 2008). Nine additional species are considered of special interest relative to climate change, as they are at or near the limits of their ranges.

Trophic State

The trophic state of a lake is based on the total weight of its living biological material at a specific location and time (Carlson and Simpson 1996). Carlson's TSIs use algal biomass as the basis for trophic state classification, and three variables (chlorophyll pigments, Secchi depth, and TP) independently estimate algal biomass, with chlorophyll being the best predictor (Carlson 1977). Carlson TSIs were compiled by Vana-Miller (2002) for 1992 from data collected by Boyle and Hoefs (1993a) and for 1999 from Whitman et al. (2002b). Data collected by Murphy

Table 11. Amphibians known in Sleeping Bear Dunes National Lakeshore (Bowen and Gillingham 2004; Anton 2007; NPSpecies 2007; Bowen and Beever 2008; Casper and Anton 2008) and their conservation status (Hecnar 2004).

Standard Scientific Name	Standard Common Name	Conservation Status in Great Lakes (Hecnar 2004)	Threats				
			Habitat Loss	Pollution	Predatory Fish	Harvest	Disease
Acris crepitans blanchardi (a)*	Blanchard's cricket frog	special concern-MI endangered-ON, WI	x	x	--	--	--
Ambystoma laterale (a)**	Blue-spotted salamander	special concern-IN, NY endangered-OH	x	--	x	--	--
Ambystoma maculatum (a,b,c,e)	Spotted salamander	--	x	x	--	--	--
*Ambystoma tigrinum tigrinum***	Eastern tiger salamander						
Anaxyrus americanus americanus (a,b,c,d,e)	Eastern American toad	--	x	x	--	--	--
*Anaxyrus fowleri***	Fowler's toad						
Hemidactylium scutatum (a,e)	Four-toed salamander	endangered-IN special concern-WI, MN	--	--	--	--	--
*Hyla chrysoscelis***	Cope's gray treefrog						
Hyla versicolor (a,d,e)	Gray treefrog	--	x	x	x	--	--
Lithobates catesbeiana (a,b,e)	American bullfrog	special concern-WI	x	x	--	x	--
Lithobates clamitans melanota (a,b,d,e)	Northern green frog	--	--	--	--	--	--
Lithobates palustris (a,e)	Pickerel frog	special concern-WI	x	x	--	--	--
Lithobates pipiens (a,b,d,e)	Northern leopard frog	special concern-IN	x	x	--	x	x
Lithobates sylvaticus (a,b,d,e)	Wood frog	--	x	x	--	--	--
Necturus maculosus maculosus (a,e)	Mudpuppy, Waterdog	special concern-IN	--	x	--	x	x
Notophthalmus viridescens (a,b,c,e)	Eastern newt	--	x	x	x	x	--
Plethodon cinereus (a,b,c,e)	Eastern red-backed salamander	--	x (?)	--	--	--	--
Pseudacris crucifer (a,b,c,d,e)	Spring peeper	--	x	x (?)	--	--	--
Pseudacris triseriata (a,e)	Western chorus frog	special concern-MI	x	x	--	--	--

a) NPSpecies 2007; b) Bowen and Gillingham 2004; c) Bowen and Beever 2008; d) Anton 2007; e) Casper and Anton 2008

*removed from SLBE list by Casper and Anton (2008)   **listed as unconfirmed by Casper and Anton (2008)
? are as listed by Hecnar (2004).   Conservation status of shaded boxes was not evaluated by Hecnar (2004)..

Table 12. Reptiles known in Sleeping Bear Dunes National Lakeshore (Bowen and Gillingham 2004; Bowen et al. 2007; NPSpecies 2007; Casper and Anton 2008).

Standard scientific name	Standard common name
Chelydra serpentina serpentina (a,b,d)	Eastern snapping turtle
Chrysemys picta marginata (a,b,d)	Midland painted turtle
*Clemmys guttata***	Spotted turtle
Coluber constrictor foxii (d)	Blue racer
Diadophis punctatus edwardsii (a,b,d)	Northern ring-neck snake
Emydoidea blandingii (a)**	Blanding's turtle
Glyptemys insculpta (a)**	Wood turtle
Graptemys geographica (d)	Northern map turtle
Heterodon platyrhinos (a,d)	Eastern hog-nosed snake
Lampropeltis triangulum triangulum (a,d)	Eastern milk snake
Nerodia sipedon sipedon (a,d)	Northern watersnake
Opheodrys vernalis (a,d)	Smooth greensnake
Pantherophis vulpinus (c,d)	Western foxsnake
Plestiodon fasciatus (a,d)	Five-lined skink
*Sistrurus catenatus catenatus***	Eastern massasauga
Storeria dekayi (a,b,d)	DeKay's brownsnake
Storeria dekayi wrightorum (a)	Midland brown snake
Storeria occipitomaculata occipitomaculata (a)**	Northern redbelly snake
Terrapene carolina (a,d)	Eastern box turtle
Thamnophis sauritus septentrionalis (a,b,d)	Northern ribbon snake
Thamnophis sirtalis sirtalis (a,b,d)	Eastern gartersnake

a) NPSpecies 2007; b) Bowen and Gillingham 2004; c) Bowen et al. 2007; d) Casper and Anton 2008

**Listed as unconfirmed by Casper and Anton (2008).

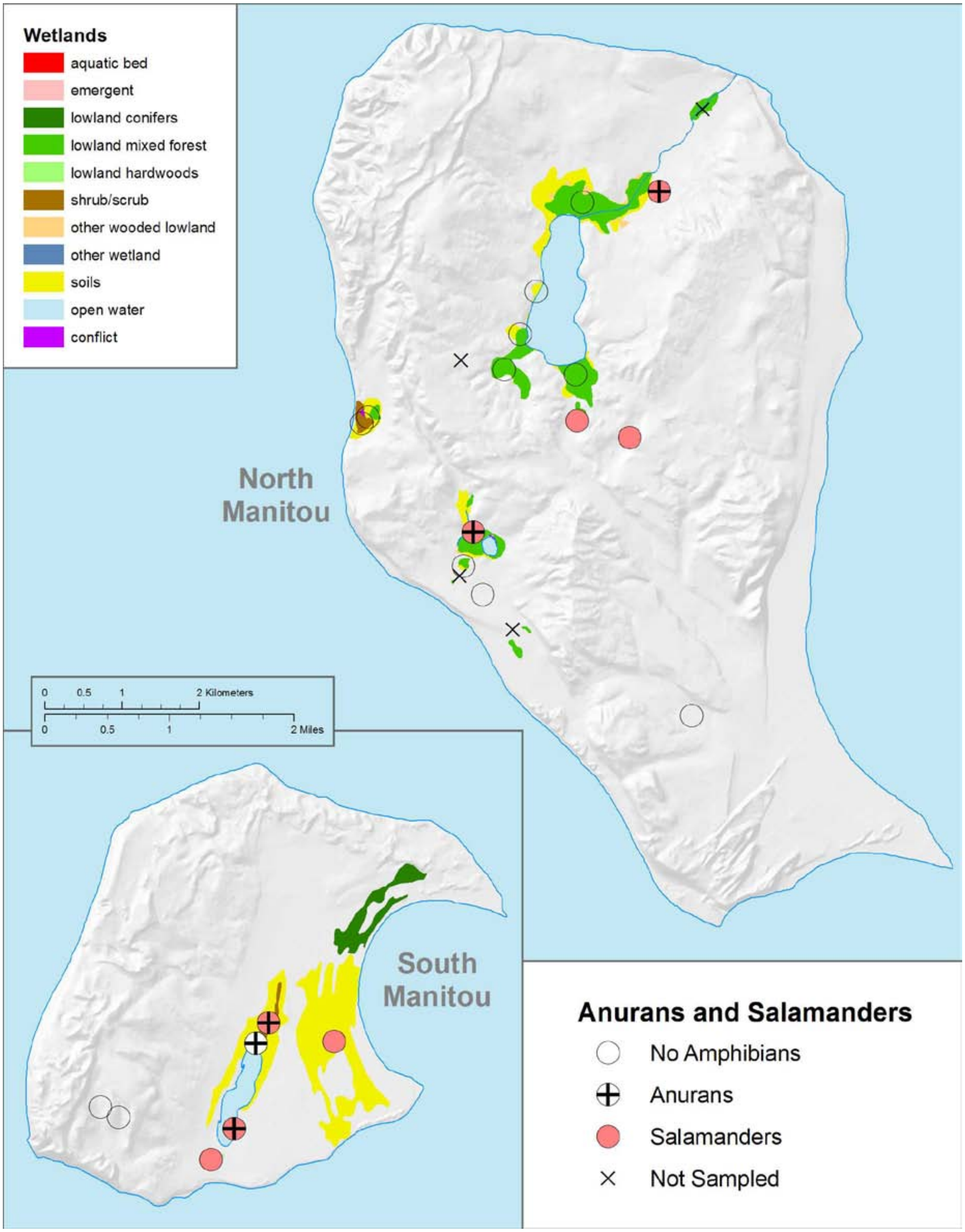

Figure 26. Locations and results of 2007 amphibian sampling on North and South Manitou Islands (Bowen and Beever 2008) (For explanation of wetlands base map, see the Wetlands methodology section).

(2003), Elias (2007), and Elias and VanderMeulen (2008) have been added to Vana-Miller's work (Table 13, Figures 27-30).

In general, TSIs were lowest for eight SLBE inland lakes in 1992 and highest in 1999, with the exception of two very high TP TSIs in 1992 (Figure 27). The 1992 values generally showed lakes as oligotrophic (<30) to mesotrophic (40-50), while 1999 values showed them as eutrophic (50-60) to hypereutrophic (>70). Secchi TSIs tended to be the least variable over time (Figure 28) Chlorophyll, considered the most reliable predictor, was in this case the most variable over time, with values for a single lake ranging from oligotrophy to hypereutrophy (Figure 29). For most of these lakes, the highest chlorophyll and TP TSIs occurred in 1999, and the lowest occurred in 1992, although for Shell and School Lakes, their highest TP TSIs occurred in 1992. Whitman et al. (2002a) attributed changes in TSIs between 1992 and 1999 to differences in sampling and analysis methods rather than a rapid change in trophic state.

Water Quality

Nutrients

We compared TP and TN values for nine SLBE inland lakes for the time periods 1990-95, 2005, and 2007. Because the number of samples is extremely limited, this comparison can give only a rough indication of trends. However, TP levels for the period of record increased in five lakes (Manitou, Florence, Bass (Leelanau), Tucker, and Round Lakes), decreased in three (Shell, North Bar, and Loon Lakes), and stayed nearly the same in School Lake. TN levels increased slightly in three lakes (Florence, Bass, and Tucker Lakes), increased greatly in two (School and Round Lakes), and decreased greatly in three (Manitou, North Bar, and Loon Lakes) (Table 14, Figure 31).

School Lake exceeded both the USEPA subecoregion reference criterion of 0.02 mg/L for TP from 1990-95 and in 2005 and the TN criterion of 0.81 mg/L in 2005, but was not sampled in 2007 (NPS 1997b; USEPA 2000; Elias 2007). Shell Lake exceeded the TN criterion in 2005 and 2007. Lake Manitou exceeded the TN criterion from 1990-95, but not in 2005 or 2007. All nine lakes had TN:TP ratios >15 and so are phosphorus limited (Table 14; Shaw et al. 1996; Elias 2007; Elias and VanderMeulen 2008).

Alkalinity

We also compared alkalinity values for nine SLBE inland lakes for the periods of record 1990-95, 2005, and 2007. Except for Loon Lake, little change occurred, or values were slightly higher (Figure 32). All lakes had well above 25 mg/L alkalinity and thus are not considered susceptible to acid rain (Sheffy 1984; Shaw et al. 1996).

Table 13. Carlson TSI values and trophic states for eight SLBE inland lakes from 1992–2007 (Vana-Miller 2002; Murphy 2003; Elias 2007; Elias and VanderMeulen 2008).

Lake	Secchi '92	Secchi '99	Secchi '03	Secchi '05	Secchi '07	Secchi Mean
Shell Lake	43	43	40	44	41	42±1.6
	M	M	M	M	M	M
North Bar Lake	47	46	49	48	--	48±1.3
	M	M	M	M		M
Tucker Lake	46	50	45	46	48	47±2.0
	M	E	M	M	M	M
School Lake	50	52	48.5	58	--	52±4.2
	E	E	M	E		M-E
Loon Lake	46	47	--	43	39	44±3.6
	M	M		M	OM	M
Round Lake	44	44	37	38	41	41±3.3
	M	M	OM	OM	M	OM-M
Otter Lake	45	47	35	--	43	43±5.3
	M	M	OM		M	OM-M
Narada Lake	40	46	51	--	--	46±5.5
	M	M	E			M-E
	Chl a '92	Chl a '99	Chl a '03	Chl a '05	Chl a '07	Chl a Mean
Shell Lake	30	50	42	38	--	40±8.3
	OM	E	M	OM		OM-M
North Bar Lake	32	58	34	45	--	42±12
	OM	E	O	M		OM-E
Tucker Lake	37	59	40	42	--	45±9.9
	OM	E	M	M		OM-E
School Lake	30	69	40	45	--	46±17
	OM	E	M	M		O-E
Loon Lake	34	54	--	43	--	44±10
	OM	E		M		OM-E
Round Lake	35	58	47	44	--	46±9.5
	OM	E	M	M		OM-E
Otter Lake	31	58	38	--	--	42±14
	OM	E	OM			O-E
Narada Lake	34	60	46	--	--	47±13
	OM	E	M			OM-E
	TP '92	TP '99	TP '03	TP '05	TP '07	TP Mean
Shell Lake	100	56	37	41	34	54±27
	H	E	OM	M	OM	O-H
North Bar Lake	37	50	34	39	--	40±7.0
	OM	E	OM	OM		OM-M
Tucker Lake	38	54	45	45	43	45±5.8
	OM	E	M	M	M	OM-E
School Lake	100	62	46	49	--	64±25
	H	E	M	M		OM-H
Loon Lake	40	54	--	38	33	41±9.0
	M	E		OM	OM	OM-M
Round Lake	44	54	38	39	41	43±6.5
	M	E	OM	OM	M	OM-M
Otter Lake	30	60	34	--	32	39±14
	OM	E	OM		OM	O-E
Narada Lake	43	60	49	--	--	51±8.6
	M	E	M			M-E

O-H=oligotrophic to hypereutrophic; OM=oligomesotrophic; OM-M=oligomesotrophic to mesotrophic; OM-E=oligomesotrophic to eutrophic; M=mesotrophic; M-E=mesotrophic to eutrophic; E=eutrophic

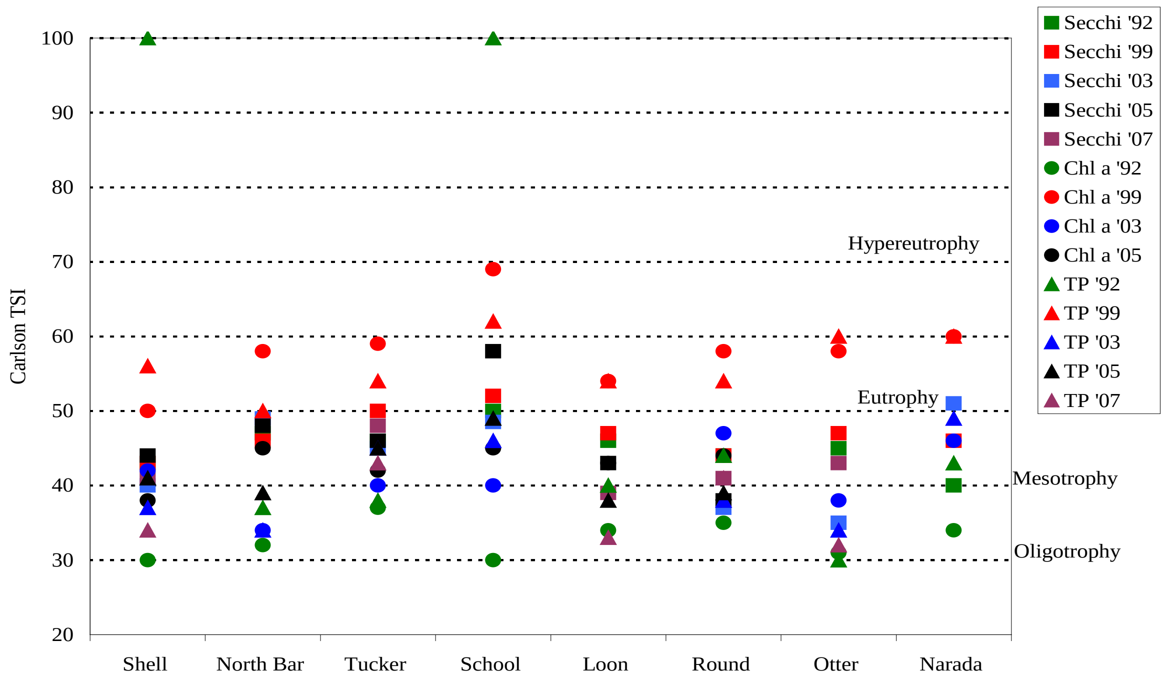

Figure 27. Carlson TSIs for inland lakes in Sleeping Bear Dunes National Lakeshore (Vana-Miller 2002; Murphy 2003; Elias 2007; Elias and VanderMeulen 2008).

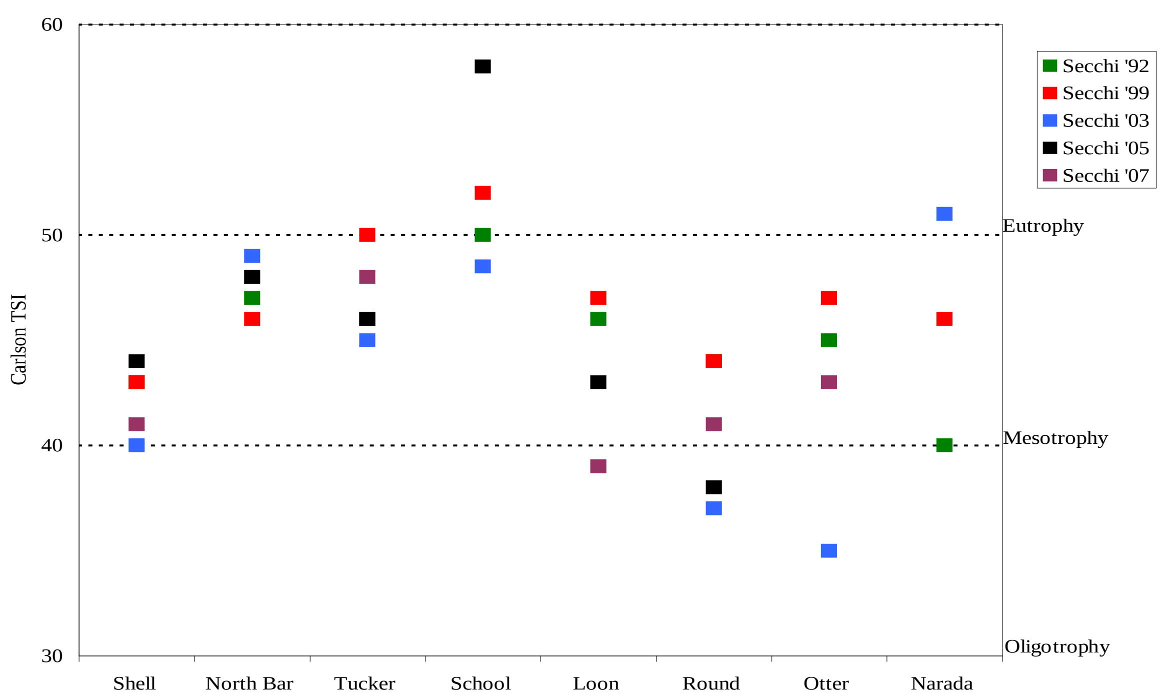

Figure 28. Carlson Secchi TSIs for inland lakes in Sleeping Bear Dunes National Lakeshore (Vana-Miller 2002; Murphy 2003; Elias 2007).

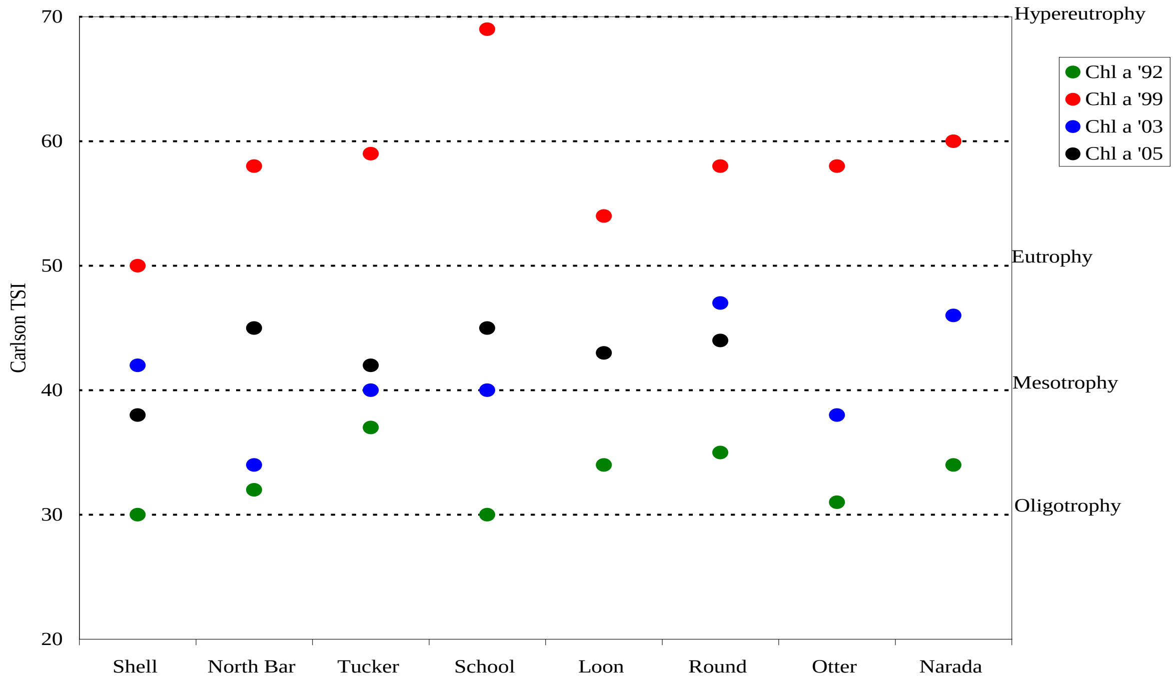

Figure 29. Carlson chlorophyll-*a* TSIs for inland lakes in Sleeping Bear Dunes National Lakeshore (Vana-Miller 2002; Murphy 2003; Elias 2007).

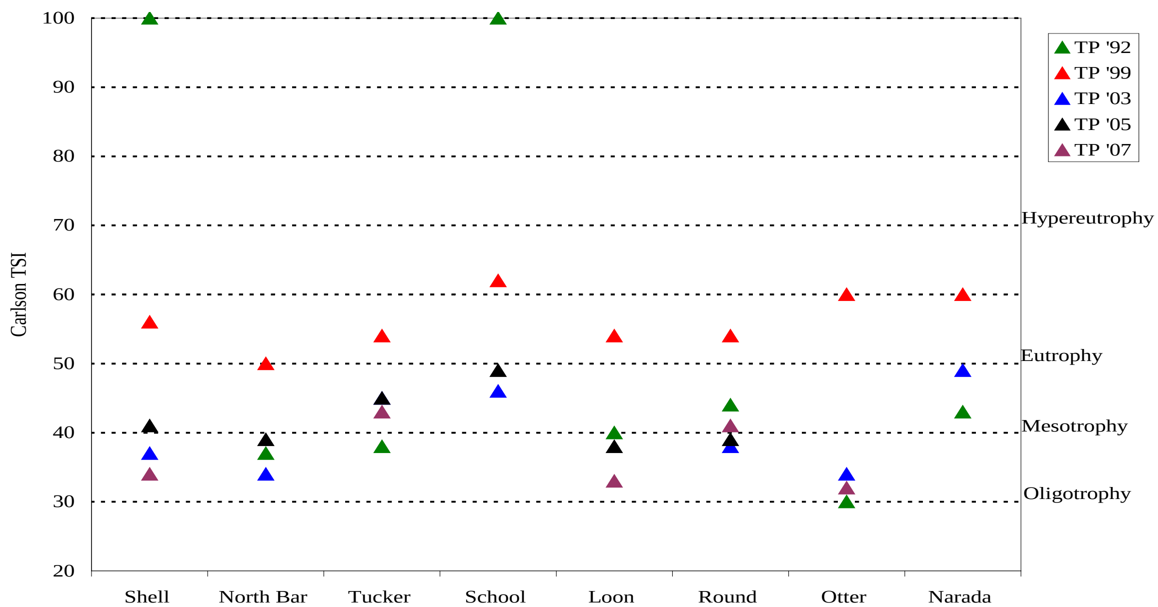

Figure 30. Carlson total phosphorus TSIs for inland lakes in Sleeping Bear Dunes National Lakeshore (Vana-Miller 2002; Murphy 2003; Elias 2007; Elias and VanderMeulen 2008).

Table 14. TP and TN levels for nine SLBE inland lakes from 1990-95, 2005, and 2007 (numbers in parentheses indicate numbers of samples) (NPS 1997b; Elias 2007; Elias and VanderMeulen 2008).

Lake	TP ’90-95 mg/L (n)	TP ‘05 mg/L (n)	TP ‘07 mg/L (n)	TN ’90-95 mg/L (n)	TN ‘05 mg/L (n)	TN ‘07 mg/L (n)	TN:TP ratio (year)
Lake Manitou	0.005	0.009	0.019	0.95	0.41	0.620	48 (2005)
	(2)	(3)	(3)	(2)	(3)	(3)	33 (2007)
Florence Lake	0.005	0.014	--	0.60	0.65	--	46 (2005)
	(2)	(3)		(2)	(3)		
Bass Lake (L)	0.007	0.009	--	0.555	0.59	--	64 (2005)
	(7)	(3)		(4)	(3)		
Tucker Lake	0.011	0.018	0.014	0.71	0.76	0.740	44 (2005)
	(5)	(3)	(3)	(3)	(3)	(3)	52 (2007)
School Lake	0.022	0.022	--	0.735	1.08	--	49 (2005)
	(7)	(2)		(3)	(2)		
Shell Lake	0.013	0.013	0.008	0.624	0.96	0.818	76 (2005)
	(6)	(2)	(3)	(4)	(2)	(3)	102(2007)
North Bar Lake	0.013	0.011	--	0.522	0.51	--	46 (2005)
	(7)	(3)		(5)	(3)		
Round Lake	0.007	0.011	0.011	0.505	0.56	0.697	51 (2005)
	(6)	(2)	(3)	(6)	(2)	(3)	63 (2007)
Loon Lake	0.014	0.011	0.006	0.570	0.22	0.516	21 (2005)
	(8)	(2)	(3)	(6)	(2)	(3)	74 (2007)

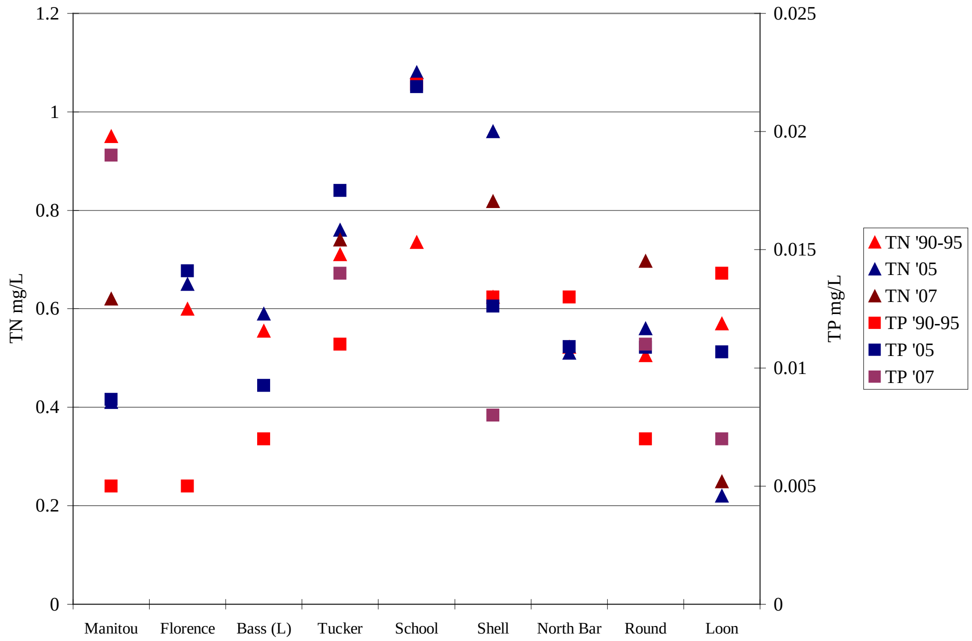

Figure 31. TP and TN values for nine SLBE lakes, 1990-95, 2005, and 2007 (NPS 1997b; Elias 2007; Elias and VanderMeulen 2008).

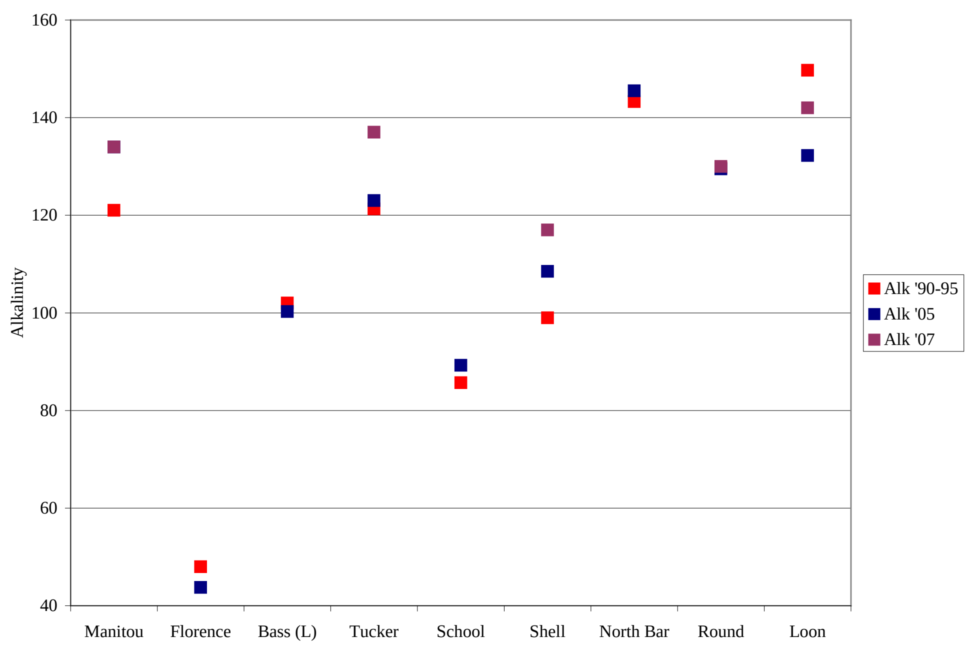

Figure 32. Alkalinity values for nine SLBE lakes, 1990-95 and 2005 (NPS 1997b; Elias 2007; Elias and VanderMeulen 2008).

Lake Sediments

Parsons et al. (ca. 2004) collected sediment cores from Crystal Lake in 2001 as part of a larger sediment study of 27 Michigan lakes. Mercury levels in Crystal Lake sediments declined from the 1500s to the mid 1700s, although levels during this time period were considered background levels. Levels next rose slowly to the mid 1800s and then sharply increased. Currently, mercury levels are above background concentrations and are increasing.

The GLKN, with cooperators from the St. Croix Watershed Research Station, is developing an environmental monitoring program for lake sediments using paleolimnological techniques and analysis of diatoms. The results will help determine a reference condition for SLBE lakes as well as reconstructing a detailed history of lake response to ecological changes that have occurred in and around the lakes during the last 150 years (NPS 2004c).

Wetlands

SLBE's wetlands can be generally classified as classic bogs; interdunal wetlands, which occur in the low areas or swales between the ancient beach ridges; and those wetlands occurring along the margins of streams, ponds, and lakes. Classic bogs are found in the Bow Lakes Unit and near Westman Road and Hwy M-22. The dune and swale complex occurs from Otter Creek to SLBE's southernmost border, near Good Harbor Bay, and near the Crystal River (NPS 2004a, 2008).

An improved wetland inventory was identified as a high priority need in the 2002 SLBE Water Resources Management Plan. Problems identified with the National Wetlands Inventory (NWI) data for SLBE include the age of the base maps, substandard aerial photography, lack of ground-truthing, and lack of information on plant associations and substrates (Vana-Miller 2002). In 2006, the MDEQ produced "Final Wetland Inventory" maps for Michigan counties based on data from three sources: the 1975-1981 NWI database (USFWS 1994), the 1978 Michigan Resource Information System (MIRIS) database (MDNR 1999), and the Soil Survey Geographic (SSURGO) database (NRCS 2007b). The Final Wetland Inventory maps (MDEQ 2006a, b) provide information only on the locations of wetlands as identified either by NWI or MIRIS, and the presence of hydric soil complexes with 15% or greater hydric soils; they do not specify the types of wetlands or the associated vegetation.

Because of the inadequacies of the NWI data alone for SLBE, we determined and mapped SLBE wetland types from data in the three original data files. Ten categories were selected to describe wetlands, mainly based on Cowardin et al. (1979):

- Open water
- Aquatic bed
- Emergent
- Other wetland (wetland with vegetation not specified as forest or shrub)
- Lowland conifers
- Lowland hardwoods
- Lowland mixed forest
- Shrub/scrub
- Other wooded lowland (lowland with unspecified types of forest or shrub vegetation)
- Soils (hydric soils not mapped as wetlands in MIRIS or NWI)

The mapping revealed poor agreement between the identification of wetlands by the three methods; 67% of the 4,067 ha of wetlands were identified by only one of the three sources. Omitting the hydric soils classification (and the open water classification because it does not exist in MIRIS) to allow a more direct comparison of wetland types in MIRIS and NWI left a total of 2,784 ha of wetlands. Fifty-three percent of these 2,784 ha were identified as wetlands only in NWI or only in MIRIS (Table 15). In only seven percent of cases did NWI and MIRIS agree on the wetland type. In 25 percent of cases, NWI and MIRIS described wetlands at different, but not mutually exclusive, levels of detail, and these wetlands were 'promoted' to a more detailed category. For example, land described in MIRIS as "other wooded wetland" and in NWI as "lowland conifers" was placed in "lowland conifers" because "other wooded wetland" does not preclude the possibility of lowland conifers being present. Two percent of wetlands were described as different types of forested wetlands in NWI and MIRIS and were resolved into a "mixed lowland forest" category. For example, land described as "lowland hardwoods" in NWI and "lowland conifers" in MIRIS were joined in this category on the assumption that some of both types of trees may have been present. The remaining 13% of wetlands were those in which significant conflicts existed between MIRIS and NWI that could not be resolved by placing them into a more detailed category. Examples include land described as "emergent" in MIRIS and "lowland conifers" in NWI, or as "shrub/scrub" in MIRIS and "open water" in NWI. A complete list of MIRIS and NWI wetland categories, and the corresponding map units for Figure 33 to Figure 40 is included as Appendix G.

Table 15. Details of degree of agreement between wetland categories in MIRIS and NWI without inclusion of hydric soils.

53%	Identified as wetland hectares only by NWI or only by MIRIS
25%	Described at different, but not mutually exclusive, levels of detail and 'promoted' to a more detailed category
13%	Described as different types by NWI and MIRIS and placed in a 'conflict' category
2%	Described as different types of forests and resolved to a "mixed lowland forest" class
7%	Described in the same category by NWI and MIRIS

Better agreement occurred when wetland classification systems were compared more generically (e.g., wooded vs. nonwooded) (Table 16). Wetland areas varied from 2,032 ha in MIRIS (which does not have a category for open water) to 2,784 ha for the combined NWI/MIRIS data. Wooded wetlands make up the majority of all SLBE wetlands under each of the mapping systems, ranging from 1,848 ha in IFMAP to 2,215 ha in the combined NWI/MIRIS data and accounting for 70-80% of all wetlands (excluding MIRIS because of the lack of an open water category). (See the Land Use and Vegetative Cover section for a detailed description of the IFMAP program).

Table 16. Wetland types and areas in hectares for NWI, MIRIS, NWI and MIRIS combined, and IFMAP.

	NWI	%	MIRIS	%	NWI+Miris*	%	IFMAP	%
open water	421.2	17.0	--	--	413.5	14.9	524.0	19.8
aquatic bed	0.6	0.0	97.1	4.8	62.0	2.2	29.4	1.1
emergent	71.5	2.9	73.3	3.6	54.7	2.0	104.5	3.9
other wetland	37.2	1.5	0.6	0.0	38.2	1.4	141.6	5.3
Total non-wooded wetland	530.4	21.4	171.0	8.4	568.4	20.4	799.5	30.2
lowland conifers	254.0	10.3	614.7	30.3	688.3	24.7	722.4	27.3
lowland hardwoods	156.6	6.3	703.6	34.6	713.6	25.6	672.0	25.4
lowland mixed forest	1,211.0	48.9	--	--	541.8	19.5	112.3	4.2
shrub/scrub	314.4	12.7	323.6	15.9	241.8	8.7	341.2	12.9
other wooded lowland	8.6	0.3	218.8	10.8	30.0	1.1	--	--
Total wooded wetland	1,944.7	78.6	1,860.6	91.6	2,215.5	79.6	1,847.9	69.8
Total	2,475.2		2,031.5		2,783.9		2,647.4	

*conflicts removed without being resolved

Predominant wetland types vary by park unit (Table 17). On North Manitou Island, wetlands were roughly divided between non-wooded (37%) and wooded (43%) types, with 19% being identified by the presence of hydric soils alone (Figure 33). On South Manitou Island, 73% of wetlands were identified on the basis of hydric soils alone (Figure 34). The Mainland-North contains the largest area of non-wooded wetlands (214 ha), consisting mainly of open water (163 ha) (Figure 35). The Bow Lakes Unit's wetlands consist mainly of non-wooded wetlands (51%) and hydric soils (37%) (Figure 36). The Mainland-Central Unit has only about 230 ha of wetlands, of which 46% are wooded and 32% are identified by hydric soils alone (Figure 36). The Mainland-South wetlands are mainly wooded (69%) and have the smallest proportion of wetlands identified by hydric soils alone (11%) (Figure 37).

Table 17. Hectares of wetlands in various mapping categories by park unit.

	North Manitou		South Manitou		Mainland-North		Mainland-Central		Mainland-South		Bow Lakes		Totals
open water	105	37%	26	11%	163	15%	18	8%	98	4%	5	29%	414
aquatic bed	--	--	--	--	1	<1%	--	--	61	3%	--	--	62
emergent	--		--		14	1%	10	4%	27	1%	4	22%	55
other wetland	--		--		37	3%	--		1	<1%	--	--	37
Total non-wooded wetlands	105	37%	26	11%	214	20%	28	12%	187	8%	9	51%	568
lowland conifers	--		32	14%	181	17%	45	19%	431	19%	<1	1%	688
lowland hardwoods	--		<1	0%	155	14%	22	9%	536	24%	1	3%	714
lowland mixed forest	111	40%	--		<1	<1%	31	13%	400	18%	--		542
shrub/scrub	5	2%	5	2%	82	7%	6	3%	143	6%	1	4%	242
other wooded lowland	5	2%	--		10	1%	4	2%	10	<1%	--		30
Total wooded wetlands	121	43%	37	16%	429	39%	107	46%	1,520	69%	2	8%	2,215
Soils	52	19%	170	73%	332	30%	74	32%	239	11%	7	37%	874
Conflict	1	<1%	--	--	120	11%	23	10%	266	12%	1	4%	411
Total	280		232		1,095		231		2,211		18		4,067

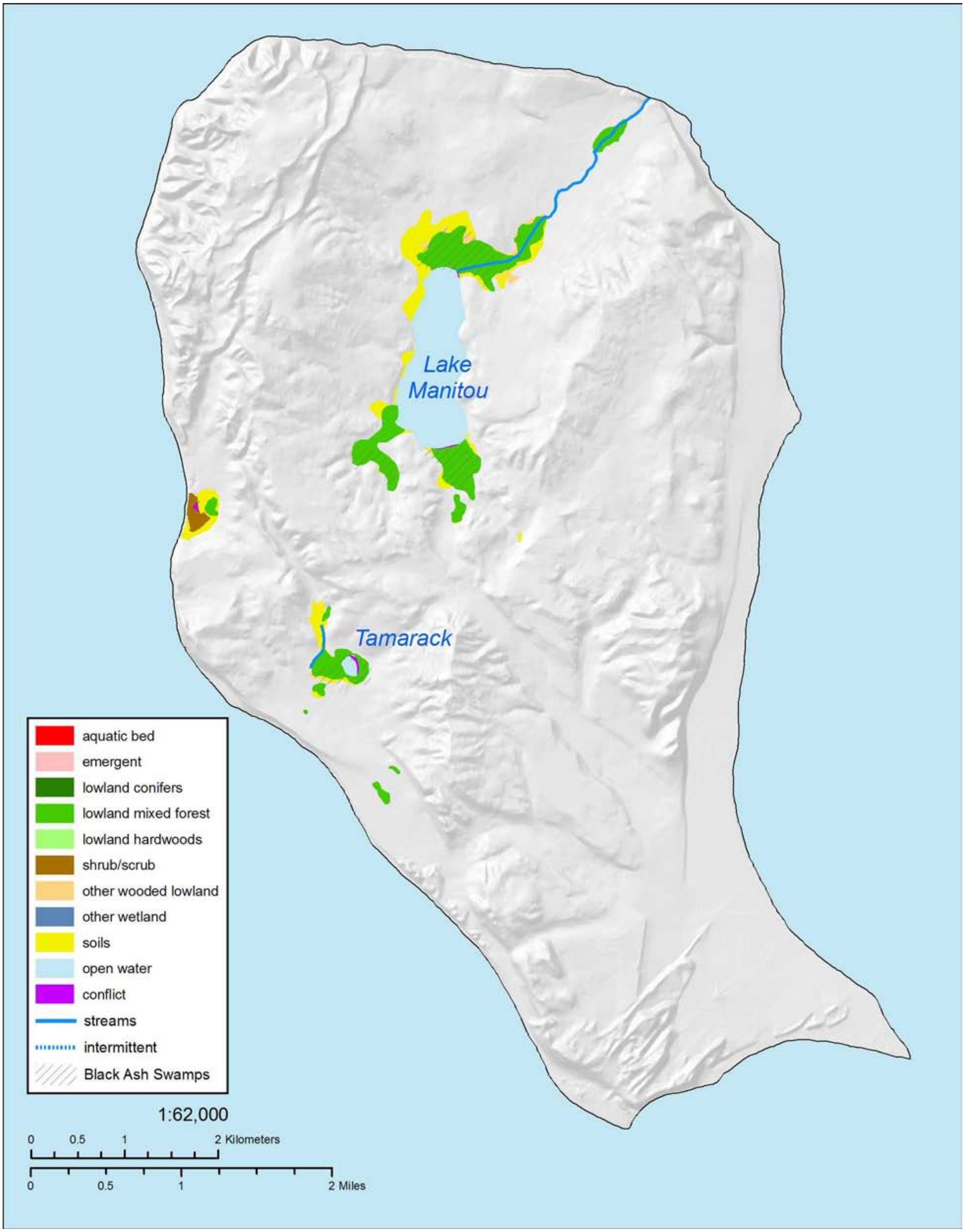

Figure 33. Water resources and wetland types of North Manitou Island (NPS 1999c; MDEQ 2006b).

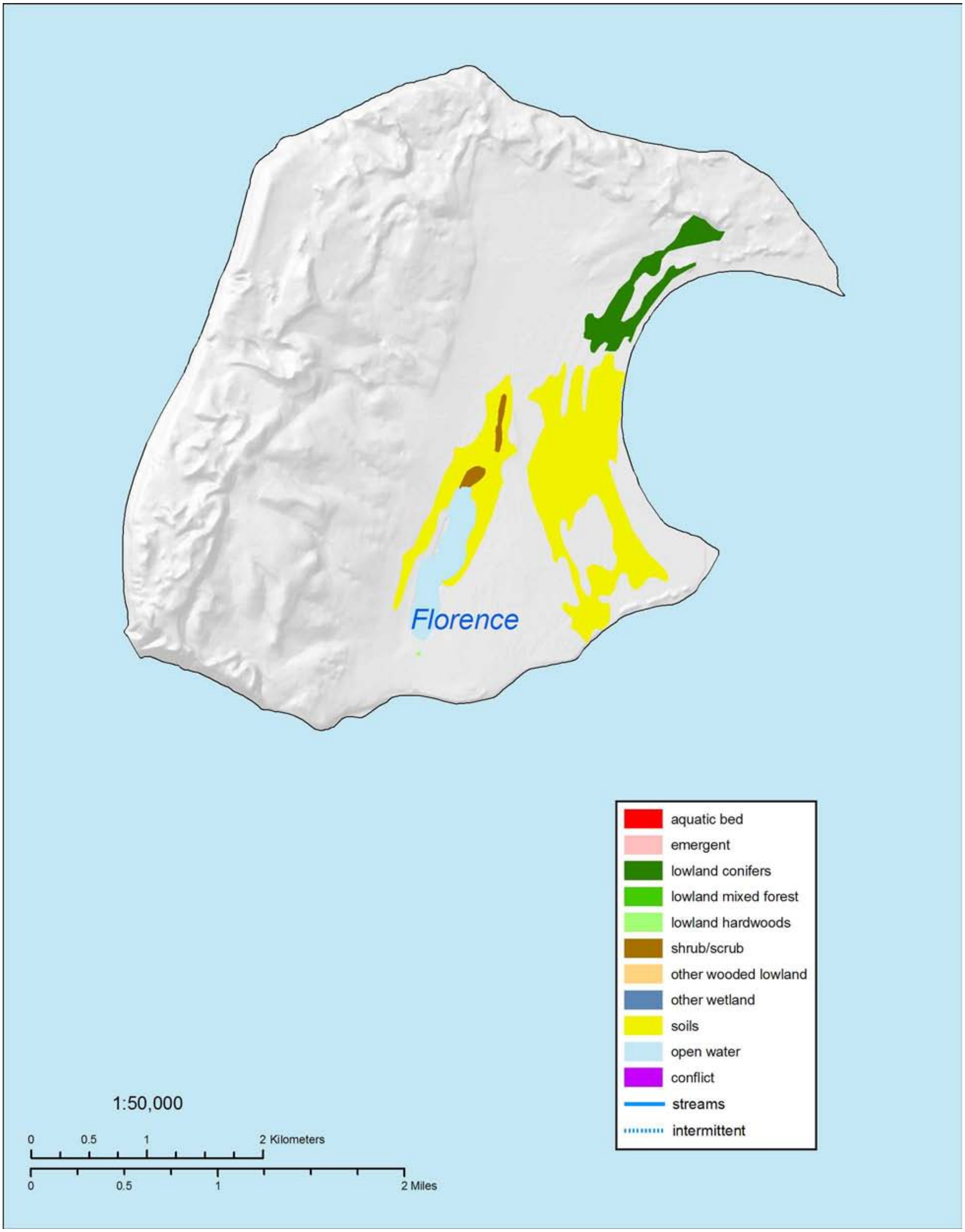

Figure 34. Water resources and wetland types of South Manitou Island (MDEQ 2006b).

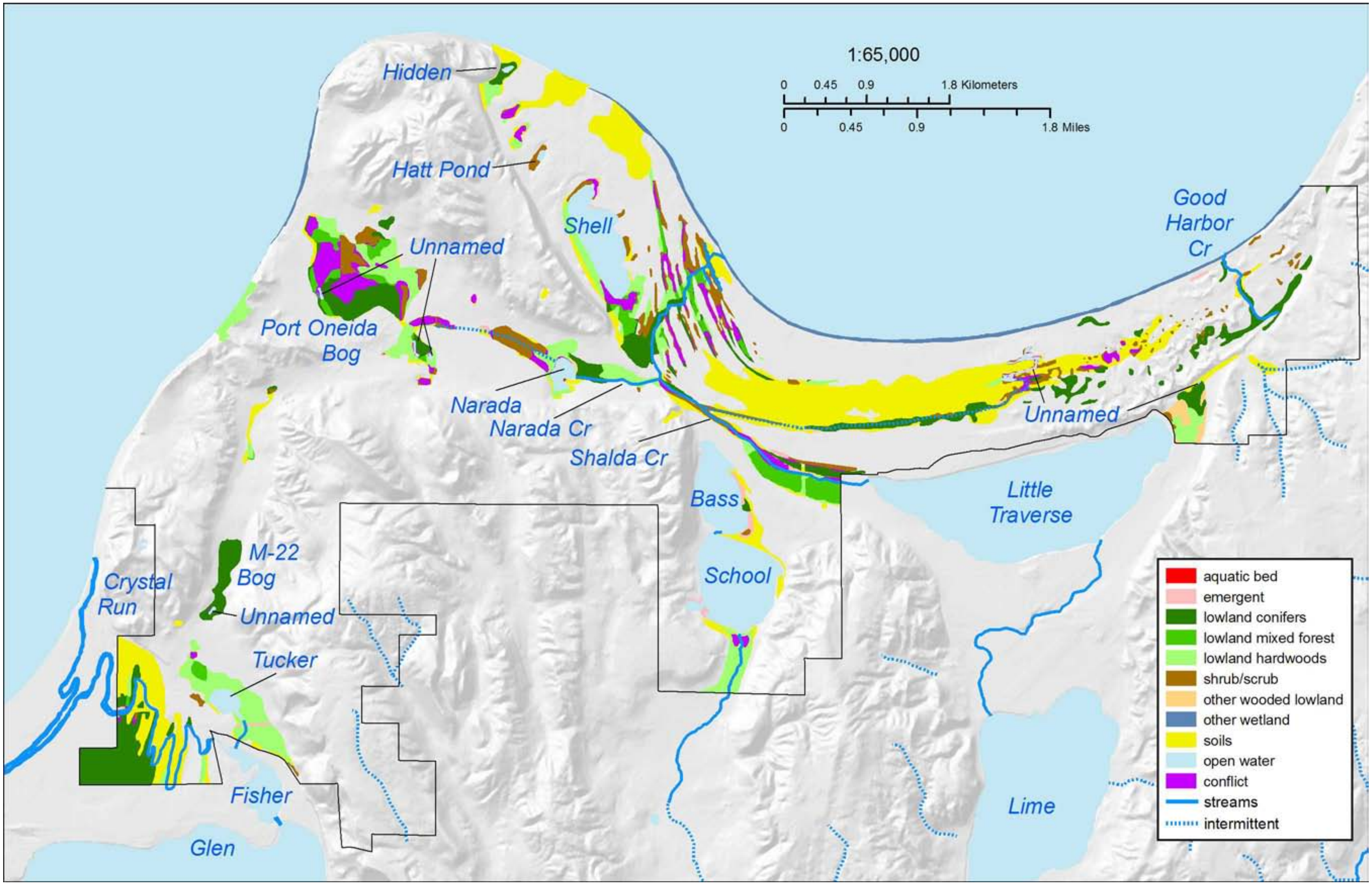

Figure 35. Water resources and wetland types of the Mainland-North Unit of Sleeping Bear Dunes National Lakeshore (MDEQ 2006b).

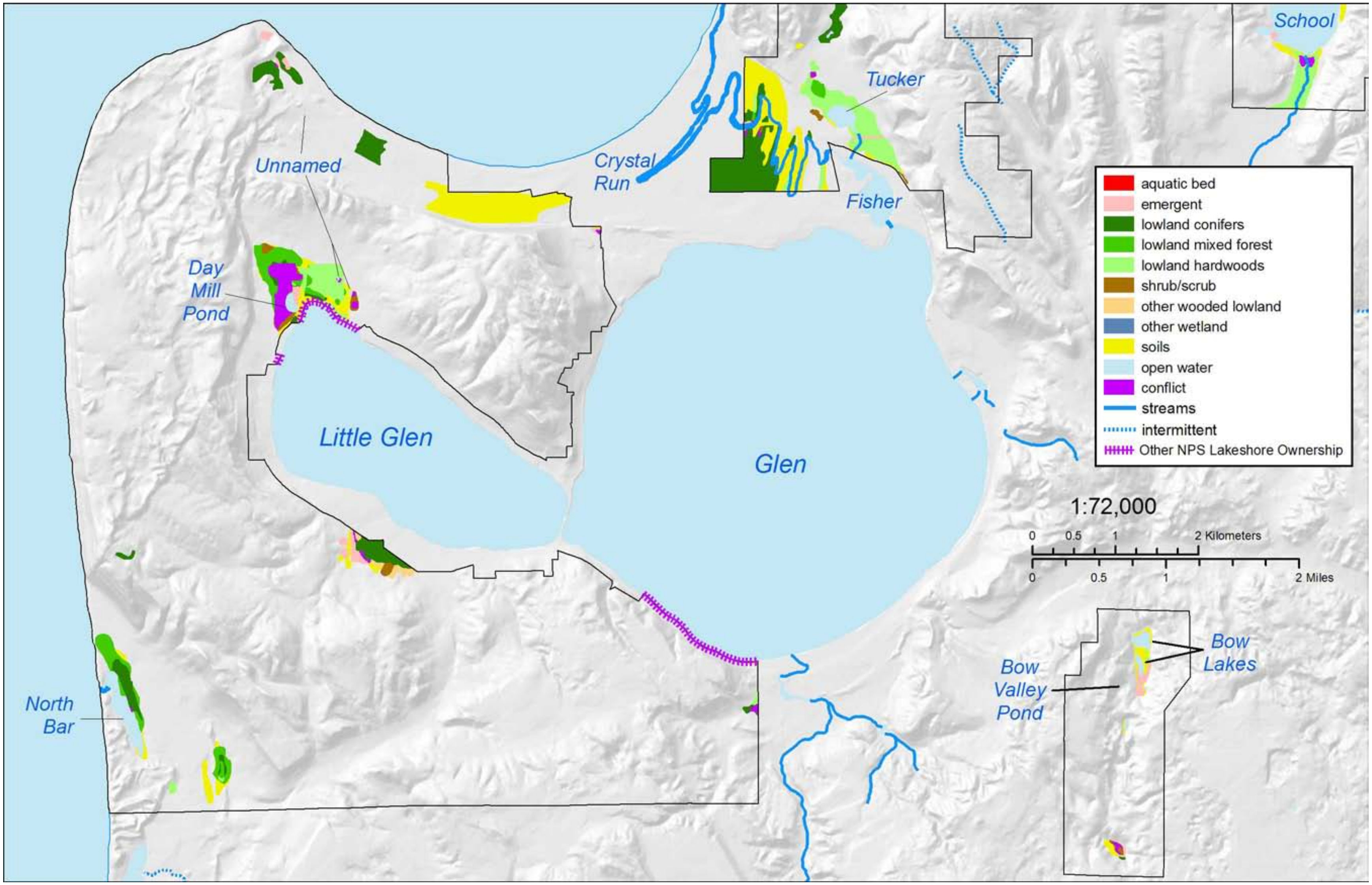

Figure 36. Water resources and wetland types of the Bow Lakes and Mainland-Central Units of Sleeping Bear Dunes National Lakeshore (MDEQ 2006b).

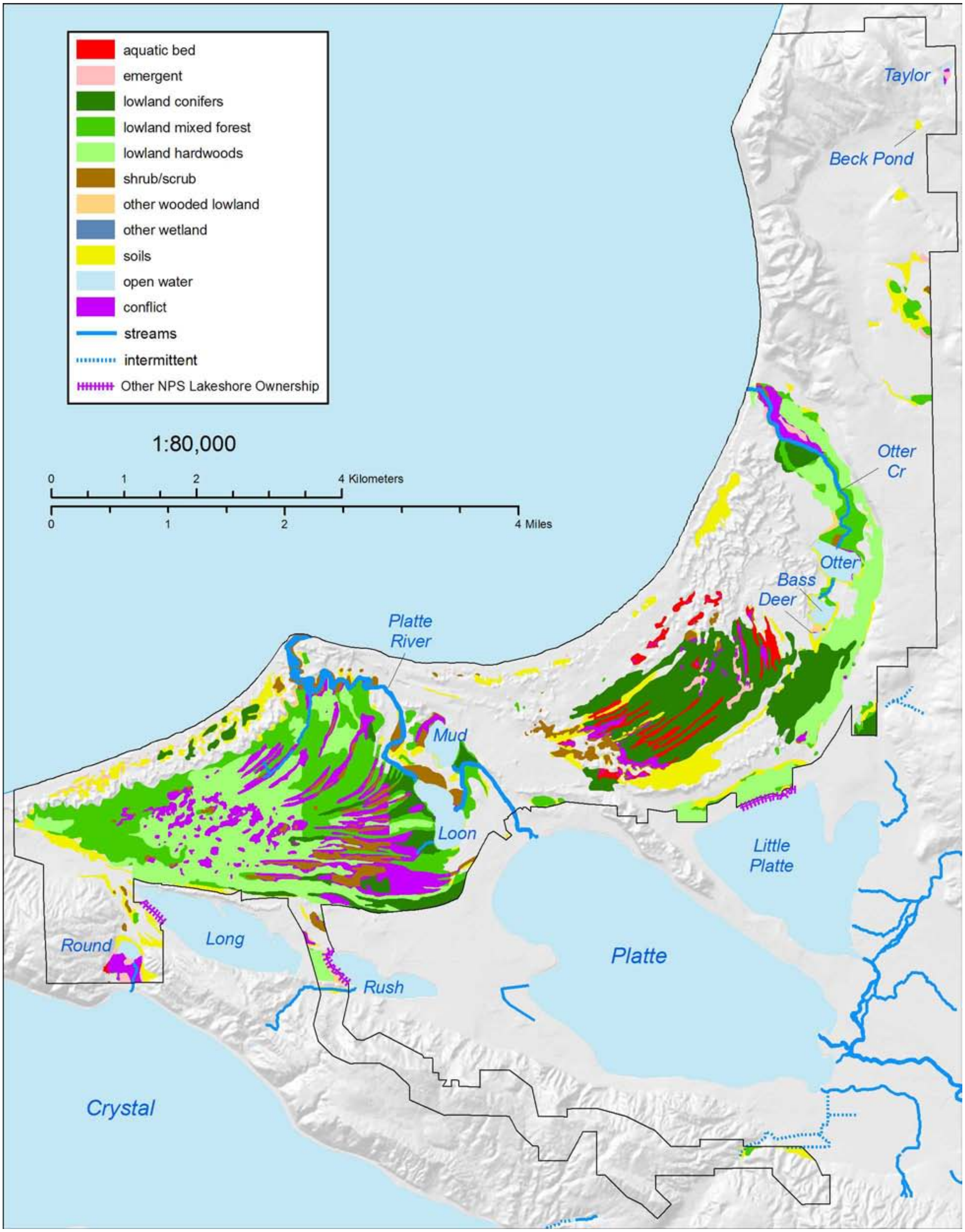

Figure 37. Water resources and wetland types of the Mainland-South Unit of Sleeping Bear Dunes National Lakeshore (MDEQ 2006a, b).

Inland Water Resource Descriptions by Park Unit

North Manitou Island

The North Manitou Island Unit of SLBE has a Lake Michigan shoreline length of 33.8 km and two named lakes (Manitou and Tamarack) with a combined total of 107.4 ha (MCGI 2006).

Lake Manitou

Lake Manitou is the largest inland lake in SLBE, with a surface area of 102-104 ha (Handy and Stark 1984; Murphy 2004a; MCGI 2006), an average depth of 6 m (Fessell 2007) and a maximum depth of 13-14 m (Figure 33; Murphy 2004a; Elias 2007). The lake is primarily supported by surface runoff (Fessell 2007). It has a small inlet at the southern end and a small intermittent outlet on the northern end that drains into a wetland. During high water years the wetland drains into Lake Michigan (Hazlett 1988). The lake bottom is sandy (Handy and Stark 1984), and includes soft marl, with abundant gravel, rock, and cobble pockets throughout (Fessell 2007), and in some areas supports macrophytes (Handy and Stark 1984). The shoreline is moderately complex, with relatively gentle slopes to the water's edge (Fessell 2007).

Hazlett (1988) studied the macrophyte and shoreline vegetation of Lake Manitou in 1986 and 1987 and reported that the lake was surrounded by northern hardwoods on the east and west shores and by black ash (*Fraxinus nigra*) swamps on the north and south shores. The floating leaf and submerged aquatic plant community consisted of 10 species: shortspike water-milfoil (*Myriophyllum sibiricum*); nodding water-nymph (*Najas flexilis*); variegated yellow pond lily (*Nuphar lutea* ssp. *variegata*); fineleaf, variableleaf, floating, and whitestem pondweeds; Illinois pondweed (*Potamogeton illinoensis*); Richardson's pondweed (*P. richardsonii*); and white water crowfoot. Emergent species included reed (*Phragmites australis*), hard-stem bulrush, and common cattail (*Typha latifolia*). Reeds currently have a significant presence on the lake shoreline (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

A recent fish survey (Fessell 2007) found six species. In order of numeric abundance, they were yellow perch, smallmouth bass, green sunfish (*Lepomis cyanellus*), white sucker (*Catostomus commersoni*), bluntnose minnow (*Pimephales notatus*), and Iowa darter (*Etheostoma exile*).

We conclude that Lake Manitou is alkaline and well-buffered, with high specific conductance, high cation levels, and nutrient levels that meet their subecoregional reference criteria (Table 18). The lake is dimictic, and oxygen deficits occur; Elias (2007) reported an anoxic layer below the thermocline, and also indicated that Lake Manitou is showing signs of eutrophication and should be closely monitored in the near future.

Tamarack Lake

Tamarack Lake, south and west of Lake Manitou (Figure 33) has a surface area of 3.72-4.01 ha (Handy and Stark 1984; MCGI 2006). The lake is shallow (2.5 m) with a soft and mucky bottom that has an odor of hydrogen sulfide (Handy and Stark 1984). Fessell (2007) reported that the lake was overgrown with the common alga *Chara* (muskgrass) and has a fish community limited to central mudminnows (*Umbra limi*), cyprinids (minnows), and centrarchids (sunfish).

Table 18. Physical and chemical water quality data for Lake Manitou, Sleeping Bear Dunes National Lakeshore (Murphy 2004a; Elias 2007; Elias and VanderMeulen 2008).

Parameter	2004 surface	2004 hypolimnion	2005 surface	2007 surface	2007 hypolimnion
Secchi disk (m)	2.8	--	2.6	1.6	--
DO saturation (%)	102.8	1.4	--	--	--
DO (mg/L)	8.5	0.15	--	9.0	--
dissolved organic carbon (DOC) (mg/L)	--	--	6.7-7.7	5.6	--
pH	8.50	7.29	8.6	8.5	--
specific conductance (µS/cm)	263	329	270	266	--
total dissolved solids (g/L)	0.2	--	--	--	--
sulfate (SO_4) (mg/L)	1.0	1.0	6.39-6.8	10	--
chloride (Cl-) (mg/L)	--	--	0.52–0.8	1.2	--
nitrate nitrogen (NO_3-N) (mg/L)	0.05	--	--	--	--
nitrate and nitrite nitrogen (NO_3+NO_2-N) (mg/L)	--	0.02	0.006-0.0175	0.002	--
ammonium nitrogen (NH_4-N) (mg/L)	0.02	<0.55	0.13	0.009	--
total kjeldahl nitrogen (TKN) (mg/L)	--	--	0.435	--	--
total nitrogen (TN) (mg/L)	--	--	0.41	0.62	--
true color (Pt-Co units)	0	--	--	--	--
total alkalinity (mg/L $CaCO_3$)	142	132	134	134	--
total hardness (mg/L $CaCO_3$)	158	156	--	--	--
calcium hardness (mg/L $CaCO_3$)	102	78	--	--	--
calcium (mg/L)	--	--	33.51	41.2	--
magnesium (mg/L)	--	--	15.52	18.6	--
potassium (mg/L)	--	--	0.55	0.61	--
sodium (mg/L)	--	--	1.38	1.7	--
SiO_2 (mg/L)	--	--	0.1-1.17	1.8	--
total phosphorus (TP) (µg/L)	24.23**	3.34	8.66-45	19	41
chlorophyll-*a* (µg/L)	24.23*	3.34*	3.88	1-1.3	--

*phaeophytin corrected

**Data in Murphy appear questionable; TP and chl-a data are identical.

2004 data based on one sample (6/15/04); 2005 data average of 1-4 samples during summer season; 2007 data average of 1-3 samples during summer season

Coulter (1904) studied the vegetative zonation from the hardwood forests to Tamarack Lake. He found a spring fed stream that flows into the black ash swamp on the west side of the lake with marsh marigold (*Caltha palustris*), golden saxifrage (*Chrysosplenium americanum*), common duckweed (*Lemna minor*), ostrich fern (*Matteucia struthiopteris*), and eastern marsh fern (*Thelypteris palustris*). Hazlett (1988) studied the macrophyte and shoreline vegetation of Tamarack Lake in 1986 and 1987 and described it as a typical bog lake. Hazlett (1991) found bog species such as leather-leaf (*Chamaedaphne calyculata*), black huckleberry (*Gaylussacia baccata*), bog laurel (*Kalmia polifolia*), larch (*Larix laricina)*, black spruce (*Picea mariana*), and velvet-leaf blueberry (*Vaccinium myrtilloides*) on the east side of Tamarack Lake. A narrow sedge mat contained water-hemlock (*Cicuta* sp.), sundew (*Drosera rotundifolia*), three-way sedge (*Dulichium arundinaceum*), spotted touch-me-not (*Impatiens capensis*), southern blue flag

(*Iris virginica*), rushes (*Juncus* spp.), tufted loosestrife (*Lysimachia thyrsiflora*), cinnamon fern (*Osmunda cinnamomea*), reed, marsh cinquefoil (*Comarum palustris*), swamp rose (*Rosa palustris*), eastern marsh fern, marsh St. John's-wort (*Triadenum fraseri*), and small cranberry (*Vaccinium oxycoccos*). The only truly aquatic macrophyte species he found was variegated yellow pond lily.

Streams, Seeps, and Groundwater

The unnamed stream that drains Lake Manitou is 3.03 km long (Figure 33; MCGI 2006). Handy and Stark (1984) indicated that it was intermittent. An unnamed stream near Tamarack Lake is 0.51 km long and does not flow into Lake Michigan. Handy and Stark (1984) stated that this stream starts out from a spring north of Tamarack Lake and had a flow of 0.01 $m^3 sec^{-1}$ on July 27, 1982. Handy and Stark (1984) found three springs on the island in 1982 (The Spring, Angell Spring, and an unnamed spring) but reported them only as seeps. They stated that the surface and ground water on the island was hard but of excellent quality that met drinking water standards.

Wetlands

North Manitou Island has 105 ha of open water in Lake Manitou and Tamarack Lake, but has no other non-wooded wetlands mapped. The island also has 121 ha of wooded wetlands, composed of 111 ha of lowland mixed forest, 5 ha of shrub/scrub, and 5 ha of other wooded lowland. Wet soils accounted for an additional 52 ha of wetland (Table 17, Figure 33).

South Manitou Island

The South Manitou Island Unit of SLBE has a Lake Michigan shoreline length of 20.7 km (MCGI 2006), one lake (Florence Lake), and no streams (Figure 34). The island, located ca 25.8 km southwest of Leland, MI, is mostly a glacial moraine and has a surface area of 2,158 ha (Gannon and Stockwell 1978). The last logging on South Manitou Island occurred in 1908, and the last year-round resident departed in 1973. Only summer residents and visitors use the island now (Vent 1973).

Florence Lake

Florence Lake, in the southeastern part of South Manitou Island (Figure 34), is oblong in shape, has a surface area of 31.4-33.2 ha (Handy and Stark 1984; Murphy 2004a; MCGI 2006), and a maximum depth of 7.9-8 m (Handy and Stark 1984; Murphy 2004a; Elias 2007). Gannon and Stockwell (1978) reported a mean depth of 3.3 m, a watershed area of 858 ha, and a shoreline development factor of 1.7 for Florence Lake.

Florence Lake is a soft water lake (Murphy 2004a) with a sandy bottom (Handy and Stark 1984); Fessell (2007) reported soft marl throughout and sparse gravel pockets along the eastern shoreline. The lake has no inlet or outlet (Rogers 1966; Elias 2007) and is primarily supported by surface runoff (Fessell 2007). The chemistry data suggests that it is isolated from the groundwater (Elias 2007).

Wooded wetlands surround the lake (Murphy 2004a). The shoreline has moderate complexity and relatively gentle slopes (Fessell 2007). Flooding along the north and south shores appears fairly common (Rogers 1966). Florence Lake was originally part of Lake Nipissing (3,500 years

BP) and became isolated due to postglacial uplift, changes in drainage, and the deposition of sand ridges (Gannon and Stockwell 1978).

Gannon and Stockwell (1978) sampled phytoplankton, zooplankton, aquatic macroinvertebrates, and fish and measured various physical and chemical variables at four stations in September 1974, and in March, May, and September 1975. A detailed bathymetric map of the lake was constructed. A mean pH of 7.9 and mean total alkalinity of 57.4 mg/L were found during the study period. Cation and nutrient levels were generally low, but chlorophyll-*a* levels were moderate (6.5-10.6 µg/L). Total alkalinity, specific conductance, ammonia-nitrogen, chloride, silica, and mineral content were 1/2-1/4 those of Lake Michigan, but nutrients and chlorophyll-*a* levels were greater. Secchi depths were also shallower in Florence Lake than in Lake Michigan. The lake usually stratified from late May to mid-September. The authors also reported on island soils; those on the island's west side were mainly pure sand and sandy loams, with some gravel and clay on the uplands and lowland plains.

One hundred thirty-two phytoplankton taxa were collected, with the blue green alga *Microcystis* the most abundant taxa. The genera *Anabena*, *Botryococcus*, *Ceratium*, *Dictyosphaerium*, and *Scenedesmus* were also commonly collected. Diatoms were not a significant component of the phytoplankton community. A fairly diverse zooplankton community was composed of 36 taxa of rotifers and 30 taxa of microcrustaceans. The common rotifers were *Keratella longispina* and *Polyarthra vulgaris*, and the common microcrustaceans were the calanoid copepods *Diaptomus oregonensis* and *Epischura lacustris*, the cyclopoid copepod *Cyclops bicuspidatus thomasi*, and the cladocerans *Bosmina longirostris, Chydorus sphaericus, Ceriodaphnia lacustris, Daphnia retrocurva*, *Holopedium gibberum*, and *Diaphanosoma leuchtenbergianum*. The zooplankton communities were vertically stratified during the summer stratified period, and the authors found differences among the littoral, profundal, and limnetic zones. More zooplankton were present in the spring (May) than in the fall (September) (Gannon and Stockwell 1978).

Aquatic macrophytes in the littoral zone included sedges, reeds, pondweeds, knotweeds (*Polygonum* sp.), bulrushes, and bladderworts. The authors found 110 macroinvertebrate taxa in Florence Lake, with approximately 50% being collected in aquatic vegetation. Most orders of aquatic insects were represented in the vegetation. The oligochaete worms, amphipods, mollusks, and dipterans dominated the soft sediments. However, in the deep portions of the lake with flocculent silts, only the phantom midge (*Chaoborus* sp.) was found; taxa that indicate eutrophic conditions such as *Chironomus* sp. and oligochaete worms were rare. The authors found a difference in composition and abundance of macroinvertebrates along a transect from shore to the profundal zone (Gannon and Stockwell 1978). Similarly, Stockwell and Gannon (1975) studied the macroinvertebrate fauna of Florence Lake and found Ephemeroptera, Odonata, Trichoptera, Coleoptera, and Hemiptera above the sediments and mainly oligochaete worms, amphipods, mollusks, and dipterans in the sediments.

Four fish species were found in Florence Lake: yellow perch, northern pike, smallmouth bass, and Iowa darter. Growth rates of yellow perch and northern pike were greater than in other Michigan lakes, but black spot and yellow grub parasites were especially common in these species. The flora and fauna were typical of other known northern Michigan inland lakes with similar physical features (Gannon and Stockwell 1978). Fessell (2007) reported that in 2004, the same four fish species and one additional species were found in Florence Lake: in order of abundance, they were yellow perch, northern pike, smallmouth bass, bluntnose minnow, and Iowa darter.

Hazlett (1988) studied the macrophyte and shoreline vegetation of Florence Lake in 1986 and 1987. He found a sparse submerged and floating aquatic vascular plant community consisting of small pondweed (*Potamogeton pusillus* ssp. *tenuissimus*), largeleaf pondweed, and variableleaf pondweed. The 12 species of shoreline and emergent plants were blue joint, twig-rush (*Cladium mariscoides*), common spikerush (*Eleocharis palustris* var. *palustris*), boneset (*Eupatorium perfoliatum*), rushes, blue flag, northern bugleweed, swamp-candle (*Lysimachia terrestris*), reed, hard-stem bulrush, a goldenrod (*Solidago gramineus*), and narrow-leaved cattail (*Typha angustifolia*). Reeds have expanded in recent years, and currently have a significant presence on the lake shoreline (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

The phytoplankton, zooplankton, and macroinvertebrate communities found generally indicated that the lake has excellent water quality. Gannon and Stockwell (1978) ranked Florence Lake as a well balanced mesotrophic lake based on chlorophyll-*a* levels, phytoplankton, zooplankton, and benthic communities. Nutrients generally varied with the seasonal cycles. Both typical eutrophic phytoplankton taxa such as *Microcystis aeruginosa* and oligotrophic taxa such as *Botryococcus* sp. and *Scenedesmus* sp. were found. Florence Lake may be sensitive to phosphorus loading due to its soft water characteristics (Gannon and Stockwell 1978) and long retention time (Vana-Miller 2002).

Recent sampling (Murphy 2004a; Elias 2007) confirms that Florence Lake is less buffered than other SLBE lakes, but meets the nutrient reference criteria for its subecoregion (Table 19). Lafrancois and Glase (2005) stated that Florence Lake was distinct from other SLBE lakes, and that it should not be considered representative of the surface waters of SLBE.

Wetlands

South Manitou Island has 26 ha of open water in Florence Lake, but has no other non-wooded wetlands mapped (Table 17, Figure 34). However, some of the areas surrounding Florence Lake and identified as wetlands by soil type may be non-wooded wetlands (Figure 34). Hazlett (1988) reported that marshes occur at both ends of the lake, dominated by herbaceous vegetation including blue joint, sedges, boneset, small purple-fringed orchid (*Platanthera psycodes*), southern blue flag, rushes, water horehound (*Lycopus americanus*), sensitive fern (*Onoclea sensibilis*), royal fern (*Osmunda regalis*), reed, water smartweed (*Polygonum amphibium*), marsh cinquefoil, bitter dock, bulrushes, deadly nightshade (*Solanum dulcamara*), eastern marsh fern, and common cattail. "Noteworthy" species associated with the lake and its wetlands include fen orchid (*Liparis loeselii*), creeping spearwort (*Ranunculus flammula* var. *filiformis*), small purple-fringed orchid, American germander (*Teucrium canadense*), and swamp-candle (Hazlett 1991). A few woody species such as Kalm's St. John's-wort (*Hypericum kalmianum*), swamp rose, willows (*Salix* spp.), and meadowsweet (*Spiraea alba*) also occasionally occur. Common bladderwort (*Utricularia macrorhiza*) is found in these sites in wet years. South Manitou Island also has 37 ha of wooded wetlands, composed of 32 ha of lowland conifers, <1 ha of lowland

Table 19. Physical and chemical water quality data for Florence Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a; Elias 2007).

Parameter	2004 surface	2004 hypolimnion	2005 surface
Secchi disk (m)	2.8	--	2.5
DO saturation (%)	101.1	2.9	--
DO (mg/L)	9.1	0.27	--
dissolved organic carbon (DOC) (mg/L)	--	--	8.8-8.9
pH	--	8.65	8.4
specific conductance (µS/cm)	100	105	111
total dissolved solids (g/L)	0.1	0.1	--
sulfate (SO_4) (mg/L)	0.9	0.9	3.15-3.4
chloride (Cl-) (mg/L)	--	--	0.75-0.8
nitrate nitrogen (NO_3-N) (mg/L)	0.4	0.4	--
nitrate and nitrite nitrogen (NO_3+NO_2-N) (mg/L)	--	--	0.005-0.011
ammonium nitrogen (NH_4-N) (mg/L)	0.3	0.4	0.03
total kjeldahl nitrogen (TKN) (mg/L)	--	--	0.68
total nitrogen (TN) (mg/L)	--	--	0.65
true color (Pt-Co units)	3	4	--
total alkalinity (mg/L $CaCO_3$)	44	46	43.75
total hardness (mg/L $CaCO_3$)	48	68	--
calcium hardness (mg/L $CaCO_3$)	34	34	--
calcium (mg/L)	--	--	12.97
magnesium (mg/L)	--	--	5.74
potassium (mg/L)	--	--	0.63
sodium (mg/L)	--	--	0.63
SiO_2 (mg/L)	--	--	0.1-0.39
total phosphorus (TP) (µg/L)	15.62	--	14.10-45
chlorophyll-*a* (µg/L)	0	--	6.86

2004 data based on one sample (6/22/04);
2005 data average of 1-4 samples during summer season

hardwoods, and 5 ha of shrub/scrub. Seventy-three percent of South Manitou Island's wetlands (170 ha) are identified only by wet soil type.

Mainland–North

The Mainland-North Unit of SLBE has a Lake Michigan shoreline length of 17.8 km and seven named and six small unnamed lakes with a combined total of 169.5 ha (MCGI 2006). The Mainland-North Unit has 165 ha of open water in Shell, Bass (Leelanau), School, Narada, Hidden, and Tucker Lakes and Hatt Pond (Table 17, Figure 35). Three named streams (Crystal River and Shalda and Good Harbor Creeks) have a combined stream length of 9.5 km. The outlet of Narada Lake (named Narada Creek by some authors) and other unnamed permanent or intermittent streams have a combined length of 13.2 km in the Mainland-North Unit (MCGI 2006).

Bass Lake (Leelanau)

Bass Lake, one of the larger lakes in the Mainland-North Unit (Figure 35), has a surface area of 37.5-38.0 ha (Murphy 2004a; MCGI 2006), a maximum depth of 7.3-9.0 m (Murphy 2004a; Elias 2007; Fessell 2007), and an average depth of 3.0-4.5 m (Fessell 2007). Sand and muck dominate the substrate, with occasional small pockets of gravel. The shoreline has sloped edges and limited complexity (Fessell 2007).

Bass Lake occasionally receives surface water inflow but does not have an outflow (Elias 2007). Murphy (2004a) reported an inlet from School Lake and a narrow bank separating the two lakes on the east side of the lake. He stated that occasionally when the water table is high, School and Bass Lakes are joined. There are three private cottages and a private boat ramp on the north shore, and the lake experiences moderate to heavy fishing pressure (Vana-Miller 2002).

Albert (1992) found 14 species of aquatic macrophytes in two transects of Bass Lake. Hazlett (1988) found 11 floating and submerged aquatic macrophyte species in 1986 and 1987; they were shortspike water-milfoil; nodding water-nymph; largeleaf, variableleaf, floating, and flatstem pondweeds; broadleaf pondweed (*Stuckenia pectinata*); leafy pondweed (*Potamogeton foliosus*); duck-potato (*Sagittaria latifolia*); and tape-grass (*Vallisneria americana*). Fessell (2007) also noted the predominance of pondweed and muskgrass (*Chara vulgaris*) in the macrophyte community. The eight species of emergent and shoreline vegetation were swamp milkweed (*Asclepias incarnata*), twig-rush, common spikerush, southern blue flag, reed, hard-stem bulrush, grass-leaved goldenrod (*Euthamia graminifolia* var. *graminifolia*), and marsh St. John's-wort (Hazlett 1988).

Nichols et al. (2004) found a large number of mussel shells but no live mussels in Bass Lake. Kelly and Price (1979) found seven fish species in Bass Lake: the bluntnose minnow, northern pike, white sucker, brown bullhead (*Ictalurus nebulosus*), yellow bullhead (*Ictalurus natalis*), bluegill, and rock bass. Fessell (2007) found all of the above species except for yellow bullhead and additionally reported largemouth bass, pumpkinseed (*Lepomis gibbosus*), mimic shiner (*Notropis volucellus*), banded killifish, and yellow perch in the lake, for a total of 11 species. White sucker, largemouth bass, and banded killifish made up 71% of the total. Physical and chemical water quality data were collected by Murphy (2004a) and Elias (2007) (Table 20).

Hatt Pond

Hatt Pond, a small pond south and east of Pyramid Point (Figure 35), is 0.7-1 ha (Murphy 2004a; MCGI 2006). The depth is <1 m, and it is surrounded by wetlands (Murphy 2004a). The watershed is relatively flat and vegetated with upland hardwoods. Hatt Pond is mainly surface water fed, and its size may change with fluctuations in annual precipitation. It has no obvious surface inlets or outlets (Fessell 2007).

The bottom is largely organic muck, and the pond supports large beds of pondweed, muskgrass, and white water lily. The pond was occupied by beaver when observed in 2003 (Fessell 2007). During the NPS 2003/2004 fish survey, only the central mudminnow was collected (Fessell 2007). Water quality parameters were measured for Hatt Pond on June 18, 2003 (Table 21) (Murphy 2004a).

Hidden Lake (Hidden Pond)

Hidden Lake (or Hidden Pond), found at the base of a large dune east of Pyramid Point (Figure 35), has a surface area of 0.5-1.0 ha, (Murphy 2004a; MCGI 2006; Fessell 2007). Although its average depth is 0.4 m, beaver had excavated some deeper (0.9-1.2 m) channels leading to a

Table 20. Physical and chemical water quality data for Bass Lake (Leelanau), Sleeping Bear Dunes National Lakeshore (Murphy 2004a; Elias 2007).

Parameter	2003 surface	2003 hypolimnion	2005 surface
Secchi disk (m)	2.8	--	3.2
DO saturation (%)	100.8	63.7	--
DO (mg/L)	9.34	6.2	--
dissolved organic carbon (DOC) (mg/L)	--	--	9.0-9.4
pH	8.65	8.28	8.6
specific conductance (µS/cm)	224	231	229
total dissolved solids (g/L)	0.1	0.1	--
sulfate (SO_4) (mg/L)	0.9	0.9	3.1-3.14
chloride (Cl-) (mg/L)	--	--	4.51-6.4
nitrate nitrogen (NO_3-N) (mg/L)	0.01	0.01	--
nitrate and nitrite nitrogen (NO_3+NO_2-N)	--	--	0.008-0.0175
ammonium nitrogen (NH_4-N) (mg/L)	0.01	0.1	0.13
total kjeldahl nitrogen (TKN) (mg/L)	--	--	0.82
total nitrogen (TN) (mg/L)	--	--	0.59
true color (Pt-Co units)	7	9	--
total alkalinity (mg/L $CaCO_3$)	96	78	100.25
total hardness (mg/L $CaCO_3$)	116	120	--
calcium hardness (mg/L $CaCO_3$)	82	100	--
calcium (mg/L)	--	--	31.49
magnesium (mg/L)	--	--	10.08
potassium (mg/L)	--	--	0.92
sodium (mg/L)	--	--	2.98
SiO_2 (mg/L)	--	--	2.7-3.65
total phosphorus (TP) (µg/L)	12.38	13.91	9.26-50
chlorophyll-*a* (µg/L)	3.02	--	3.24
chlorophyll-*a* phaeophytin corrected (µg/L)	0.84		

2003 data based on one sample (6/4/03);
2005 data average of 1-4 samples during summer season

Table 21. Physical and chemical water quality data for Hatt Pond, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	06/18/03 surface
Secchi disk (m)	0.2
DO saturation (%)	130.1
DO (mg/L)	10.7
pH	7.98
specific conductance (µS/cm)	385
total dissolved solids (g/L)	0.2
sulfate (SO_4) (mg/L)	1
nitrate nitrogen (NO_3-N) (mg/L)	0.01
ammonium nitrogen (NH_4-N) (mg/L)	0.03
true color (Pt-Co units)	80
total alkalinity (mg/L $CaCO_3$)	126
total hardness (mg/L $CaCO_3$)	88
calcium hardness (mg/L $CaCO_3$)	36
total phosphorus (TP) (µg/L)	21.5
chlorophyll-*a* (µg/L)	2.25

lodge at the north end of the pond in 2003 (Fessell 2007). Hidden Lake has no obvious surface inlets or outlets (Fessell 2007) and is surrounded by white cedar (*Thuja occidentalis*) swamp (Hazlett 1988; Fessell 2007). The bottom is largely organic muck, with small pockets of sand (Fessell 2007).

Hazlett (1988), in 1986 and 1987, found four species of floating and submerged aquatic macrophytes: water smartweed, largeleaf and floating pondweeds, and variegated yellow pond lily. Fessell (2007) also reported muskgrass. In the fen area near the south shore, Hazlett (1988) found twig-rush, showy lady-slipper (*Cypripedium reginae*), Joe-Pye-weed (*Eupatorium maculatum*), northern green orchid (*Platanthera aquilonis*), buckbean (*Menyanthes trifoliata*), and marsh arrow grass (*Triglochin palustre*).

Five fish species have been collected from Hidden Lake. Kelly and Price (1979) found the fathead minnow (*Pimephales promelas*), northern redbelly dace (*Phoxinus eos*), and brook stickleback (*Culaea inconstans*) in Hidden Lake. Fessell (2007) did not find the brook stickleback in 2003, but did find two additional fish, the bluegill and pumpkinseed. Northern redbelly dace was most common. Murphy (2004a) collected physical and chemical water quality data at the time of the 2003 fish survey (Table 22).

Narada Lake

Narada Lake is 6.5-6.6 ha (Figure 35; MCGI 2006; Fessell 2007). In 2003, a beaver impoundment had created approximately 6 ha of inundated uplands and standing timber, some of which has died, around the lake (Fessell 2007). Narada Lake is fed by groundwater, and Narada Creek flows out of it into Shalda Creek. The maximum depth is 9.4 m (Murphy 2004a). The shoreline is moderately complex, with an abrupt bank (Fessell 2007). The lake bottom is chiefly soft muck with muskgrass covering most of the basin (Kelly and Price 1979).

Table 22. Physical and chemical water quality data for Hidden Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	06/23/03 results
Secchi disk (m)	1.2
DO saturation (%)	65.8-84.1
DO (mg/L)	5.89-7.39
pH	8.21-8.28
specific conductance (µS/cm)	262-267
total dissolved solids (g/L)	0.2
sulfate (SO_4) (mg/L)	0.9
nitrate nitrogen (NO_3-N) (mg/L)	0.01
ammonium nitrogen (NH_4-N) (mg/L)	0.04
true color (Pt-Co units)	30
total alkalinity (mg/L $CaCO_3$)	126
total hardness (mg/L $CaCO_3$)	142
calcium hardness (mg/L $CaCO_3$)	96
total phosphorus (TP) (µg/L)	25.9
chlorophyll-*a* (µg/L)	3.65
chlorophyll-*a* (µg/L) phaeophytin corrected	0.66

Hazlett (1988), in 1986 and 1987, found that a beaver dam on an old road just east of the lake had resulted in flooding of a white cedar swamp on the east side and a black ash swamp on the west side of the lake and a change in the shoreline vegetation. He found 10 species of floating and submerged aquatic macrophytes: coontail (*Ceratophyllum demersum*); common duckweed; twoleaf water-milfoil (*Myriophyllum heterophyllum*); variegated yellow pond lily; white water lily (*Nymphaea odorata*); small, floating, and whitestem pondweeds; bladderworts; and water-meal (*Wolffia punctata*). He also found 15 species of emergent and shoreline plants: blue joint, sedges, swamp loosestrife (*Decodon verticillatus*), spotted touch-me-not, northern bugleweed (*Lycopus uniflorus*), tufted loosestrife, wild mint (*Mentha arvensis*), sensitive fern, reed canary grass (*Phalaris arundinacea*), swamp rose, pussy willow (*Salix discolor*), hard-stem bulrush, deadly nightshade, narrow-leaved bur-reed (*Sparganium emersum*), and common cattail. Fessell (2007) also observed variegated yellow pond lily and noted that the highest densities of lilies and pondweed are found within the flooded timber.

Heuschele (2000) found that Narada Lake had the highest richness of sponges of any SLBE lake surveyed. Kelly and Price (1979) found the alewife, golden shiner (*Notemigonus crysoleucas*), white sucker, brook stickleback, bluegill, largemouth bass, pumpkinseed, and yellow perch in Narada Lake. Fessell (2007) found a somewhat different fish community in 2003. Four species were the same, four additional species were found, and four species found by Kelly and Price (1979) were not found by Fessell (2007), who reported (in order of abundance) brown bullhead, largemouth bass, northern pike, rock bass, yellow perch, bluegill, pumpkinseed, and central mudminnow. Physical and chemical water quality data collected at the time of the 2003 fish survey are included in Table 23.

Table 23. Physical and chemical water quality data for Narada Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	10/22/03 surface	10/22/03 hypolimnion
Secchi disk (m)	1.2	--
DO saturation (%)	80.8	67.3
DO (mg/L)	8.8	7.4
pH	8.2	8.05
specific conductance (µS/cm)	349	351
total dissolved solids (g/L)	0.2	0.2
sulfate (SO_4) (mg/L)	0.9	0.9
nitrate nitrogen (NO_3-N) (mg/L)	0.02	0.01
ammonium nitrogen (NH_4-N) (mg/L)	0.08	0.05
true color (Pt-Co units)	12	15
total alkalinity (mg/L $CaCO_3$)	124	130
total hardness (mg/L $CaCO_3$)	156	162
calcium hardness (mg/L $CaCO_3$)	116	120
total phosphorus (TP) (µg/L)	19.84	20.15
chlorophyll-*a* (µg/L)	25.38	

School Lake

School Lake, a large lake south of Bass Lake (Figure 35), has a surface area of 70.7-71.2 ha (MCGI 2006; Fessell 2007). It has a nearly flat bottom, and averages about 1.5 m in depth, but with a deeper hole (approximately 6 m) in a cove at the southwestern end of the lake. The shoreline has limited complexity (Fessell 2007). School Lake occasionally receives surface water inflow that comes through a black ash swamp, but there is no lake outlet (Elias 2007). Handy and Stark (1984) stated that the lake had an outlet, but no inlet, and was groundwater fed. They found that the water level varied only 0.30 m from 1980-1982.

Near the east side of the lake and inlet, Hazlett (1988) found 13 species of floating and submerged aquatic macrophytes in 1986 and 1987: common duckweed; nodding water-nymph; variegated yellow pond lily; white water lily; largeleaf, curly leaf, leafy, variableleaf, floating, broadleaf, and flatstem pondweeds; duck-potato; and tape-grass. Albert (1992) was unable to establish transects because the lake was too shallow and rough, but he found 26 species of aquatic macrophytes, with 23 species being totally aquatic. Three pondweed species (variableleaf, largeleaf, and floating) and nodding water-nymph were found scattered among the poorly consolidated organic sediments. Fessell (2007) noted that most of the lake bottom has no macrophyte cover, but that the southern end has colonies of pondweed, coontail, elodea (*Elodea canadensis)*, and white water lily covering the bottom. Hazlett (1988) noted that rushes, sedges, and cattails were found along the shoreline, as did Fessell (2007).

A small area of emergent wetland is found on the west side of School Lake. Hazlett (1988) listed the emergent and shoreline species of School Lake as blue joint, twig-rush, elliptic spikerush (*Eleocharis elliptica*), common spikerush, water horsetail (*Equisetum fluviatile*), boneset, Joe-Pye-weed, small purple-fringed orchid, larger Canadian St. John's-wort (*Hypericum majus*), southern blue flag, short-headed rush (*Juncus brachycephalus*), knotted rush (*J. nodosus*), cardinal flower (*Lobelia cardinalis*), Ontario lobelia (*L. kalmii*), northern bugleweed, purple loosestrife, wild mint, sensitive fern, switch grass (*Panicum virgatum*), water smartweed, marsh cinquefoil, duck-potato, hard-stem bulrush, chair maker's rush, common skullcap (*Scutellaria galericulata*), grass-leaved goldenrod, eastern marsh fern, deadly nightshade, and marsh St. John's-wort. The edge of School Lake near the inlet was the only location where water-parsnip (*Sium suave*) was found during this study.

Kelly and Price (1979) found the northern pike, bluntnose minnow, yellow bullhead, bluegill, largemouth bass, and pumpkinseed in School Lake. Fessell (2007) reported nine fish species from School Lake. Four species were in common with Kelly and Price (1979): northern pike, bluegill, largemouth bass, and pumpkinseed. Fessell (2007) did not find the bluntnose minnow or yellow bullhead, but did find five additional species for the lake: mimic shiner, brown bullhead, banded killifish, rock bass, and yellow perch. Motor use is allowed on School Lake, and access is high (Fessell 2007).

Physical and chemical water quality measurements for School Lake are shown in Table 24. Elias (2007) found that this lake had the highest DOC levels of the nine SLBE lakes she sampled (13.4 mg/L). She stated that because School Lake is shallow and subject to frequent resuspension of bottom materials, its DOC may be due to production by algae and macrophytes. She also found that TP and TN levels (21.9 µg/L and 1.08 mg/L, respectively) exceeded the USEPA reference criteria levels for its subecoregion. Fessell (2007) reported that DO at the bottom 1.2 m of the cove was less than 3 mg/L, and the lake has a history of winterkill.

Shell Lake (Briggs Lake)

Shell Lake, a relatively long, narrow lake north of Narada Creek (Figure 35) has a surface area of 41.3 ha (MCGI 2006; Fessell 2007) and a maximum depth of 4 m in three connected deeper channels running perpendicular to the west shoreline of the lake. The west side is bordered by steep contours of upland hardwoods; relatively flat, mixed hardwood and conifer stands are found to the south and east. The lake has a shallow, muck bottom, with an average depth of approximately 2.4 m. The shoreline has moderate complexity (Fessell 2007). Elias (2007) reported that Shell Lake does not have surface water connections; it probably receives water from groundwater discharge and the catchment watershed as surface flow.

Hazlett (1988) found sparse populations of 10 species of floating and submerged aquatic macrophytes in 1986 and 1987: common duckweed; nodding water-nymph; variegated yellow pond lily; white water lily; water smartweed; variableleaf, Illinois, floating, and broadleaf pondweeds; and bladderworts. The emergent and shoreline vegetation included blue joint, northern reedgrass (*Calamagrostis stricta* ssp. *inexpansa*), a sedge, twig-rush, spikerushes, Joe-Pye-weed, southern blue flag, reed, hard-stem bulrush, grass-leaved goldenrod, eastern marsh fern, and common cattail. Fessell (2007) also reported a shoreline dominated by bulrush, sedge, and cattail colonies, and sparse macrophyte cover on the lake bottom, composed mainly of muskgrass, pondweed, coontail, and white water lily. A small cove at the north end of the lake has greater water lily and pondweed densities.

Twelve fish species have been collected from Shell Lake. Kelly and Price (1979) found the bluntnose minnow, white sucker, banded killifish, bluegill, largemouth bass, pumpkinseed, smallmouth bass, Iowa darter, and yellow perch. Fessell (2007) did not find the white sucker or smallmouth bass but did find the Johnny darter, mimic shiner, and sand shiner. Bluntnose

Table 24. Physical and chemical water quality data for School Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a; Elias 2007).

Parameter	2003 surface	2003 hypolimnion	2005 surface
Secchi disk (m)	1.9-3.6	--	1.1
DO saturation (%)	74.3	11.1	--
DO (mg/L)	7.0	1.2	--
dissolved organic carbon (DOC) (mg/L)	--	--	11.0-13.4
pH	8.2	7.2	8.8
specific conductance (µS/cm)	209	384	212
total dissolved solids (g/L)	0.1	0.2	--
sulfate (SO_4) (mg/L)	1.0	1.0	3.7-5.8
chloride (Cl-) (mg/L)	--	--	7.7-9.5
nitrate nitrogen (NO_3-N) (mg/L)	0.01	0.01	--
nitrate and nitrite nitrogen (NO_3+NO_2-N)	--	--	0.005-0.006
ammonium nitrogen (NH_4-N) (mg/L)	0.06	0.7	0.04
total kjeldahl nitrogen (TKN) (mg/L)	--	--	0.815
total nitrogen (TN) (mg/L)	--	--	1.08
true color (Pt-Co units)	24	27	--
total alkalinity (mg/L $CaCO_3$)	92	86	89
total hardness (mg/L $CaCO_3$)	110	108	--
calcium hardness (mg/L $CaCO_3$)	70	80	--
calcium (mg/L)	--	--	24.56
magnesium (mg/L)	--	--	10.78
potassium (mg/L)	--	--	0.70
sodium (mg/L)	--	--	3.51
SiO_2 (mg/L)	--	--	12.5-16.36
total phosphorus (TP) (µg/L)	20.56	17.66	21.90-55
chlorophyll-*a* (µg/L)	--	--	4.5
chlorophyll-*a* (µg/L) phaeophytin corrected	1.34-9.01	--	--

2003 data based on one sample (06/11/03);
2005 data average of 1-4 samples during summer season

minnows were 51% of the catch, and bluegills were 29%. Fessell (2007) reported marked differences between Shell Lake and other lakes in the Shalda Creek watershed, especially the absence of bullheads and the growth of bluegills and pumpkinseeds at rates higher than the state average. It was also the only lake sampled in the Shalda Creek watershed in 2003 to have species of darters.

Physical and chemical water quality data were collected during the 2003 fish survey (Murphy 2004a) and later by Elias (2007) and Elias and VanderMeulen (2008) (Table 25). TN and TP levels (0.96 mg/L and 12.61 µg/L, respectively) exceeded the USEPA reference criteria levels for its subecoregion (Elias 2007).

Tucker Lake

Tucker Lake, near the Crystal River (Figure 35, Figure 38) has a surface area of 6.9-7.1 ha and a maximum depth of 3-3.7 m (Murphy 2004a; MCGI 2006; Elias 2007; Fessell 2007). The lake is surrounded by wetlands and is connected to Fisher Lake by a short channel (Murphy 2004a;

Table 25. Physical and chemical water quality data for Shell Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a; Elias 2007; Elias and VanderMeulen 2008).

Parameter	2003 surface	2005 surface	2007 surface	2007 hypolimnion
Secchi disk (m)	4.2	3.0	3.8	--
DO saturation (%)	107.9-124.8	--	--	--
DO (mg/L)	9.4-10.6	--	8.7	--
dissolved organic carbon (DOC) (mg/L)	--	9.0-10.0	6.9	--
pH	8.6-8.7	8.5	8.8	--
specific conductance (µS/cm)	247-263	262	253	--
total dissolved solids (g/L)	0.2	--	--	--
sulfate (SO_4) (mg/L)	27	16.7-20.02	21.8	--
chloride (Cl-) (mg/L)	--	1.1-1.16	1.2	--
nitrate nitrogen (NO_3-N) (mg/L)	0.01	--	--	--
nitrate and nitrite nitrogen (NO_3+NO_2-N)	--	0.005-0.011	0.014	--
ammonium nitrogen (NH_4-N) (mg/L)	0.03	0.07	0.036	--
total kjeldahl nitrogen (TKN) (mg/L)	--	0.785	--	--
total nitrogen (TN) (mg/L)	--	0.96	0.818	--
true color (Pt-Co units)	6	--	--	--
total alkalinity (mg/L $CaCO_3$)	94	108.5	117	--
total hardness (mg/L $CaCO_3$)	146	--	--	--
calcium hardness (mg/L $CaCO_3$)	90	--	--	--
calcium (mg/L)	--	32.94	30.2	--
magnesium (mg/L)	--	14.32	12	--
potassium (mg/L)	--	0.41	0.38	--
sodium (mg/L)	--	1.57	1.4	--
SiO_2 (mg/L)	--	10.7-13.66	1.2	--
total phosphorus (TP) (µg/L)	10.14	12.61-50	8	9
chlorophyll-*a* (µg/L)	1.6	2.15	--	--

2003 data based on one sample (6/17/03); 2005 data average of 1-4 samples during summer season; 2007 data average of 1-3 samples during summer season

Figure 38. Tucker Lake in Sleeping Bear Dunes National Lakeshore (Photo by D. Mechenich).

Fessell 2007). The basin is uniform and shallow with a soft organic bottom. The average depth is approximately 2.7 m. The shoreline has moderate complexity with an abrupt bank (Fessell 2007).

Hazlett (1988) in 1986 and 1987 found 14 species of floating and submerged aquatic macrophytes: common duckweed; shortspike water-milfoil; twoleaf water-milfoil; nodding water-nymph; variegated yellow pond lily; white water lily; largeleaf, leafy, variableleaf, floating, broadleaf, and Richardson's pondweeds; bladderworts; and tape-grass. The emergent and shoreline vegetation included swamp milkweed, blue joint, longhair sedge (*Carex comosa*), water lilies, royal fern, marsh cinquefoil, duck-potato, deadly nightshade, and common cattail. He also found five species of shoreline herbs. Albert (1992) did not establish transects due to shallow depth (generally <1.8 m), but reported 13 aquatic macrophyte species from Tucker Lake, with the most common being shortspike water-milfoil; largeleaf, floating, and broadleaf pondweeds; and common bladderwort. A thick benthic layer of organic debris and heavy plant cover existed throughout the lake except at the center. Fessell (2007) also reported a flourishing aquatic plant community, with pondweed, muskgrass, and pond lily abundant. Reeds have significantly expanded in recent years in the wetland near the lake off Westman Road (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Eleven fish species have been collected from Tucker Lake. Kelly and Price (1979) reported northern pike, bluegill, largemouth bass, pumpkinseed, rock bass, and yellow perch. Fessell

(2007) found all of the above species as well as the central mudminnow, brown bullhead, yellow bullhead, and Iowa darter. Murphy (2004a) also reported the black crappie (*Pomoxis negromaculatus*), but did not indicate the survey in which it was found. Bluegills were 64% of the catch in the 2003 survey (Fessell 2007).

Physical and chemical water quality data were collected at the time of the 2003 fish survey (Murphy 2004a), as well as by Elias (2007) and Elias and VanderMeulen (2008) (Table 26). In the 2005 lake survey, Elias (2007) found the second highest DOC levels (12.0 mg/L) in Tucker Lake and indicated that it was probably due to allochthonous sources. A 2 ha area next to Tucker Lake was used by the residents of Glen Arbor as a dump site from the 1900s to the 1960s (Enviroscience 1995), and remediation work has been completed at the site. However, SLBE staff do not believe that the full extent of the dump is known and are making efforts to further study the site.

Table 26. Physical and chemical water quality data for Tucker Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a; Elias 2007; Elias and VanderMeulen 2008).

Parameter	2003 surface	2005 surface	2007 surface	2007 hypolimnion
Secchi disk (m)	2.4	2.6	2.3	--
DO saturation (%)	85.2-105.6	--	--	--
DO (mg/L)	8.0-9.7	--	8.4	--
dissolved organic carbon (DOC) (mg/L)	--	11.0-12.0	9.7	--
pH	8.1-8.3	8.3	8.2	--
specific conductance (µS/cm)	258-276	262	249	--
total dissolved solids (g/L)	0.2	--	--	--
sulfate (SO_4) (mg/L)	0.9	3.5-4.83	6.2	--
chloride (Cl-) (mg/L)	--	1.26-1.4	1.6	--
nitrate nitrogen (NO_3-N) (mg/L)	0.01	--	--	--
nitrate and nitrite nitrogen (NO_3+NO_2-N)	--	0.005-0.007	0.005	--
ammonium nitrogen (NH_4-N) (mg/L)	0.01	0.025	0.022	--
total kjeldahl nitrogen (TKN) (mg/L)	--	0.8	--	--
total nitrogen (TN) (mg/L)	--	0.76	0.74	--
true color (Pt-Co units)	23	--	--	--
total alkalinity (mg/L $CaCO_3$)	108	123	137	--
total hardness (mg/L $CaCO_3$)	142	--	--	--
calcium hardness (mg/L $CaCO_3$)	98	--	--	--
calcium (mg/L)	--	35.08	44.8	--
magnesium (mg/L)	--	12.67	13.3	--
potassium (mg/L)	--	0.32	0.5	--
sodium (mg/L)	--	1.05	1.2	--
SiO_2 (mg/L)	--	5.8-7.72	1.1	--
total phosphorus (TP) (µg/L)	14.4	17.5-55	15	13
chlorophyll-*a* (µg/L)		3.12	--	--
chlorophyll-*a* phaeophytin corrected (µg/L)	1.58	--	--	--

2003 data based on one sample (6/4/03); 2005 data average of 1-4 samples during summer season; 2007 data average of 1-3 samples during summer season

Unnamed Ponds

Six small bodies of water in the Mainland-North Unit include a total of 4.9 ha (MCGI 2006). Hazlett (1998) found five species of floating and submerged aquatic plants and nine species of shoreline emergent plants in the small pond north of the turn circle on Lake Michigan Road.

Crystal River and Watershed

The Crystal River watershed includes Fisher, Tucker, Glen, and Little Glen Lakes (Figure 35, Figure 36; Boyle and Hoefs 1993a). The Crystal River is about 10 km long; approximately 4 km lies within SLBE boundaries (MCGI 2006; Fessell 2007). In 2004, a boundary change added 42 ha of a globally rare dune and swale feature to SLBE (Public Law 108-229 2004). The Crystal River is a fourth order stream, and its origin lies just outside the SLBE boundary in Fisher Lake (Vana-Miller 2002). Linton (1987) found that the Crystal River had the highest percentage (4.8%) of riffles/total length of the four SLBE streams studied. Runs occupied the greatest percentage (82.8%) of total river miles. Fessell (2007) reported that relatively little groundwater is thought to enter the river to moderate its temperature fluctuations, although Handy and Stark (1984) stated that springs and seeps provided water to the river.

Curry (1977) found high bacteria counts along the shorelines of Big and Little Glen Lakes and in the Crystal River. The counts in the lakes coincided with occurrences of *Cladophora* sp. and suggested nutrient seepage from septic systems. In Big Glen Lake, 71% of the properties with septic systems older than 10 years had *Cladophora* growing along the shoreline.

White (1987) studied the macroinvertebrate populations of the river and indicated that taxa richness was high, gatherers and filterers were abundant, and grazers were present. These populations suggested that the water quality was high, and pollutants or eutrophication did not appear to be a problem.

Sayles (1988) conducted a biological survey on July 20, 1987 to assess background conditions prior to development of a golf course proposed near the Crystal River. Three stations were established, and water quality, fish, macroinvertebrates, and stream physical data were collected. Habitat and substrate were highly variable from Glen Lake to the river mouth at Lake Michigan. Macrophyte beds near the headwaters were extensive. At Station 1 (below Fisher Lake), aquatic macrophytes, including pondweeds and hornwort (*Ceratophyllum* sp.), covered 30% of the bottom. At station 2 (above Hwy M-22), there were no riffle areas, and the current was slower than at station 1. Pondweeds, eelgrass (*Vallisneria* sp.), hornwort, and muskgrass covered about 70% of the sand and muck substrate. The flow and substrate at station 3 (near the mouth) were similar to station 2, but macrophytes (mostly pondweeds) covered less than 10% of the bottom. The Crystal River is classified as a coldwater stream, but no trout or salmon were collected. Fish communities were similar at all three stations and included primarily bluegills, creek chubs (*Semotilus atromaculatus*), and Johnny darters. Station 2 had the greatest diversity of fish species. The study also found that macroinvertebrate communities were similar at all stations and indicated good water quality. Nutrients such as phosphorus and nitrogen were low, but did show a slight increase at station 3 that was probably related to land use and accumulated river miles (Sayles 1988).

Hazlett (1988) found 12 species of floating and submerged aquatic macrophytes in 1986 and 1987: elodea; common duckweed; shortspike water-milfoil; nodding water-nymph; white water lily; curly leaf, Illinois, broadleaf, Richardson's, and flatstem pondweeds; bladderworts; and tape-grass. He also found 28 species of shoreline herbs. Albert (1992) established four transects and found 67 aquatic macrophyte species. He recommended that the discharge of the Crystal River should be more carefully monitored and that the instream flow requirements for recreational and biological uses of the river be determined.

A qualitative biological survey of the Crystal River was conducted by Flower and Walker (1999a, b). Their study focused on the existing habitat and aquatic macroinvertebrate communities and compliance with water quality standards. They sampled only one station within SLBE and ranked the aquatic macroinvertebrate community there as acceptable.

A small dam approximately 0.4 km downstream of Fisher Lake regulates water levels in Glen Lake under a 1945 court order (Vana-Miller 2002). Historically, the flow was controlled by adding or removing boards within the dam, but in June 2001, adjustable gates were installed that allowed for easier control. Since 1941, a manual gauge record has been maintained by volunteers. These records indicate that lake levels have been generally maintained within a range of 15-34 cm, and the lake elevation generally does not vary more than 3-6 mm from one day to the next. The USGS has sporadically measured flow in the Crystal River since August 1946 at several locations, and Leelanau Conservancy provided 53 flow measurements from 1990 to 1991 (Albright et al. 2002).

In 2001, dam upgrade work resulted in a fish kill when river flow was reduced or shut down for approximately 18 hours (Vana-Miller 2002). As a result, a technical committee was formed, with members from the Glen Lake Association, Crystal River Preservation Association, MDEQ, and the US Department of Interior. Lake and river levels were monitored several times a week. The USGS estimated that 2.9 km below the dam, average 7-day low flow levels were 0.85 $m^3 sec^{-1}$ for a 2-year recurrence interval and 0.68 $m^3 sec^{-1}$ for a 10-year recurrence interval. Flow rates varied from a low of 0.65 $m^3 sec^{-1}$ in August 1980 to a high of 2.6 $m^3 sec^{-1}$ in May 1979 over a four-year period. The USGS determined that 23 cm of water depth over a 3-6 m width of channel was needed to float canoes, maintain submerged stream substrates, and protect aquatic organisms, which required a minimum of 0.85 $m^3 sec^{-1}$ of flow from the lake (Albright et al. 2002).

USGS staff gauges and a continuous stream gauge monitoring system were installed in 2003, and a three-year USGS hydrologic study followed on the Crystal River in 2004 (Murphy 2004a). An on-line system monitored continuous water level, specific conductance, and water temperature from 2004-2006, and data can be referenced at http://mi.water.usgs.gov. Results indicated that the Crystal River gains, loses, and regains water throughout the basin (Murphy 2004a). Droughts in the last several years have made dam management very challenging, with extremely low water levels recorded on the Glen Lakes and Crystal River (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

An ecologic study of the Crystal River was also conducted by the USGS Great Lakes Science Center (Murphy 2004a). The stream corridor was evaluated for woody debris, overhanging vegetation, shade, pools, riffles, and undercut banks. Temperature, DO, specific conductance, total dissolved solids, and pH were recorded for each station, and a macroinvertebrate assessment was made using a kick-net. One set of physical and chemical water quality data from the study was recorded in Murphy (2004a; Table 27).

Table 27. Physical and chemical water quality data for Crystal River, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	07/21/04 results
DO saturation (%)	61.4-117.8
DO (mg/L)	6.32-9.45
pH	8.1-8.5
specific conductance (µS/cm)	252-300
total dissolved solids (g/L)	0.2

Thirty-one fish species have been observed in surveys of the Crystal River since the 1960s. A 1998 survey showed that the five most abundant species were rock bass, Johnny darter, hornyhead chub (*Nocomis bigutatus*), central mudminnow, and smallmouth bass. The MDNR classifies the Crystal River as a type 3 trout stream, which means that fishing is open all year to all species (Fessell 2007).

Good Harbor Creek

Good Harbor Creek is a small tributary to Lake Michigan's Good Harbor Bay (Figure 35). It is approximately 1.2-1.3 km long and originates in groundwater seeps in a wetland and beaver pond (Murphy 2004a; Fessell 2007). Seven fish species were found in the beaver impoundment; in order of abundance, they are banded killifish, northern redbelly dace, central mudminnow, pumpkinseed, bluntnose minnow, bluegill, and brown bullhead (Fessell 2007). Physical and chemical water quality data were collected during the fish survey (Table 28; Murphy 2004a).

Table 28. Physical and chemical water quality data for Good Harbor Creek, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	05/12/04 results
DO saturation (%)	104.1
DO (mg/L)	9.89
pH	7.82
specific conductance (µS/cm)	418
total dissolved solids (g/L)	0.3
sulfate (SO_4) (mg/L)	9
nitrate nitrogen (NO_3-N) (mg/L)	1.6
ammonium nitrogen (NH_4-N) (mg/L)	0.015
true color (Pt-Co units)	15
total alkalinity (mg/L $CaCO_3$)	96
total hardness (mg/L $CaCO_3$)	174
calcium hardness (mg/L $CaCO_3$)	150

Narada Creek

Narada Creek flows 0.94 km through wetlands of lowland conifers and speckled alders (*Alnus incana* ssp. *rugosa*) from the outlet of Narada Lake to the confluence with Shalda Creek (Figure 35). Several beaver dams influence it throughout its course (Murphy 2004a; Fessell 2007).

Twelve fish species have been collected from Narada Creek. Kelly and Price (1979) found only the creek chub, but Fessell (2007) added the central mudminnow, blacknose shiner (*Notropis heterolepis*), common shiner, northern redbelly dace, white sucker, brook stickleback, bluegill, pumpkinseed, Johnny darter, bluntnose minnow, and yellow perch, with common shiner and creek chub being most abundant. Physical and chemical water quality data were collected for Narada Creek at the time of Fessell's (2007) survey (Table 29; Murphy 2004a).

Table 29. Physical and chemical water quality data for Narada Creek, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	05/13/04 results
DO saturation (%)	72.8
DO (mg/L)	7.15
pH	7.94
specific conductance (µS/cm)	354
total dissolved solids (g/L)	0.2
sulfate (SO_4) (mg/L)	0.9
nitrate nitrogen (NO_3-N) (mg/L)	0.05
ammonium nitrogen (NH_4-N) (mg/L)	0.08
true color (Pt-Co units)	19
total alkalinity (mg/L $CaCO_3$)	90
total hardness (mg/L $CaCO_3$)	168
calcium hardness (mg/L $CaCO_3$)	132
total phosphorus (TP) (µg/L)	14.14
chlorophyll-*a* phaeophytin corrected (µg/L)	0.0

Shalda Creek and Watershed

The Shalda Creek watershed includes Lime and Little Traverse Lakes, which are outside SLBE (Figure 35; Boyle and Hoefs 1993a). Shalda Creek flows through SLBE from its headwaters at the outflow of Little Traverse Lake.

Shalda Creek, which is also known as Sucker Creek, is 4.3 km long (MCGI 2006) and is a third order stream (Vana-Miller 2002). Linton (1978) found that riffles comprised 0.7% of the total river miles, and sand bottom runs comprised 74.3%. The remainder of the river miles occurred in marl bottom runs (25.0%). Gravel substrates near the mouth are commonly used by spawning anadromous salmonids (Fessell 2007). Only a few short-term discharge data sets are available for Shalda Creek due to the absence of permanent USGS gaging stations. The average discharge is approximately 0.3 m^3sec^{-1}. Fessell (2007) reported that the stream is thought to receive little groundwater input, although Boyle and Hoefs (1993a) reported numerous springs.

Boyle and Hoefs (1993a) found extensive marl deposits and macrophyte beds throughout the length of the river, except near the mouth, where gravel riffles were present. White (1987) found a diverse and well-balanced macroinvertebrate community near the mouth. Hazlett (1988) found a diverse herb community in the white cedar swamp below the Little Traverse Lake outlet in 1986 and 1987, including eight species of ferns, six overstory species, and five woody understory species. Albert (1992) established three transects and found a total of 56 species of aquatic macrophytes in Shalda Creek, including a population of state-threatened cutleaf waterparsnip in marl near the headwaters.

Twenty-seven fish species have been collected from Shalda Creek. Kelly and Price (1979) found the Chinook salmon, central mudminnow, bluntnose minnow, common shiner, creek chub, sand shiner, white sucker, banded killifish, slimy sculpin, bluegill, largemouth bass, Johnny darter, and yellow perch. They also noted that the USFWS had found American brook lamprey (*Lampetra lamottei*) at the creek mouth in previous studies. Fessell (2007) did not report finding the Chinook salmon, sand shiner, slimy sculpin, or largemouth bass in 2003, but found additional species including the bowfin (*Amia calva*), alewife, brown trout, rainbow trout, northern pike, emerald shiner, hornyhead chub, longnose dace, mimic shiner, mottled sculpin, pumpkinseed, rock bass, and smallmouth bass. Shalda Creek is designated by the MDNR as a type 4 trout stream, meaning that species except for brook trout, brown trout, and Atlantic salmon may be harvested year-round. Physical and chemical water quality data were collected during the 2003 fish survey (Table 30; Murphy 2004a).

Table 30. Physical and chemical water quality data for Shalda Creek, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	7/2/03 results
DO saturation (%)	81.9-90.6
DO (mg/L)	7.7-8.2
pH	8.1-8.3
specific conductance (µS/cm)	355-359
total dissolved solids (g/L)	0.2
sulfate (SO_4) (mg/L)	33-37
nitrate nitrogen (NO_3-N) (mg/L)	0.09-0.10
ammonium nitrogen (NH_4-N) (mg/L)	0.03
true color (Pt-Co units)	5
total alkalinity (mg/L $CaCO_3$)	134-150
total hardness (mg/L $CaCO_3$)	178-186
calcium hardness (mg/L $CaCO_3$)	114-130
total phosphorus (TP) (µg/L)	13.86
chlorophyll-*a* (µg/L)	5.63
chlorophyll-*a* phaeophytin corrected (µg/L)	0.66

Unnamed Streams

Unnamed streams in the Mainland-North Unit include three Shalda Creek tributaries parallel to and near the Lake Michigan shoreline with a combined length of 0.77 km, a 1.36 km intermittent stream above Narada Lake, a 0.1 km stream connecting School and Bass Lakes, a 3.86 km intermittent stream east of Shalda Creek and north of Bass Lake, a 0.25 km stream connecting Tucker Lake to Fisher Lake, a 0.7 km stream south of School Lake, 2.89 km of intermittent streams east of Tucker Lake, and 2.32 km of intermittent stream south of Good Harbor Creek (Figure 35; MCGI 2006).

M-22 Bog

This *Sphagnum* bog is located east of Westman Rd. off Hwy M-22 (Figure 35). In the open water areas at the southern end, Hazlett (1988) found pond-lilies and hidden-fruited bladderwort (*Utricularia geminiscapa*), but the rest of the bog was dominated by leather-leaf and 12 species of floating and submerged aquatic macrophytes: elodea; common duckweed; shortspike water-milfoil; nodding water-nymph; white water lily; curly leaf, Illinois, broadleaf, Richardson's, and flatstem pondweeds; bladderworts; and tape-grass. He also found 11 species of shoreline herbaceous plants.

Port Oneida Bog

This bog is located northeast of the intersection of Port Oneida and Kelderhouse Roads (Figure 35). Hazlett (1988) found during 1986 and 1987 that the bog was dominated by leather-leaf. Emergents included rushes, reed canary grass, wool-grass (*Scirpus cyperinus*), marsh St. John's-wort, and common cattail. He also found the floating and submergent species water-shield (*Brassenia schreberi*), elodea, floating pondweed, broadleaf pondweed, the rare Oakes' pondweed, and bladderworts.

Wetlands

The south shore of Narada Lake includes 0.6 ha of aquatic bed. Fourteen ha of emergent wetland are scattered throughout the Mainland-North Unit. An additional 37 ha of other non-wooded wetlands are found along the Lake Michigan shores of Good Harbor Bay and south of Pyramid Point. Wooded wetlands in the Mainland-North Unit are 181 ha of lowland conifers, 155 ha of lowland hardwoods, 82 ha of shrub/scrub, and 10 ha of other wooded lowlands. Wet soils accounted for an additional 332 ha of wetland (Figure 35).

Hazlett (1988) described large swales along Shalda Creek south of Lake Michigan Road alternating with dune ridges. He also described a wetland with two depressions located between Hidden Lake and the end of Lake Michigan Road that has surface water for most of the year. It was dominated by willows and contained seven species of submergent plants, eleven emergent vegetation species, and five species of floating plants.

Bow Lakes

The Bow Lakes Unit contains the two Bow Lakes with individual surface areas of 3.3 and 1.4 ha, Bow Valley Pond (0.1 ha), and an unnamed lake locally known as Kettle Pond (0.6 ha), for a total of 5.5 ha (Figure 36; MCGI 2006). These are glacial kettle lakes that are surrounded by bogs, fens, wet meadows, and marshes and positioned between two high wooded bluffs. They have no public access. Little information is available on the Bow Lakes with the exception of Hazlett's (1988) macrophyte study. These lakes are located primarily on private property, and NPS requests to visit the sites have been denied in recent years (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

The Bow Lakes Unit also includes 3.9 ha of emergent wetlands (Table 17). Hazlett (1988) describes "the most noteworthy aquatic habitats" of the Bow Lakes area as a spring-fed fen and the bog at the section's south end. The fen has an extensive sedge mat and is lined with white cedar on its outside edges. Sedge species found there were water sedge (*Carex aquatilis*), large yellow sedge (*C. flava*), elk sedge (*C. garberi*), bottlebrush sedge (*C. hystericina*), inland sedge

(*C. interior*), wooly-fruit sedge, twig-rush, elliptic spikerush, thinleaf cottonsedge (*Eriophorum viridicarinatum*), and hard-stem bulrush. Other species included Joe-Pye-weed, southern blue flag, sensitive fern, and balsam groundsel (*Packera paupercula*) (Hazlett 1988).

The bog occurs in a depression largely covered by peat moss (*Sphagnum* spp.) and has a variable water table, with water 0.3-0.6 m deep. In small openings near the center, Hazlett (1988) found a cotton-grass (*Eriophorum virgatum*), narrow-panicle rush (*Juncus brevicaudatus*), water smartweed, and hidden-fruited bladderwort. The rest of the mat was dominated by leather-leaf, with bog-rosemary (*Andromeda glaucophylla*), chokeberry (*Aronia prunifolia*), sundew, bog laurel, rannoch-rush (*Scheuchzeria palustris*), small cranberry, and sweet white violet (*Viola blanda*). Species found in or along the bog moat were wheat sedge (*Carex atherodes*), fringed willow-herb (*Epilobium ciliatum*), rattlesnake mannagrass (*Glyceria canadensis*), larger Canadian St. John's-wort, a touch-me-not (*Impatiens balsamea*), common duckweed, northern bugleweed, wild mint, royal fern, reed canary grass, water smartweed, lady's thumb (*Polygonum persicaria*), marsh cinquefoil, hooked crowfoot (*Ranunculus recurvatus*), wool-grass, common skullcap, eastern marsh fern, marsh St. John's-wort, and bladderworts (Hazlett 1988).

The Bow Lakes Unit also contains 2 ha of wooded wetlands and 7 ha of wetlands identified by wet soils alone.

Mainland-Central

The Mainland-Central Unit of SLBE has a Lake Michigan shoreline length of 13.7 km (MCGI 2006). There are four named lakes (Day Mill Pond, Little Glen, Glen, and North Bar Lakes) and three small unnamed lakes (Figure 36; MCGI 2006). Excluding Glen and Little Glen Lakes, which are mostly outside SLBE boundaries, the combined lake surface area is 15.3 ha (MCGI 2006).

Day Mill Pond

Day Mill Pond is a shallow (<1 m) 2.0-2.3 ha pond (Murphy 2004a; MCGI 2006) near the base of the Dune Climb (Figure 36, Figure 39). Historically, a canal connected the pond to Little Glen Lake on its east side near the public beach, and the pond was used for a lumber mill. After Hwy 109 was completed, the canal was replaced by a culvert that has become filled with sediment and debris, preventing fish passage between the pond and lake. The pond has also become filled with sediments, largely organic muck (Fessell 2007), and it most likely is anoxic under the ice (Murphy 2004a). The pond was dry in summer 2007, but refilled after the connection with Little Glen Lake was reestablished through the culvert (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). Kelly and Price (1979) found that northern pike was the only fish species present in the lake. Fessell (2007) found only the central mudminnow.

Hazlett (1988) found extensive growth of submergent and floating aquatic macrophytes and vascular plants in 1986 and 1987. Species of floating and submerged aquatic macrophytes included coontail; elodea; common duckweed; shortspike water-milfoil; nodding water-nymph; Illinois, floating, broadleaf, Richardson's, and flatstem pondweeds; and common bladderwort. Relatively rare species for SLBE were star duckweed, greater duckweed, Robbins' pondweed, and Hill's pondweed. The 12 species of emergent and shoreline vegetation were swamp

Figure 39. Day Mill Pond in Sleeping Bear Dunes National Lakeshore (Photo by D. Mechenich).

milkweed, spotted water-hemlock (*Cicuta maculata*), fowl manna grass (*Glyceria striata*), spotted touch-me-not, variegated yellow pond lily, reed, water smartweed, marsh cinquefoil, duck-potato, common skullcap, narrow-leaved bur-reed, and common cattail. Fessell (2007) noted a "luxuriant" growth of muskgrass, pondweed, and water lilies in 2003.

Glen Lake

Glen Lake has a surface area of 1,973 ha (MCGI 2006), but only a small area of the southern shore is within SLBE boundaries (Figure 36). The lake is highly developed, with many private residences and two marinas along the shoreline. Hatlems Creek enters the lake along the southern end, and the lake's outflow flows into Fisher Lake which in turn flows into the Crystal River (Murphy 2004a). Keilty (1992) provided a summary of the limnologic data and developed a gross annual water budget for the lake. Groundwater and precipitation account for approximately 75% of the water input, and surface runoff approximately 25%. Annually, about 60% of the outflow occurs through the Crystal River, and 40% is lost through evaporation and groundwater losses. On a multi-year to decade scale, climatic changes probably have the greatest effect on mean lake levels and annual river discharges.

A dam below Glen Lake controls the outflow to the Crystal River. Historically, the flow was controlled by adding or removing boards within the dam, but in June 2001, adjustable gates were installed that allowed for easier control (Albright et al. 2002). Since 1941, a manual gage record has been maintained by volunteers. These data show that lake levels have been maintained within a general range of 15-34 cm, and the lake elevation generally does not vary more than 3-6 mm from one day to the next. Maintaining adequate flow in the Crystal River to float canoes and protect stream substrates and aquatic organisms would create a drop of only 5 cm in the Glen Lake level over a one month period at record low river flow (Albright et al. 2002). Droughts in the last several years have made dam management very challenging, with extremely low water levels recorded on the Glen Lakes and Crystal River (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Hazlett (1988) in 1986 and 1987 found only a sparse population of fineleaf pondweed (*Stuckenia filiformis* ssp. *filiformis*) along the SLBE shoreline and no emergent plants. Glen Lake is the only location in SLBE where the federal-endangered Michigan monkey-flower is found (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). Kelly and Price (1979) reported 18 fish species in Glen Lake: brook trout, lake trout, splake, rainbow trout, brown trout, coho salmon, Chinook salmon, lake herring, white sucker, spottail shiner, sand shiner, emerald shiner, rock bass, largemouth bass, smallmouth bass, bluegill, Johnny darter, and yellow perch.

Little Glen Lake

This polymictic lake has a surface area of 573 ha (MCGI 2006) and a maximum depth of 4.3 m (Vana-Miller 2002). Only areas along the north and northwest shoreline are within the park boundaries (Figure 36). Many private residences ring the rest of the lake shoreline. This lake has experienced high fecal bacterial levels. SLBE created a green belt (vegetated strip) at the site of the former swimming beach to reduce surface runoff high in waterfowl feces and associated bacteria.

An open wet area near the former Little Glen Lake beach includes blue joint, sedges, three-way sedge, spikerush, Joe-Pye-weed, yellow avens (*Geum aleppicum*), small purple-fringed orchid, spotted touch-me-not, southern blue flag, tufted loosestrife, sensitive fern, royal fern, reed, marsh cinquefoil, hard-stem bulrush, wool-grass, deadly nightshade, eastern marsh fern, marsh St. John's-wort, and common cattail. Woody species in this area include speckled alder, white birch (*Betula papyrifera*), silky dogwood (*Cornus amomum*), black ash, Michigan holly (*Ilex verticillata*), swamp rose, raspberries (*Rubus* sp.), and willows (Hazlett 1988).

Kelly and Price (1979) reported 11 fish species for Little Glen Lake: rainbow trout, lake herring, white sucker, bluntnose minnow, spottail shiner, emerald shiner, rock bass, largemouth bass, yellow perch, Johnny darter, and brown bullhead.

North Bar Lake

North Bar Lake, also known as Perry Lake by local residents, has a surface area of 12.0-12.5 ha (Murphy 2004a; MCGI 2006), a maximum depth of 9.4-10 m (Murphy 2004a; Elias 2007), and a mean depth of 3.1-6.1 m (Whitman et al. 2002b; Fessell 2007). This closed basin lake located northwest of the village of Empire (Figure 36, Figure 40) was historically an embayment of Lake Michigan. Although there is no paved road access to North Bar Lake, public use has destabilized its dunes and reduced native vegetation (Vana-Miller 2002). North Bar Lake has been extensively studied compared to most SLBE inland lakes.

There is a black ash swamp just north of the access road and a white cedar swamp south of the road (Vana-Miller 2002). The black ash swamp is the only known SLBE location for Clinton's

Figure 40. North Bar Lake in Sleeping Bear Dunes National Lakeshore (Photo by D. Mechenich).

wood fern (*Dryopteris clintoniana*) (Hazlett 1988). The shoreline of North Bar Lake has sand dunes on the west and north sides, and the east and south sides are forested (Whitman et al. 2002b). It exhibits moderate complexity and is dominated by sedges and bulrushes. Most of the shoreline has an abrupt bank, but sloped sand beaches occur on the north end (Fessell 2007). The littoral zone is mostly sand, but muck and marl deposits occur in the deeper portions of the lake (Whitman et al. 2002b; Fessell 2007).

Handy and Stark (1984) noted that the sand bar separating North Bar Lake from Lake Michigan occasionally washes out (in their study, at the end of June 1979, June and July 1980, and near the end of September 1982). Humans have destabilized the dunes, causing sand to migrate into the outlet area. This migration, combined with low water levels on Lake Michigan, has likely caused disruption of the hydrologic cycle noted by Handy and Stark (1984). It appears that a significant portion of North Bar Lake has also filled in with these shifting dunes (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). Elias (2007) also noted that North Bar Lake did not have permanent surface water connections but that it was periodically connected to Lake Michigan, and the lake probably received water from groundwater discharge and the catchment watershed as surface flow. Murphy (2004a) reported that the lake is fed by groundwater and has an inlet at the southeast end.

In the limnetic zone, Whitman et al. (2002b) found the phytoplankton community dominated by diatoms in 1997 (85.0-98.6%). “Yellow-green” algae (chrysophytes) were also commonly collected (0.4-10%). Peak abundance occurred early in the season and declined in July and August. Forty-six taxa of phytoplankton were collected. The littoral phytoplankton community was similar to the limnetic community. In May and June of 1998 diatoms comprised only 60% of the limnetic community, but by July they increased to levels similar to 1997. Diatoms comprised 98.4 % of the limnetic phytoplankton community in 1999, and no other group exceeded 1%. The most dominant genus over the three year period was *Cyclotella*, but *Synedra, Chlorochromonas*, and *Cryptomonas* were also commonly found. Chlorophyll-*a* levels ranged from 3-8 mg/L in the early season and then peaked at 13 mg/L in August in 1997 and 16 mg/L in September 1998.

The mean density of the zooplankton community was similar in the limnetic zone in 1997 (221 ± 72 individuals/liter) and 1998 (251 ± 52 individuals/liter), but the seasonal change in densities between years was different, peaking in September in 1997 and May in 1998 (Whitman et al. 2002a). Densities were lower in the littoral than the limnetic zone. Thirty-eight taxa were collected, with rotifers dominant. Commonly collected zooplankton were *Kellicottia longispina*, *Keratella* spp., *Polyarthra* spp., *Ploesoma truncatum, Diacyclops thomasi, Tropocyclops prasinus mexicanus*, and *Bosmina longirostris*. The littoral and limnetic zooplankton communities were only 23% similar except in May (75%), and the similarity between years was only 54%. The authors collected zebra mussel veligers in the limnetic zone in August and September of 1998 and noted that they had not been present in 1997 samples (Whitman et al. 2002b).

In 1997, the total macroinvertebrate density in North Bar Lake was 2000 m^{-2}, and no difference was found between the profundal and littoral zones. The Margalef and Shannon-Wiener diversity indices indicated slightly higher diversities in the littoral zone. Chironomidae was the dominant macroinvertebrate group collected in both zones, comprising over 50%, and tubificid worms were the second most abundant taxa. *Chaoborus* sp. was the most abundant taxa collected. In 1998 the macroinvertebrate densities were slightly higher in the profundal zone, and Margalef’s diversity index indicated that the littoral zone was more diverse. The most abundant taxonomic group in the littoral zone was Oligochaeta (Whitman et al. 2002b).

Hazlett (1988) found 14 species of floating and submerged aquatic macrophytes in 1986 and 1987: elodea; twoleaf water-milfoil; Eurasian water-milfoil; nodding water-nymph; variegated yellow pond lily; white water lily; largeleaf, curly leaf, leafy, variableleaf, Illinois, broadleaf, and Richardson’s pondweeds; and bladderworts. The greatest abundance occurred at the south end of the lake. The seven species of emergent and shoreline herbs Hazlett (1988) reported were swamp milkweed, blue joint, Joe-Pye-weed, cardinal flower, water horehound, water dock (*Rumex verticillatus*), and hard-stem bulrush. Whitman et al (2002b) also reported that aquatic macrophytes were common in the littoral zone, and pondweeds were abundant. Fessell (2007) reported pondweeds, muskgrass, water smartweed, and water lilies, mainly in the shallower portion of the lake at the south end.

Sixteen fish species have been collected from North Bar Lake. Kelly and Price (1979) found alewife, northern pike, sand shiner, spottail shiner, longear sunfish (*Lepomis megalotis*), smallmouth bass, Johnny darter, and yellow perch. The 2003/2004 NPS study did not report finding alewife or spottail shiner, but added bluntnose minnow, common carp, banded killifish, brook silversides, bluegill, largemouth bass, pumpkinseed, and rock bass to the list of fish found in the lake. Bluegill, sand shiner, and bluntnose minnow comprised the largest portion of the catch numerically (Fessell 2007).

Whitman et al. (2002b) found that North Bar Lake stratified in early June in 1997 and destratified by October, and it was stratified by mid-May in 1998. Fessell (2007) also noted that the lake had stratified by the first sampling session in June, and that on at least two occasions DO at the surface was approximately 1 mg/L lower than at mid-depth. Whitman et al. (2002b) noted that TN was higher in North Bar Lake than in the other two SLBE lakes they studied. They indicated that phosphorus was probably the limiting nutrient for this lake, and that it could be classified as mesotrophic based on chlorophyll-a levels. TP and ammonia levels were low throughout the study period. Elias (2007) found that North Bar Lake had high concentrations of chloride (9.6 mg/l) compared to the other lakes she sampled in the park except for Round Lake. She indicated that these high levels might be due to the close proximity of the lake to roads and road salting. Other physical and chemical water quality data collected at the time of the fish survey (Murphy 2004a) and in 2005 (Elias 2007) are found in Table 31.

Fisher Lake and Unnamed Lakes

Fisher Lake is a relatively shallow 23 ha lake outside the boundaries of SLBE (Figure 36). It is important as the headwaters of the Crystal River; a small marina is found there. It is surrounded by homes and cottages, and boat traffic is substantial (Vana-Miller 2002). The inlet is a small outlet stream from Glen Lake. Three additional small unnamed depressions in the Mainland-Central Unit of SLBE have a combined surface area of 0.56 ha (Figure 36; MCGI 2006).

Wetlands

The Mainland-Central Unit has few wetlands. North Bar Lake and Day Mill Pond are included in the 18 ha of open water (Table 17, Figure 36). Ten ha of emergent wetlands are found south of Little Glen Lake, on the northeast side of Day Mill Pond, and near Sleeping Bear Point. The marshy area north of Day Mill Pond is characterized by swamp milkweed, yellow rocket (*Barbarea vulgaris*), fringed willow-herb, Joe-Pye-weed, boneset, spotted touch-me-not, reed, wild black current (*Ribes americanum*), wool-grass, common cattail, stinging nettle (*Urtica dioica*), and sedges (Hazlett 1988). Wooded wetlands in the Mainland-Central Unit are 45 ha of lowland conifers, 22 ha of lowland hardwoods, 31 ha of lowland mixed forest, 6 ha of shrub/scrub, and 4 ha of other wooded lowlands. Seventy-four ha are identified as wetlands by soil type alone.

Mainland-South

The Mainland-South Unit of SLBE has a Lake Michigan shoreline length of 18.0 km (MCGI 2006). There are ten named lakes (Bass [Benzie], Deer, Little Platte, Long, Loon, Mud, Otter, Round, Rush, and Taylor Lakes) and 76 small unnamed lakes with a combined total surface area of 131.4 ha, not including Long and Rush Lakes. SLBE includes 0.41 km of shoreline on Long Lake and 0.64 km on Rush Lake (MCGI 2006). There are two named streams (Otter Creek and Platte River) within the Lakeshore boundaries in this Unit with a combined length of 11.1 km, and 3.15 km of unnamed streams (Figure 37; MCGI 2006).

Table 31. Physical and chemical water quality data for North Bar Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a; Elias 2007).

Parameter	2003 surface	2003 hypolimnion	2005 surface
Secchi disk (m)	1.65	--	2.2
DO saturation (%)	121.1 (4 m)	1.8	--
DO (mg/L)	11.09 (4 m)	0.19	--
dissolved organic carbon (DOC) (mg/L)	--	--	3.5-4.3
pH	8.4	8.0	8.3
specific conductance (µS/cm)	317	349	329
total dissolved solids (g/L)	0.2	0.2	--
sulfate (SO_4) (mg/L)	0.9	0.9	7.0 -9.4
chloride (Cl-) (mg/L)	--	--	4.07-9.6
nitrate nitrogen (NO_3-N) (mg/L)	0.2	0.18	--
nitrate and nitrite nitrogen (NO_3+NO_2-N)	--	--	0.122-0.335
ammonium nitrogen (NH_4-N) (mg/L)	0.015	0.02	0.06
total kjeldahl nitrogen (TKN) (mg/L)	--	--	0.4
total nitrogen (TN) (mg/L)	--	--	0.51
true color (Pt-Co units)	12	5	--
total alkalinity (mg/L $CaCO_3$)	152	154	145.5
total hardness (mg/L $CaCO_3$)	166	178	--
calcium hardness (mg/L $CaCO_3$)	118	120	--
calcium (mg/L)	--	--	44.29
magnesium (mg/L)	--	--	15.38
potassium (mg/L)	--	--	0.57
sodium (mg/L)	--	--	1.59
SiO_2 (mg/L)	--	--	5.4-5.48
total phosphorus (TP) (µg/L)	7.81	12.31	10.90-45
chlorophyll-*a* (µg/L)	1.47	--	4.33
chlorophyll-*a* (µg/L) phaeophytin corrected	0.38	--	--

2003 data based on one sample (06/25/03);
2005 data average of 1-4 samples during summer season

Bass Lake (Benzie)

Bass Lake in Benzie County is in the Otter Creek watershed and is the second lake in the chain of Deer-Bass-Otter (Figure 37). It has a surface area of 10.9-11.0 ha (Murphy 2004a; MCGI 2006) and a maximum depth of 8 m (Murphy 2004a). The lake inlet is on the south shore, and the outlet is on the north shore. The lake is spring fed but does receive surface water from an inlet coming from Deer Lake. Bass Lake drains into Otter Lake, but beaver activity has intermittently constricted the flow of both the inlet and outlet streams. The shoreline exhibits moderate complexity, with an abrupt bank and sharp dropoffs. The lake is surrounded by white cedar swamp to the north and south and by upland hardwoods on the western shoreline. The bottom substrates are soft marl and organic muck (Fessell 2007). Zebra mussels have been found in Bass Lake (Vana-Miller 2002).

Hazlett (1988) found the largest number of submerged aquatic species on the west shore of the lake in 1986 and 1987, including the following 16 species: coontail; elodea; water star-grass (*Heteranthera dubia*); twoleaf water-milfoil; nodding water-nymph; variegated yellow pond lily; white water lily; largeleaf, small, leafy, variableleaf, broadleaf, Richardson's, and flatstem pondweeds; narrowleaf pondweed (*Potamogeton strictifolius*); and tape-grass. He found 12 species of aquatic emergent and shoreline plants: swamp milkweed, sedges, common spikerush, water horsetail, Joe-Pye-weed, boneset, royal fern, water smartweed, hard-stem bulrush, chair maker's rush, common skullcap, and eastern marsh fern. Albert (1992) studied the aquatic macrophyte community of Bass Lake, but he did not establish plot sampling. He found 15 species in the lake. Fessell (2007) reported average macrophyte abundance, distributed in patches throughout the lake and with highest densities in cove areas. Beds are comprised chiefly of pondweed, muskgrass, white water lily, and coontail, while shoreline macrophytes include bulrush, sedges, and cattail.

Sixteen fish species have been collected from the lake. Kelly and Price (1979) found bluntnose minnow, black bullhead (*Ictalurus melas*), bluegill, largemouth bass, longear sunfish, pumpkinseed, rock bass, Iowa darter, Johnny darter, and yellow perch in Bass Lake. Fessell (2007) found all of the above species as well as Chinook and coho salmon, central mudminnow, northern pike, white sucker, and black crappie. Bluegill was the most common species (73%). Physical and chemical water quality data were collected at the time of the 2003 fish survey (Table 32).

Table 32. Physical and chemical water quality data for Bass Lake (Benzie), Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	11/4/03 surface	11/4/03 hypolimnion
Secchi disk (m)	3.6	--
DO saturation (%)	89.1	82.9
DO (mg/L)	10.0	9.3
pH	8.4	8.3
specific conductance (µS/cm)	283	380
total dissolved solids (g/L)	0.2	0.2
sulfate (SO_4) (mg/L)	0.9	0.9
nitrate nitrogen (NO_3-N) (mg/L)	0.13	0.13
ammonium nitrogen (NH_4-N) (mg/L)	0.19	0.2
true color (Pt-Co units)	11	9
total alkalinity (mg/L $CaCO_3$)	100	98
total hardness (mg/L $CaCO_3$)	148	148
calcium hardness (mg/L $CaCO_3$)	88	96
total phosphorus (TP) (µg/L)	9.47	--
chlorophyll-*a* phaeophytin corrected (µg/L)	20.56	--

Beck Pond

Beck Pond is an old human-made stock pond <1 ha in area, situated approximately 50 m north of Stormer Road and about 300 m east of Hwy M-22 in Leelanau County (Fessell 2007). It is spring-fed from a forest seep and has an outlet where it bleeds back into the forest (Murphy 2004a). The bottom is mainly organic muck and clay, and it has little aquatic vegetation except for sparse cattails and pondweeds. Only the white sucker and green sunfish were found in 2004, and the green sunfish were likely stocked (Fessell 2007). Physical and chemical water quality data were collected during the fish survey and are included in Table 33 (Murphy 2004a).

Table 33. Physical and chemical water quality data for Beck Pond, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	5/19/04
DO saturation (%)	60.2
DO (mg/L)	6.1
pH	7.9
specific conductance (μS/cm)	444
total dissolved solids (g/L)	0.3
sulfate (SO_4) (mg/L)	0.9
nitrate nitrogen (NO_3-N) (mg/L)	0.03
ammonium nitrogen (NH_4-N) (mg/L)	0.015
true color (Pt-Co units)	47
total alkalinity (mg/L $CaCO_3$)	140
total hardness (mg/L $CaCO_3$)	184
calcium hardness (mg/L $CaCO_3$)	134
total phosphorus (TP) (μg/L)	41.04

Deer Lake

Deer Lake is a very small (1.8-2.0 ha) spring fed pond (Murphy 2004a; MCGI 2006; Fessell 2007) and is the upper lake in the Otter Creek watershed (Figure 37). The average depth is 3.7 m and maximum depth is 6.7 m (Fessell 2007), deep for its size compared to other SLBE lakes. White cedar swamp borders it to the north and south, and upland hardwoods are found along both western and eastern shorelines. The shoreline has moderate complexity, with an abrupt bank and sharp dropoffs. The bottom substrates are soft marl and organic muck. Much of the lake’s water is likely input through groundwater along the southern shore (Fessell 2007). A short outlet channel connects Deer Lake with Bass Lake (Murphy 2004a). Beaver activity has heavily clogged this connection with downed trees (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Hazlett (1988) studied the macrophyte and shoreline vegetation of Deer Lake in 1986 and 1987. The lake usually has large mats of floating muskgrass, typical of lime lakes. He found the following 13 species of floating leaf and submerged aquatic vascular plants: elodea; water star-grass; common duckweed; twoleaf water-milfoil; variegated yellow pond lily; white water lily; largeleaf, floating, broadleaf, Richardson’s, and flatstem pondweeds; common bladderwort; and water-meal. He also found 10 species of aquatic emergent and shoreline plants: swamp milkweed, blue joint, sedges, common spikerush, Joe-Pye-weed, southern blue flag, royal fern, reed canary grass, duck-potato, and eastern marsh fern. Fessell (2007) also reported abundant macrophytes, consisting of beds of pondweed, muskgrass, white water lily, and coontail, and bulrushes, sedges, and cattails along the shoreline.

Eleven fish species have been collected from Deer Lake. Kelly and Price (1979) found northern pike, largemouth bass, and Iowa darter. Fessell (2007) did not report finding the Iowa darter, but did find eight additional fish records for the pond: blacknose shiner, bluntnose minnow, brown bullhead, black crappie, bluegill, pumpkinseed, rock bass, and yellow perch. Bluegill made up 83% of the numeric catch. Physical and chemical water quality data were collected at the time of the fish survey (Table 34; Murphy 2004a).

Table 34. Physical and chemical water quality data for Deer Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	7/12/04 surface	7/12/04 hypolimnion
Secchi disk (m)	4.3	--
DO saturation (%)	112.2	1.9
DO (mg/L)	9.6	0.2
pH	8.2	7.6
specific conductance (µS/cm)	287	404
total dissolved solids (g/L)	0.2	0.3
sulfate (SO_4) (mg/L)	3	1
nitrate nitrogen (NO_3-N) (mg/L)	0.02	0.02
ammonium nitrogen (NH_4-N) (mg/L)	0.015	0.015
true color (Pt-Co units)	48	43
total alkalinity (mg/L $CaCO_3$)	136	174
total hardness (mg/L $CaCO_3$)	140	170
calcium hardness (mg/L $CaCO_3$)	64	72
total phosphorus (TP) (µg/L)	10.17	--
chlorophyll-*a* phaeophytin corrected (µg/L)	0.99	--

Little Platte Lake

Little Platte Lake is located about 0.3 km north of Platte Lake. Its surface area is 325-363 ha (Canale et al. 2006; MCGI 2006), and its maximum depth is 2.4 m. About one-half of the flow of the North Branch of the Platte River passes through Little Platte Lake. SLBE owns 0.9 km of Little Platte Lake shoreline (Figure 37); just to the west is about 3.7 km of MDNR-owned wetland (Canale et al. 2006).

Little Platte Lake was not included in surveys of SLBE aquatic plants (Hazlett 1988) or fish (Kelly and Price 1979; Fessell 2007). Fessell (2007) did cite a 1981 MDNR study in which most aquatic vegetation observed was submerged and along the eastern shoreline. Twelve species of fish were found in the study; in order of numerical abundance, they were bluegill, pumpkinseed, brown bullhead, rock bass, white sucker, northern pike, largemouth bass, longnose gar (*Lepisosteus osseus*), yellow perch, tiger muskie (*Esox lucius* x *Esox masquinongy*), bowfin, and black crappie. Carp have also been observed.

Canale et al. (2006) compared water quality variables for Little Platte and Platte Lakes in 2005. Little Platte Lake is 4-6^{o}C warmer than Platte Lake during winter, which the authors attributed to groundwater inflows. TP in Little Platte Lake is about double that of Platte Lake (10-25 µg/L), and Little Platte Lake has more algal activity, leading to higher levels of chlorophyll and turbidity. The authors reported DO levels at or near saturation; however, Fessell (2007) indicated that Little Platte Lake may winterkill during severe winters.

Long Lake

Long Lake is 132-135 ha (MCGI 2006; Fessell 2007) and has a maximum depth of 6 m. The shoreline has limited complexity, with gentle slopes to the water's edge (Fessell 2007). Only a limited area on the northwest end of the lake is within SLBE's boundaries (Figure 37; Murphy 2004a). Approximately half of the shoreline is developed and has limited nearshore vegetation. Nearshore vegetated areas are dominated by bulrushes and scattered colonies of sedge and cattail, while backbays are mainly dominated by water lilies and duck-potato (Fessell 2007).

Kelly and Price (1979) did not survey the fish population of Long Lake; the most recent fishery survey before Fessell (2007) was performed by the MDNR in 1985. Fessell (2007) reported that the MDNR found mainly brown bullhead (62% of the total catch). Other species included golden shiner, northern pike, largemouth bass, smallmouth bass, bluegill, and pumpkinseed. Fessell (2007) found the same fish, although he found far fewer brown bullhead and golden shiner. In addition, he found bluntnose minnow, banded killifish, rock bass, Iowa darter, Johnny darter, logperch (*Percina caprodes*), and yellow perch. Physical and chemical water quality data were collected at the time of the fish survey (Table 35; Murphy 2004a).

Table 35. Physical and chemical water quality data for Long Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	9/9/04 surface
Secchi disk (m)	1.2
DO saturation (%)	108
DO (mg/L)	9.3
pH	8.7
specific conductance (µS/cm)	186
total dissolved solids (g/L)	0.1
sulfate (SO_4) (mg/L)	5
nitrate nitrogen (NO_3-N) (mg/L)	0.01
ammonium nitrogen (NH_4-N) (mg/L)	0.015
true color (Pt-Co units)	9
total alkalinity (mg/L $CaCO_3$)	100
total hardness (mg/L $CaCO_3$)	96
calcium hardness (mg/L $CaCO_3$)	52
total phosphorus (TP) (µg/L)	17.44
chlorophyll-*a* phaeophytin corrected (µg/L)	0.3

Loon Lake

Loon Lake has a surface area of 38 ha (MCGI 2006) and a maximum depth of 19 m (Elias 2007). The lake is a flow-through basin for the Platte River, which enters at the eastern end and drains from the northern end (Figure 37; Vana-Miller 2002; Fessell 2007). A small unnamed tributary stream also feeds the lake from the southwest. The lake basin is relatively steep, especially near the lake's eastern end, and a large larch peat bog is found along the west shoreline. The bottom substrates are sand, marl, and organic muck with areas of gravel along the eastern shoreline. The shoreline has moderate complexity (Fessell 2007). There is one home along the shoreline as well as a boat landing that allows recreational access (Whitman et al. 2002b; NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Stockwell and Gannon (1975) reported that Loon Lake had a mean depth of 9 m, a volume of $8.5x10^7$ m^3, and a fetch of 494 m. The southern end of the lake was the deepest (21 m), and the mean Secchi depth was 4 m. They constructed a bathymetric map of Loon Lake and calculated the “flushing” time as 12 days for the lake, which they thought important to the maintenance of good water quality. They found 29 species of rotifers and cladocerans and indicated that the zooplankton community was similar to that of Platte Lake. They suggested that based on the abundance of cladocerans and cyclopoid copepods, the lake was evolving to a eutrophic state.

Whitman et al. (2002b) described Loon Lake as a hard water lake with an elongate shape which tapers to a point at the northwest corner. They found that the shoreline dropped off steeply on the south and west ends of the lake. The lake sediments were fine silt and sand in the littoral zone and fine sediment in the profundal zone. The southwest corner was mostly a wetland, and wetlands occurred around the lake mixed in with wooded areas. The lake was dimictic and stratified from approximately late-May to mid-October during 1997 and 1998.

Whitman et al. (2002b) sampled Loon Lake for littoral and limnetic phytoplankton from June to September 1997 and for only limnetic phytoplankton from May to September 1998. Diatoms dominated in both years, making up 95-98% of the phytoplankton community in June and July 1997. Chlorophyta (green algae) usually made up only a small percentage of the phytoplankton community through the sampling period; however, in July 1998 they comprised 14%, and cryptomonads were generally fairly common. Total phytoplankton abundance generally increased throughout the growing season, and a total of 48 taxa were collected in 1998. The diatom *Cyclotella* sp. was the dominant taxa collected in their study, usually constituting over 50% of the entire community. *Chlorochromonas* spp. and *Synedra* spp. were also commonly collected. The growth dynamics of the phytoplankton community, and diatoms in particular, during 1998 suggested that late turnover, lower nutrient availability, or other factors were limiting growth. During 1997, chlorophyll-*a* exhibited fairly uniform levels throughout the season but increased sharply in September; however, in 1998 it was highest in May and decreased until September (Whitman et al. 2002b).

The zooplankton community in Loon Lake was dominated by rotifers (Whitman et al. 2002a). Zooplankton densities in 1997 peaked around 400 individuals/L in early July, largely due to *Conochilus unicornis*. In 1998, the greatest numbers occurred in May. *Keratella* sp. was more important, and *C. unicornis* was not as abundant. Overall limnetic zooplankton densities in 1998 were approximately half as high as in 1997. Zooplankton density in the littoral zone was generally lower than in the limnetic zone during all sampling periods, and *Keratella* sp. was the dominant taxon. Thirty-five zooplankton taxa were collected during the study, and the community similarity between the littoral and limnetic zone was only 66%. Common limnetic zooplankton included the cladoceran *Bosmina longirostris* and the copepod *Diacyclops thomasi*, and common limnetic rotifers included *C. unicornis*, *Kellicottia longispina*, *Keratella* spp., and *Polyarthra* spp. The authors concluded that Loon Lake had high zooplankton diversity.

Hazlett (1988) found six species of floating and submerged aquatic macrophytes in 1986 and 1987: coontail; Eurasian water-milfoil; variegated yellow pond lily; and curly leaf, floating, and broadleaf pondweeds. The emergent and shoreline vegetation included Joe-Pye-weed, boneset, cardinal flower, royal fern, eastern marsh fern, and sedges. Fessell (2007) reported moderate to heavy abundance of pondweed, muskgrass, water lily, elodea, and coontail, and colonies of bulrush, sedges, and cattail along shore. Purple loosestrife is also established at several points along the shoreline.

Whitman et al. (2002b) found higher macroinvertebrate densities in 1997 and 1998 in the profundal zone than in the littoral zone, although Margalef's and Shannon-Wiener diversity indices indicated that the littoral zone was more diverse in 1997. In 1997, the profundal benthic community was comprised mostly of *Chaoborus* sp. (45%) and tubificid worms (44%). In the littoral zone, the community consisted mostly of sphaeriid clams (60%) and chironomids (13%), and *Hexagenia* sp. mayflies were also commonly encountered. In 1998, chironomids dominated the littoral zone. Oligochaetes comprised more than 50% of the benthos collected in the profundal zone, and chironomids and chaobrids were also common.

Edsall (2001) developed a protocol for using burrowing mayflies (*Hexagenia*) to assess ecosystem health, and Edsall and Phillips (2004) used the protocol to assess the health and cultural eutrophication of Loon Lake and the lower Platte River ecosystem. The property owners on Platte Lake had initiated legal action to reduce the nutrient loading from the MDNR's Platte River State Fish Hatchery, which they believed was increasing algae blooms and reducing water clarity. Edsall and Phillips (2004) found that the DO concentration in Loon Lake was 7.3 mg/L at the surface and 0.6 mg/L at the bottom of the thermocline. *Hexagenia* nymphs were not found at depths of 9.2-12.8 m in Loon Lake; the authors attributed this to *Hexagenia*'s requirement for DO levels of 7.5 mg/L or higher. Nymphs were found only in mud and fine sand substrates to a depth not greater than 6.1 m in Loon Lake.

Edsall and Phillips (2004) cited the studies of Brown and Funk (1940) and Kelly and Price (1979) to describe changes in the historic fish communities in Loon Lake. DO loss in the deeper waters of Loon Lake has been occurring over the last 65 years; Brown and Funk (1940) reported that the deeper waters of Loon Lake had sufficient DO to support fish populations including cisco (lake herring) and trout, which have high oxygen requirements, but Kelly and Price (1979) found only warm-water fish species in Loon Lake. Edsall and Phillips (2004) further cited the studies of Whelan (1999), Whitman et al. (2002b), and McMacken (2003) to conclude that high algal production degraded water quality and caused lowered DO levels at depth in Loon and Platte Lakes during the summer stratified period. Citing an overall cultural eutrophication of the Platte River watershed, Edsall and Phillips (2004) indicated that there should be concern about the nutrient loading to these systems, and that the nutrient source is probably outside SLBE's boundaries. Loon Lake did not show obvious effects of eutrophication, which indicated that Platte Lake was probably trapping most of the nutrients.

Twenty-three fish species have been collected from Loon Lake from the 1970s to the present (Murphy 2004a). Kelly and Price (1979) reported finding shorthead redhorse (*Moxostoma macrolepidotum*), pumpkinseed, and rock bass in the lake. Fessell (2007) did not report finding the shorthead redhorse but did report 21 additional fish records for the lake: sea lamprey, longnose gar, bowfin, alewife, central mudminnow, northern pike, bluntnose minnow, common carp, common shiner, hornyhead chub, sand shiner, spottail shiner, white sucker, brown bullhead, bluegill, largemouth bass, smallmouth bass, Johnny darter, walleye, channel catfish (*Ictalurus punctatus*), and yellow perch.

Brown and Funk (1940) found a low DO level (0.4 mg/L) in the hypolimnion of Loon Lake during July and August. Whitman et al. (2002b) reported that Loon Lake was stratified from approximately late May through mid-October. The common vertical DO profile exhibited during the sampling periods was clinograde, and DO was reduced in the bottom layers. However, during June 1997 and May-June 1998, the profile was slightly orthograde. No DO was found in the deeper depths of Loon Lake in August and September 1998 and 1999. Elias (2007) also found an anoxic layer in the bottom 9-10 m below the thermocline.

Whitman et al. (2002b) did not find significant (P >0.09) differences in water chemistry variables between years or between the epilimnion and hypolimnion and littoral and limnetic zones. Phosphorus and nitrogen levels were generally below the detection limits, and ammonia was detected only on a few sampling dates. They concluded, based on water chemistry analyses they performed, that Loon Lake was in good condition. However, they reported that in 1977, elevated TP levels in the lake sediments (80-478 mg/L) and a high nitrogen/phosphorus ratio (31.5) (Wetzel 1975) indicated cultural eutrophication of Loon Lake, as did the low DO levels at depth. The anoxia of the lower water levels probably facilitates the mobilization of phosphorus from the sediments. This condition may lower the nitrogen/phosphorus ratio and favor production of blue-green algae. They cited the Platte River State Fish Hatchery as a source of phosphorus to the river and Loon Lake.

Elias (2007) found high concentrations of sodium (5.78 mg/L) compared to the other lakes she sampled in the park except for Round Lake, and indicated that the source might be road salt. Physical and chemical water quality data collected by Murphy (2004a), Elias (2007), and Elias and VanderMeulen (2008) are included as Table 36.

Mud Lake

Mud Lake has a surface area of 21.0-23.9 ha (Stockwell and Gannon 1975; Murphy 2004a; MCGI 2006) and a maximum depth of 0.6 m (Murphy 2004a). It is located approximately 1 km upstream from Loon Lake and drains to the Platte River via a very small stream (Figure 37). The north end of Mud Lake is surrounded by property owned by the MDNR, and is where the harvest weir for the lower Platte River is located. Murphy (2004a) found that the lake was spring fed and had an average depth of 0.2 m. Fessell (2007) noted temperature differences that indicated probable groundwater influence. The basin contains approximately 1 m of loosely consolidated FPOM, with a sandy bottom beneath (Fessell 2007). Stockwell and Gannon (1975) also indicated that the lake sediments were soft flocculent "silty muds" and partially decomposed plant material. The shoreline gently slopes to the water's edge and is limited in complexity (Fessell 2007).

Hazlett (1988) studied the macrophyte and shoreline vegetation of Mud Lake in 1986 and 1987. He also noted that the lake was shallow and had a sandy bottom with a suspension of black organic matter. The outlet of the lake passes though a white cedar swamp for a short distance. He found that floating and submerged aquatic macrophytes were rare except for a few variegated yellow pond lilies and white water lilies, bladderworts, pondweeds, and duck-potato. The 12 species of emergent and shoreline vegetation found were blue joint, twig-rush, bald spike rush (*Eleocharis erythropoda*), cinnamon fern, royal fern, *Sagittaria latiflora*, hard-stem bulrush,

Table 36. Physical and chemical water quality data for Loon Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a; Elias 2007; Elias and VanderMeulen 2008).

Parameter	2004 surface	2004 hypolimnion	2005 surface	2007 surface	2007 hypolimnion
Secchi disk (m)	3.3	--	3.2	4.3	--
DO saturation (%)	104.5	0.8	--	--	--
DO (mg/L)	8.7	0.1	--	9.1	--
dissolved organic carbon (DOC) (mg/L)	--	--	3.3-4.5	3.5	--
pH	8.5	7.7	8.4	8.4	--
specific conductance (µS/cm)	307	340	310	312	--
total dissolved solids (g/L)	0.2	0.2	--	--	--
sulfate (SO_4) (mg/L)	12	0.9	7.1-10.05	6	--
chloride (Cl-) (mg/L)	--	--	7.9	8.5	--
nitrate nitrogen (NO_3-N) (mg/L)	0.03	0.03	--	--	--
nitrate and nitrite nitrogen (NO_3+NO_2-N)	--	--	0.012-0.09	0.071	--
ammonium nitrogen (NH_4-N) (mg/L)	0.01	0.52	0.02	0.021	--
total kjeldahl nitrogen (TKN) (mg/L)	--		0.37	--	--
total nitrogen (TN) (mg/L)	--		0.22	0.249	--
true color (Pt-Co units)	18	20	--	--	--
total alkalinity (mg/L $CaCO_3$)	144	170	132.25	142	--
total hardness (mg/L $CaCO_3$)	206	162	--	--	--
calcium hardness (mg/L $CaCO_3$)	98	116	--	--	--
calcium (mg/L)	--	--	41.99	41.5	--
magnesium (mg/L)	--	--	12.42	12	--
potassium (mg/L)	--	--	0.66	0.67	--
sodium (mg/L)	--	--	5.78	10.7	--
SiO_2 (mg/L)	--	--	7.14-7.8	6.7	--
total phosphorus (TP) (µg/L)	10.07	17.48	10.68-45	6	14
chlorophyll-*a* (µg/L)	--	--	3.39	--	--
chlorophyll-*a* phaeophytin corrected (µg/L)	0.3	--	--	--	--

2004 data based on one sample (8/4/04); 2005 data average of 1-4 samples during summer season; 2007 data average of 1-3 samples during summer season

wool-grass, small bur-reed (*Sparganium minimum*), eastern marsh fern, marsh St. John's-wort, and common cattail. Stockwell and Gannon (1975) had earlier found that the vegetation surrounding Mud Lake was mostly swampy lowland vegetation with some woody species occurring along the southern border and suggested that the lake was in a late stage of hydrarch succession. Fessell (2007) reported that the shoreline was dominated by bulrush and sedge colonies, and that water lilies were abundant.

Thirteen fish species have been collected from Mud Lake (Fessell 2007). Kelly and Price (1979) found northern pike, bluntnose minnow, sand shiner, banded killifish, bluegill, largemouth bass, rock bass, smallmouth bass, and Johnny darter. Fessell (2007) did not find northern pike, bluntnose minnow, banded killifish, rock bass, smallmouth bass, or Johnny darter, but did find four additional fish species: central mudminnow, pumpkinseed, Iowa darter, and yellow perch.

Bluegill and pumpkinseed were most abundant in Fessell's (2007) study. He reported that because of the lake's proximity to the Platte River, its fish community may have significant temporal variation.

Stockwell and Gannon (1975) found that Mud Lake was less hard than either Loon or Platte Lakes. Alkalinity and specific conductance were >50% lower than other sites, and nutrients were also lower. They found 25 species of zooplankton in the lake. They suggested maintaining Mud Lake as a natural area but recommended construction of picnic grounds to increase the recreational value of the lake. Physical and chemical water quality data were collected at the time of Fessell's (2007) fish survey (Murphy 2004a) and are included inTable 37.

Table 37. Physical and chemical water quality data for Mud Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	7/28/04 surface
Secchi disk (m)	0.4
DO saturation (%)	119.1
DO (mg/L)	9.5
pH	8.6
specific conductance (µS/cm)	323
total dissolved solids (g/L)	0.2
sulfate (SO_4) (mg/L)	1
nitrate nitrogen (NO_3-N) (mg/L)	0.02
ammonium nitrogen (NH_4-N) (mg/L)	0.015
true color (Pt-Co units)	20
total alkalinity (mg/L $CaCO_3$)	144
total hardness (mg/L $CaCO_3$)	150
calcium hardness (mg/L $CaCO_3$)	114
total phosphorus (TP) (µg/L)	22.48
chlorophyll-*a* phaeophytin corrected (µg/L)	0.3

Otter Lake

Otter Lake is spring fed and is the lower and largest lake in the Otter Creek watershed, located approximately 3.3 km upstream of the mouth of Otter Creek (Figure 37; MCGI 2006; Fessell 2007). It has a surface area of 25.9 ha (MCGI 2006) and a maximum depth of 6.4 m (Murphy 2004a). The lake inlet is located along the south shore, and the outlet to Otter Creek is on the north shore, bordered by white cedar swamps. Both streams have intermittent beaver activity that affects the water levels of Otter Lake. The drainage to the west is principally upland hardwoods (Fessell 2007). A large spring is found off the northeast shore of the lake (Murphy 2004a). Handy and Stark (1984) found that the water level varied only about 0.15 m from May 1979 until January 1980, and that groundwater was the main water source. The lake has a soft marl bottom with bands of sand and gravel substrates and a shoreline of moderate complexity with an abrupt bank (Fessell 2007).

Hazlett (1988) studied the macrophyte and shoreline vegetation of Otter Lake in 1986 and 1987. He found large mats of floating muskgrass, typical of lime lakes, and 15 species of floating leaf and submerged aquatic vascular plants: twoleaf water-milfoil; nodding water-nymph; variegated yellow pond lily; white water lily; largeleaf, small, Fries', variableleaf, Illinois, floating, broadleaf, Richardson's, Robbins', and flatstem pondweeds; and tape-grass. He also found 13 species of aquatic emergent and shoreline plants: purple-stem beggar-ticks (*Bidens connata*), blue joint, northern reedgrass, water sedge, Joe-Pye-weed, boneset, spotted touch-me-not, ostrich fern, watercress (*Nasturtium officinale*), mad dog skullcap (*Scutellaria lateriflora*), hard-stem bulrush, eastern marsh fern, and common cattail. Albert (1992) also studied the aquatic macrophyte community of Otter Lake by establishing three sampling transects. He found a total of 35 species of aquatic macrophytes and an additional four species that did not occur along the pre-established transects. Most macrophyte species occurred along the shallow littoral shelf, but Illinois, floating, Richardson's, and flatstem pondweeds, nodding water-nymph, and variegated yellow pond lily occurred at deeper depths (60-200 cm). He also found a new population of state-threatened Hill's pondweed in shallow water zones. Fessell (2007) reported an average abundance of macrophytes in patches throughout the lake. Bed vegetation consisted chiefly of pondweed, muskgrass, and coontail, while shoreline macrophytes included bulrushes, sedges, and cattails.

Eighteen fish species have been collected from Otter Lake (Fessell 2007). Kelly and Price (1979) found the bluntnose minnow, common shiner, creek chub, sand shiner, white sucker, black crappie, largemouth bass, Johnny darter, and yellow perch. Fessell (2007) did not report finding the creek chub or sand shiner, but found nine additional species: coho salmon, northern pike, blacknose shiner, brown bullhead, banded killifish, bluegill, pumpkinseed, smallmouth bass, and Iowa darter. Physical and chemical water quality data collected during the most recent fish survey are included as Table 38 (Murphy 2004a)

Table 38. Physical and chemical water quality data for Otter Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	10/27/03 surface
Secchi disk (m)	4.8
DO saturation (profile) (%)	86-89
DO (profile) (mg/L)	9.4-9.8
pH (profile)	8.4-8.5
specific conductance (profile) (µS/cm)	248-252
total dissolved solids (profile) (g/L)	0.2
sulfate (SO_4) (mg/L)	10
nitrate nitrogen (NO_3-N) (mg/L)	0.13
ammonium nitrogen (NH_4-N) (mg/L)	0.17
true color (Pt-Co units)	8
total alkalinity (mg/L $CaCO_3$)	108
total hardness (mg/L $CaCO_3$)	150
calcium hardness (mg/L $CaCO_3$)	100
total phosphorus (TP) (µg/L)	5.41
chlorophyll-*a* phaeophytin corrected (µg/L)	4.31

Round Lake

Round Lake, one of the smaller and most southern lakes in SLBE (Figure 37) has a surface area of 6.1-6.2 ha (MCGI 2006; Fessell 2007), an average depth of 2-3 m (Fessell 2007), and a maximum depth of 8 m (Elias 2007). Substrates are primarily sand with some gravel along the north shore (Fessell 2007). Conflicting reports are given about the surrounding terrain. Whitman et al. (2002b) reported that Round Lake was positioned fairly flat on the landscape, without steeply sloping shores. Fessell (2007) reported an abrupt bank along the southern shoreline and relatively steep land containing upland hardwoods and conifers to the north. Murphy (2004a) reported that the lake was enclosed by a large wetland. All agreed that the southern end of the lake was a wetland; Whitman et al. (2002b) described it as marshy, while Murphy (2004a) reported a bog, and Fessell (2007) reported a 13 ha cattail marsh bordered by white cedar swamp.

Round Lake is the only SLBE lake that is part of the Crystal Lake watershed. A small 462 m long tributary stream flowing southward through a marsh is the outlet that connects Round Lake to Crystal Lake (Whitman et al. 2002b). Round Lake receives input from a small stream to the southwest (Fessell 2007). Motors are prohibited in Round Lake and access is generally limited to canoes and small boats (Fessell 2007).

Whitman et al. (2002b) found that diatoms were the dominant phytoplankton collected throughout 1998 and were most dominant in July (89%). Blue green algae (Cyanophyta) were generally poorly represented, but they increased to 10% of the total in September. Phytoplankton density increased from May to July and then decreased through the remainder of the season. Peak density occurred in July, and 35 different phytoplankton species were collected through 1998. Common algal species collected included *Cyclotella* sp., *Synedra* sp., *Chlorochromonas* sp., and *Chroococcus* sp. Phytoplankton densities in May 1999 were similar to those in May 1998. Chlorophyll-*a* levels in the epilimnion were fairly uniform (5-9 mg/L) throughout the summer of 1998 but peaked sharply in July (15 mg/L) and decreased in August.

Whitman et al. (2002a) sampled the limnetic zooplankton community and found a mean density of 189 ± 50 individuals/L during the summer. The peak density occurred in May (400 individuals/L). They collected a total of 31 taxa, dominated by rotifers (Rotifera) and *Keratella* sp. The second most abundant zooplankton were the cyclopoid copepods, with *Tropocyclops prasinus mexicanus* being the most common. The zooplankton community of Round Lake was typical of the region.

Hazlett (1988) in 1986 and 1987 found that the lake had a marl bottom, and identified 10 species of floating and submerged aquatic macrophytes: shortspike water-milfoil; nodding water-nymph; variegated yellow pond lily; white water lily; largeleaf, Fries', Illinois, and broadleaf pondweeds; common bladderwort; and lesser bladderwort (*Utricularia minor*). The emergent and shoreline vegetation included nine species: marsh bellflower (*Campanula aparinoides*), Joe-Pye-weed, boneset, sedges, twig-rush, rushes, hard-stem bulrush, chair maker's rush, and common cattail. A floating sedge mat on Round Lake's south side included swamp milkweed, blue joint, marsh bellflower, water-hemlock, twig-rush, sundew, elliptic spikerush, thinleaf cottonsedge, Joe-Pye-weed, boneset, rushes, Ontario lobelia, northern bugleweed, buckbean, royal fern, reed, marsh cinquefoil, hard-stem bulrush, hooded lady's-tresses (*Spiranthes romanzoffiana*), eastern marsh fern, marsh St. John's-wort, common cattail, and sweet white violet. Woody species scattered across the sedge mat and around its outer edges include white birch, bog birch (*Betula pumila*), silky dogwood, red-osier dogwood (*Cornus sericea* ssp. *sericea*), swamp loosestrife, sweet gale (*Myrica gale*), white pine (*Pinus strobus*), swamp rose, sage willow (*Salix candida*), pussy willow, and white cedar (Hazlett 1988). Fessell (2007) reported that bulrushes, sedges, reeds, and cattails dominated the shoreline, water lilies dominated the littoral zone along the south shore, and pondweed and muskgrass were moderately abundant.

Whitman et al. (2002b) found significantly higher macroinvertebrate densities in the littoral zone than the profundal zone. Margalef's and Shannon-Wiener indices indicated that diversity was much higher in the littoral than in the limnetic zone. Gastropoda (snails) was the most dominant macroinvertebrate collected in the littoral zone, but chironomids (Diptera) were also very common. Diptera, including Chaoboridae, Chironomidae and Ceratopogonidae, dominated the profundal zone.

Fifteen fish species have been found from the lake. Kelly and Price (1979) found nine species: blacknose shiner, bluntnose minnow, golden shiner, sand shiner, white sucker, banded killifish, largemouth bass, Johnny darter, and yellow perch. Fessell (2007) did not find the blacknose shiner and golden shiner, but did find six additional species: fathead minnow, bluegill, pumpkinseed, rock bass, Iowa darter, and smallmouth bass. Sand shiner made up 46% of the total catch.

Whitman et al. (2002b) stated that Round Lake was an alkaline, hard water, clear lake with a mean Secchi depth of 3.2 m between April and September 1998. Further, it was a typical northern dimictic lake that stratified during the summer months (by May in 1997 and 1998). They found low nutrient levels, with nitrate, nitrite, ammonia, and TP generally below the detection limits. They suggested that Round Lake was oligotrophic or slightly mesotrophic. Elias (2007) found that Round Lake had the highest concentrations of chloride (15.1 mg/L) and sodium (12.04 mg/L) of the nine lakes she sampled in the park. She indicated that these high levels might be due to the close proximity of the lake to Hwy M-22, which receives road salt. Elias (2007) found that this lake was the only one of the nine that consistently had Secchi depths greater than the USEPA reference criteria of 3.2 m. Physical and chemical water quality data collected by Murphy (2004a), Elias (2007), and Elias and VanderMeulen (2008) are included as Table 39.

Rush Lake

Rush Lake, located outside SLBE's boundaries, is approximately 300 m east of Long Lake (Figure 37; Fessell 2007). Approximately 600 m of shoreline at the lake's west end is bordered by the SLBE Benzie Corridor, and is currently in private ownership. The lake has a surface area of 48 ha (MCGI 2006) but it is probably best considered a large interdunal pond, as it is shallow and largely surrounded by white cedar swamps (Vana-Miller 2002; Fessell 2007). There are two private residences on the lake (Vana-Miller 2002). Kelly and Price (1979) reported that Rush Lake contained northern pike, golden shiner, bluegill, pumpkinseed, and Iowa darter.

Taylor Lake

Taylor Lake is a small depression located approximately 350 m east of Hwy M-22 and about 0.6 km north of Stormer Road in Leelanau County (Figure 37; Fessell 2007). It has a surface area of 1.3 ha (MCGI 2006) and an average depth of 2 m (Fessell 2007). The drainage is rolling upland hardwoods. It is largely supplied by surface water, but has no evident surface inlets; an outlet occurs at the southern end. The bottom is mainly organic muck, sand, and clay (Fessell 2007).

Table 39. Physical and chemical water quality data for Round Lake, Sleeping Bear Dunes National Lakeshore (Murphy 2004a; Elias 2007; Elias and VanderMeulen 2008).

Parameter	2004 surface	2004 hypolimnion	2005 surface	2007 surface	2007 hypolimnion
Secchi disk (m)	3.7	--	4.6	3.8	--
DO saturation (%)	117.4	2.5	--	--	--
DO (mg/L)	8.7	0.2	--	8.5	--
dissolved organic carbon (DOC) (mg/L)	--	--	7.2-7.7	7.3	--
pH	8.7	7.1	8.7	8.7	--
specific conductance (µS/cm)	324	686	319	320	--
total dissolved solids (g/L)	0.2	0.4	--	--	--
sulfate (SO_4) (mg/L)	3	0.9	7.2-9.67	9.63	--
chloride (Cl-) (mg/L)	--	--	15.1-18.25	20.6	--
nitrate nitrogen (NO_3-N) (mg/L)	0.02	0.02	--	--	--
nitrate and nitrite nitrogen (NO_3+NO_2-N)	--	--	0.0045-0.007	0.013	--
ammonium nitrogen (NH_4-N) (mg/L)	0.015	0.015	0.05	0.047	--
total kjeldahl nitrogen (TKN) (mg/L)	--	--	0.695	--	--
total nitrogen (TN) (mg/L)	--	--	0.56	0.697	--
true color (Pt-Co units)	10	11	--	--	--
total alkalinity (mg/L $CaCO_3$)	136	126	129.5	130	--
total hardness (mg/L $CaCO_3$)	134	144	--	--	--
calcium hardness (mg/L $CaCO_3$)	80	84	--	--	--
calcium (mg/L)	--	--	29.62	33	--
magnesium (mg/L)	--	--	15.91	16.2	--
potassium (mg/L)	--	--	0.59	0.67	--
sodium (mg/L)	--	--	12.04	14	--
SiO_2 (mg/L)	--	--	5.7-6.72	1.4	--
total phosphorus (TP) (µg/L)	15.53	--	10.87-45	11	14
chlorophyll-*a* (µg/L)	--	--	3.88	1.8	--
chlorophyll-*a* phaeophytin corrected (µg/L)	0.3	--	--	--	--

2004 data based on one sample (7/26/04); 2005 data average of 1-4 samples during summer season; 2007 data average of 1-3 samples during summer season

Hazlett (1988) in 1986 and 1987 reported a floating sedge mat that was ringed with an open moat. In the moat he found water-shield, common duckweed, variegated yellow pond lily, white water lily, water smartweed, and floating pondweed. He also found six sedges and 14 other species of aquatic plants on the mat. Fessell (2007) described the central part of the lake as being dominated by a floating mat of a sphagnum moss (*Sphagnum magellanicum*), and noted a diverse plant community including water smartweed, tape-grass, water lily, and cattails. This lake was surveyed for fish, but none were found (Fessell 2007), probably because it is a very shallow lake with low pH and alkalinity (Murphy 2004a).

Unnamed Lakes
A total of 76 unnamed lakes/ponds/depressions are found within the Mainland-South Unit, with a total surface area of 25.5 ha (Figure 37; MCGI 2006). No surveys of these systems were found.

Otter Creek and Watershed
The Otter Creek watershed within SLBE includes Otter Creek and the lakes it flows through, Deer, Bass (Benzie), and Otter Lakes. Otter Creek is a third order stream that occurs totally within SLBE boundaries (Figure 37; Vana-Miller 2002). The total length is 3.7 km (MCGI 2006).

Otter Creek is somewhat unique among SLBE streams in having many springs and seeps. Groundwater is the main source of water for both Otter Lake and Otter Creek, and the amount of groundwater inflow determines the flow of Otter Creek during low flow periods (Handy and Stark 1984). The springs originate east and north of the Otter Creek lakes, probably from groundwater flow in the old Glen Lake glacial drainage (Vana-Miller 2002). The springs and seeps cause Otter Creek's temperatures to be generally lower than in other lotic systems in SLBE (Linton 1987).

Deer Lake forms the headwaters of Otter Creek, and a 0.03 km stretch connects it to Bass Lake. The upper reach of Otter Creek (0.37 km) connects Bass and Otter Lakes, and the lower reach is the outlet for Otter Lake (Murphy 2004a). The Otter Creek outflow from Otter Lake begins on the lake's north side. It has a northerly flow through a white cedar swamp and then enters an open marsh. Cedar swamps border the stream for most of its length. The creek receives water from several smaller spring-fed tributaries, including Aral Springs, which is the largest (Hazlett 1988). At the lower end, the creek flows through a large wetland before flowing into Lake Michigan. An ephemeral oxbow or vernal pond near the mouth of the creek not far from Lake Michigan is of concern due to frequently high *E. coli* levels (Murphy 2004a; McMahon 2007).

Hazlett (1988) found the macrophyte and shoreline vegetation of Otter Creek to be among the most diverse in SLBE. He found an extensive growth of sedges in the section of the river north of the marsh and 11 submerged and floating aquatic vascular plants in 1986 and 1987: water star-grass; mare's-tail; common duckweed; twoleaf water-milfoil; variegated yellow pond lily; Fries', floating, broadleaf, and Richardson's pondweeds; white water crowfoot; and common bladderwort. Emergent and shoreline herbs along the creek include blue joint, marsh marigold, marsh bellflower, sedges, reed canary grass, water dock, duck-potato, hard-stem bulrush, bur-reeds, and eastern marsh fern. Otter Creek is the only place where mare's-tail was found in SLBE, and it is the only mainland location for white water crowfoot (Hazlett 1988). Characteristic shoreline shrubs include speckled alder, chokeberry, red-osier dogwood, swamp loosestrife, sweet gale, swamp rose, and sage willow.

A sedge mat on Otter Creek contains some bladderwort species, as well as marsh cinquefoil, hard-stem bulrush, and common cattail. Scattered shrubs around the edge of the mat are speckled alders, sweet gale, swamp rose, and willows. Along the creek's edge upstream of the sedge mat, bog species such as larch, pitcher-plant (*Sarracenia purpurea*), and sundew are found (Hazlett 1988). A white cedar swamp on the west side of Otter Creek near the wooded dunes includes balsam fir (*Abies balsamea*), white birch, white pine, and larch, with a herbaceous understory of jack-in-the-pulpit (*Arisaema triphyllum*), lady fern (*Athyrium filix-femina*), rattlesnake fern (*Botrychium virginianum*), sedges, dwarf enchanter's-nightshade (*Circaea alpina*), blue bead-lily (*Clintonia borealis*), goldthread (*Coptis trifolia*), striped coralroot (*Corallorhiza striata*), early coralroot (*C. trifida*), bunchberry (*Cornus canadensis*), bladder fern (*Cystopteris bulbifera*), crested shield fern (*Dryopteris cristata*), wild strawberry (*Fragaria virginiana*), creeping snowberry (*Gaultheria hispidula*), purple avens (*Geum rivale*), oak fern (*Gymnocarpium dryopteris*), blunt leaved orchid (*Platanthera obtusata*), twinflower (*Linnaea borealis*), Canada mayflower (*Maianthemum canadense*), partridgeberry (*Mitchella repens*), naked miterwort (*Mitella nuda*), cinnamon fern, royal fern, fringed polygala (*Polygala paucifolia*), eastern marsh fern, American starflower (*Trientalis borealis*), velvet-leaf blueberry, and sweet white violet. A fen-like area within this white cedar swamp provides habitat for bog-rosemary, leather-leaf, spikerush, bog candle (*Platanthera dilatata*), buckbean, white water lily, shrubby cinquefoil (*Dasiphora fruticosa* ssp. *floribunda*), pitcher-plant, three-leaf Solomon's seal (*Maianthemum trifolium*), and horned bladderwort. On the east side of the creek, the vegetation of the Aral Springs area around the cold springs includes a few species not found on the west side including golden saxifrage, yellow monkey-flower (*Mimulus glabratus* var. *jamesii*), and cutleaf waterparsnip, a state-threatened species.

Albert (1992) also studied the aquatic macrophyte community of Otter Creek. He established three transects and found a total of 56 species of aquatic macrophytes, including yellow monkey-flower near the headwaters of Otter Creek and the state-threatened cutleaf waterparsnip.

Thirteen fish species have been collected from upper Otter Creek: central mudminnow, blacknose shiner, bluntnose minnow, common shiner, creek chub, white sucker, brook stickleback, bluegill, largemouth bass, pumpkinseed, rock bass, Iowa darter, and yellow perch (Fessell 2007). Twenty-two fish species have been collected from lower Otter Creek, including all those from the upper creek except for the Iowa darter, and adding the northern pike, brook trout, blacknose dace, hornyhead chub, longnose dace, sand shiner, spottail shiner, banded killifish, mottled sculpin, and smallmouth bass (Fessell 2007). The USFWS has also reported finding coho salmon in Otter Creek in some of its surveys conducted since 1960 (Fessell 2007).

Handy and Stark (1984) reported the water quality in Otter Lake and Otter Creek was "excellent" from 1979-1981. White (1987) studied the macroinvertebrate populations of Otter Creek and stated that the stream did not have problems with eutrophication or physical disturbance. Physical and chemical water quality data collected at the time of the 2003 fishery survey are included as Table 40.

Platte River

The Platte River watershed is the largest and most studied watershed within SLBE (Boyle and Hoefs 1993a). The geologic features of the Platte River watershed include outwash and glacial channels, rolling and high moraines and lakes, and old lake beds (Martin 1955 in Boyle and Hoefs 1993a). The total river length is 97 km, but only 7.5 km (7%) occurs within the boundaries of SLBE (MCGI 2006). The Platte River is a fifth order stream (Vana-Miller 2002) with a watershed of 498 km^2, approximately 32 km^2 of which is within SLBE (MCGI 2006). Most of the river occurs within Benzie County (Vana-Miller 2002). The Platte River has the greatest flow

Table 40. Physical and chemical water quality data for Otter Creek, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	7/14/2003
DO saturation (%)	136.7
DO (mg/L)	11.3
pH	8.6
specific conductance (µS/cm)	338
total dissolved solids (g/L)	0.2
sulfate (SO_4) (mg/L)	16
nitrate nitrogen (NO_3-N) (mg/L)	0.02
ammonium nitrogen (NH_4-N) (mg/L)	0.37
true color (Pt-Co units)	3
total alkalinity (mg/L $CaCO_3$)	108
total hardness (mg/L $CaCO_3$)	184
calcium hardness (mg/L $CaCO_3$)	128
total phosphorus (TP) (µg/L)	10.65
chlorophyll-*a* (µg/L)	3.4
chlorophyll-*a* phaeophytin corrected (µg/L)	0.71

of SLBE streams (Handy and Stark 1984). Linton (1978) found that the percentage of riffles/total stream length was 0.5%, and the largest percentage of river length was runs (78.9%).

The Platte River receives water from the North Branch of the Platte River and Carter and Brundage Creeks (Boyle and Hoefs 1993a). The tributary streams encompass approximately 48.3 km of stream length. Little Platte, Platte, Long, Loon, Mud, and Rush Lakes also provide drainage directly or indirectly to the Platte River (Stockwell and Gannon 1975). Handy and Stark (1984) stated that springs and seeps provided most of the water to the river, and Boyle and Hoefs (1993a) also indicated that groundwater was an important water source. Within SLBE boundaries, the Platte River begins just west of the outflow of Platte Lake, flows through Loon Lake, and receives water from the Mud Lake outflow before draining into Lake Michigan (Figure 37; Boyle and Hoefs 1993a). The distance from the lowest lake, Loon Lake, to Lake Michigan is about 4.8 km (MCGI 2006). At the river's mouth, a long beach bar causes the river to bend sharply to the east (Figure 41; Vana-Miller 2002). The river drops 65 m between Lake Ann and Lake Michigan (Kenaga and Evans 1982).

Swimming is popular at the mouth from Memorial Day to Labor Day. The use of the lower river is mainly kayaking and canoeing during the summer months (Vana-Miller 2002). At the Hwy M-22 bridge there is a canoe rental service for trips down the Platte River to the mouth. At the mouth, a park operated by Lake Township is heavily used as a boat launch and take-out. Fishing is mainly concentrated in the spring for steelhead, and in September and October for coho and king salmon, but the fall season is the most heavily fished (Vana-Miller 2002). The mouth of the Platte River is dredged by SLBE in September, starting the day after Labor Day, to provide boating access to Lake Michigan for the fall salmon run.

Figure 41. Mouth of the Platte River, Sleeping Bear Dunes National Lakeshore. Signs indicate piping plover nesting area (photo by D. Mechenich).

The state of Michigan operates the Platte River State Fish Hatchery, and its presence has led to conflicts with downstream property owners about the hatchery discharge's water quality as well as water flow volumes. Many of the studies done on the Platte River have been generated by, or have commented on, the hatchery's effects on the Platte River ecosystem. One such study sampled the sediments of Brundage Creek, the Platte River (outside SLBE boundaries), the Platte River State Fish Hatchery waste ponds, and Platte Lake on October 30, 1979 to evaluate the high levels of heavy metals found by Grant (1979) in 1976 (Kenaga 1980). The hatchery did not cause elevated levels of heavy metals in the Platte River. However, zinc and copper in the hatchery waste treatment sediments in the shot pond exceeded the USEPA's 1977 "moderately polluted" dredge spoil criteria. Lead exceeded the USEPA "moderately polluted" dredge spoil criterion in the aeration lagoon. Sediment samples from Platte Lake did not have the high values for chromium, copper, nickel, lead and zinc that Grant (1979) reported. All metals were found to be in the USEPA "non-polluted" dredge spoil category except for manganese, which was in the USEPA "heavily polluted" range in Brundage Creek, the supply water source for the hatchery. All metal concentrations in the Platte River downstream of the hatchery were comparable to concentrations upstream (Kenaga 1980).

Stream discharge was measured from 1971-1982 by Handy and Stark (1984) and from 1990-1992 by Boyle and Hoefs (1993a). A USGS gaging station started operation on the Platte River 0.6 km west of Honor, Michigan in March 1990 as a result of a court case brought by the Platte Lake Improvement Association against the State of Michigan. The mean discharge of the Platte River from 1990-2007 was 3.5 m^3sec^{-1} with a mean annual maximum and minimum discharge of

4.2 m^3sec^{-1} and 2.9 m^3sec^{-1}, respectively. From 1990-2007 the highest mean monthly discharge of 3.9 m^3sec^{-1} was in April and the lowest mean monthly discharge of 3.3 m^3sec^{-1} was in August. The highest daily mean discharge of 10.9 m^3sec^{-1} occurred on October 25, 1991, and the lowest daily mean of 2.5 m^3sec^{-1} occurred on July 17, 2000.

According to Poff's (1996) classification system, the Platte River, as well as the Crystal River and Otter and Shalda Creeks, are either Stable Groundwater or Superstable Groundwater streams (Vana-Miller 2002). The Platte River has high flow stability, low susceptibility to drying due to the significant groundwater input, and low flow variability (low coefficient of variation of daily flows). Vana-Miller (2002) stated that based on the high flow stability of the Platte River, the biotic communities are probably more controlled by biologic processes within the stream than by environmental variability.

Stockwell and Gannon (1975) sampled eight sites on the lower Platte River and measured DO, alkalinity, pH, chloride, TP, soluble reactive phosphorus, magnesium, sodium, calcium, potassium, nitrate-N, ammonia-N, and silica. DO was at near saturation at all sites, and pH varied from 8.2-8.6. They reported that Platte Lake served as a phosphorus and nitrogen sink. Zooplankton, phytoplankton, and chlorophyll-*a* were also evaluated. Chlorophyll-*a* levels were moderate (2.15-21.07 mg/L). The zooplankton and phytoplankton communities were thought to be leakages from Platte and Loon Lakes. They stated that the water quality of the Platte River was dependent on the water quality of Platte Lake and suggested that the Park Service monitor the water quality of Platte Lake on a regular basis (Stockwell and Gannon 1975).

Hildebrand (1971) studied the benthos of the Platte River and found 36 different taxa with good populations of Trichoptera and Ephemeroptera that generally indicated "good" water quality. Taube (1974) collected 34 species of fish in the Platte River from 1967-1972, with trout and salmon commonly collected. Kenaga and Evans (1982) stated that the Platte River had good trout populations. They noted that the village of Honor was the only highly developed area along the course of the river, but that the shoreline of Platte Lake was mostly privately owned and developed. They found that the Platte River's resident fish community had changed very little from 1940-1982, and the benthic macroinvertebrate community had also remained unchanged from 1970-1982.

White (1987) found abundant aquatic macrophytes along the lower reaches of the Platte River as well as near the outflows of Platte and Loon Lakes. These macrophytes reduce carbon dioxide and promote marl deposition in the river. The predominant macroinvertebrates below the lake outflows were filter feeders such as caddisflies that capitalize on nutrients and the seston outflowing from the lakes. In the middle reaches of the Platte River below the lakes, marl deposition was greatly reduced, as was macrophyte biomass. There, the trophic guilds of aquatic macroinvertebrates were mainly gatherers and scrapers, indicating an increase in periphyton and a decrease in marl deposition. White found few macrophytes and macroinvertebrates at the river mouth and reduced marl deposition.

Hazlett (1988) found 20 species of floating and submerged aquatic plants in 1986 and 1987: coontail; elodea; water star-grass; common duckweed; water-marigold; shortspike water-milfoil; Eurasian water-milfoil; nodding water-nymph; variegated yellow pond lily; white water lily;

Polygonum amplifolius; Fries', variableleaf, Illinois, floating, broadleaf, Richardson's, and flatstem pondweeds; bladderworts; and tape-grass. The shoreline herbs included marsh marigold, sedges, turtle-head (*Chelone glabra*), spikerushes, southern blue flag, tufted loosestrife, purple loosestrife, royal fern, reed canary grass, marsh cinquefoil, hard-stem bulrush, deadly nightshade, bur-reeds, eastern marsh fern, and common cattail. He stated that the shoreline vegetation of the Platte River near its mouth was much reduced compared to 40 years prior, when the marginal vegetation greatly encroached near the center of the river and grassy meadows were common. He attributed these changes to both increased boat and canoe traffic and increased water level in the river, but he felt that the increased water level was probably the most important. Albert (1992) also studied the aquatic macrophyte community of the Platte River. He established seven transects and found a total of 62 species.

Fessell (2007) noted that the portion of the Platte River within SLBE was classified as coolwater and inhabited by warmwater to coolwater fish species such as rock bass and river minnows, with seasonal migrations of salmonids including steelhead, brown trout, coho, and Chinook salmon. He cited Kelly and Price's (1979) observation that the Platte River has SLBE's most diverse fish assembly, and related it to the unique temperature regime caused by being both lake and groundwater-fed. Kelly and Price (1979) noted that four native species of lampreys were found in the Platte River and Lakes by USFWS crews: chestnut lamprey (*Ichthyomyzon castaneus*), northern brook lamprey (*I. fossor*), silver lamprey (*I. unicuspis*), and American brook lamprey. They also noted that some fish in the Platte River and Lakes were found in no other SLBE watersheds: longnose gar, bowfin, common carp, muskellunge, silver redhorse (*Moxistoma anisurum*), shorthead redhorse, and lake chub (*Couesius plumbeus*).

A 2000 Clean Water Act funding grant was used to begin developing a watershed management plan for the Platte River over a two year period (MDEQ 2007j). Problems with road crossings and stormwater runoff were identified in 2002, resulting in the upgrades of four crossings, identification of priority landowners within the Land Protection Program, and a public education program. Aquatic macroinvertebrates were sampled at five sites in 2003, and all five were rated as "acceptable" based on macroinvertebrate community (MC) scores of 0 to +3. The rating indicated that the Platte River was meeting established water quality standards. Changes occurred in the relative abundance of some taxa between 1998 and 2003, but not outside the range of expected annual variations, and, in general, more taxa were found in 2003 than in 1998. Habitat assessments were completed at their five sampling locations, and observations were made at nine other locations. Habitat quality varied from "good" to "excellent" at their five sites, similar to Walker's (1999) findings.

Water chemistry samples were taken at ten sampling stations, five of which had been previously sampled by Walker (1999). Most parameters varied from below reliable detection limits to low concentrations. Nutrients were low at all stations except station 7 and below the village of Honor, where higher levels of nitrate/nitrite-N were found. Higher levels of ammonia were found below the Platte River State Fish Hatchery compared to above it. Stream bank erosion problems due to poorly constructed or maintained road crossings were noted but not reflected in the habitat assessments or macroinvertebrate community analyses. They concluded that based on the MC, habitat conditions, and water chemistry, water quality standards were met at all their stations (MDEQ 2007j).

Unnamed Streams

Very little is known about the unnamed streams in the Mainland-South Unit. The combined length of these short streams is 3.15 km (MCGI 2006). The individual lengths of the unnamed streams are as follows: southwest tributary to the Platte River (a large swale that may be in part human-made)-1.53 km, stream connecting Mud Lake to the Platte River-0.18 km, tributary stream to Loon Lake-0.32 km, stream connecting Round and Crystal Lakes-0.30 km, tributary stream to Rush Lake-0.41 km, and intermittent streams-0.42 km (Figure 37; MCGI 2006).

Aral Springs

The Aral Springs are a collection of at least 13 marl groundwater discharge springs and seeps that emerge from a white cedar swamp along Otter Creek and supply water to Otter Creek and Otter Lake (Murphy 2004a; Fessell 2007). They result in one of the most rare wetland types in North America, the calcareous fen.

Hazlett (1991) reported golden saxifrage, cutleaf waterparsnip, and yellow monkey-flower in the Aral Springs area. Observed aquatic vegetation has also included muskgrass, water-parsnip, and elodea (Fessell 2007). Heuschele (1999) reported working on an on-going survey of the aquatic macroinvertebrates of Aral Springs. Fessell (2007) found five fish species: brook trout (*Salvelinus fontinalis*), central mudminnow, brook stickleback, mottled sculpin, and yellow perch in the springs. Physical and chemical water quality data were collected from spring C3 during the fishery survey and are included as Table 41 (Murphy 2004a).

Table 41. Physical and chemical water quality data for Aral Spring C3, Sleeping Bear Dunes National Lakeshore (Murphy 2004a).

Parameter	5/19/04
DO saturation (%)	80
DO (mg/L)	8.81
pH	7.8
specific conductance (µS/cm)	345
total dissolved solids (g/L)	0.2
sulfate (SO_4) (mg/L)	2
nitrate nitrogen (NO_3-N) (mg/L)	2
ammonium nitrogen (NH_4-N) (mg/L)	0.03
true color (Pt-Co units)	13
total alkalinity (mg/L $CaCO_3$)	166
total hardness (mg/L $CaCO_3$)	144
calcium hardness (mg/L $CaCO_3$)	120

Wetlands

The Mainland-South Unit of SLBE contains over half of the park's wetlands. The 97.9 ha of open water include Otter, Bass (Benzie), Deer, Mud, Loon, Round, and Taylor Lakes as well as a few unnamed lakes (Table 17, Figure 37). Areas of aquatic bed (61.4 ha) occur on Round Lake and interspersed with lowland conifer areas southeast of Platte Bay, and areas of emergent wetlands (26.8 ha) occur in those two locations, along Lake Michigan south of Platte Bay, and along Otter Creek, Taylor Lake, and a few other scattered locations. Other wetlands in the Mainland-South Unit are 431 ha of lowland conifers, 536 ha of lowland hardwoods, 400 ha of lowland mixed forest, 143 ha of shrub/scrub, and 10 ha of other wooded lowlands. Two hundred thirty-nine ha of wetlands were identified by soils alone.

Coastal pools (areas of open water) and dune pannes (low, moist sites) are scattered throughout SLBE, but are most common on the open dunes of Platte Bay at SLBE's southern end (Hazlett 1988). They also occur east of Sleeping Bear Point, along Good Harbor Bay, and on South Manitou Island at Sandy Point. Their vegetation is predominantly herbaceous, with sedges, spikerushes, and rushes as dominants. Other common herbs include mat panic grass (*Dichanthelium acuminatum* var. *fasciculatum*), balsam groundsel, Ontario lobelia, and white camus (*Zigadenus glaucus*).

Groundwater

Groundwater is important to SLBE aquatic ecology because it is connected to the park's springs, lakes, and other surface waters (Ozaki 2001). In the SLBE vicinity, a glacial aquifer consists of sand and gravel deposits 150-270 m thick (Handy and Stark 1984). Ninety-seven percent of Benzie County wells and 94% of Leelanau County wells use the glacial aquifer as a water source (Apple and Reeves 2007). The Traverse Group, consisting primarily of fossiliferous limestone, underlies the glacial aquifer in all of SLBE, including the islands. One percent of wells in Leelanau County and less than one percent in Benzie County are known to use the Traverse Group as an aquifer (Apple and Reeves 2007).

The potential yield of the glacial aquifer within SLBE can be estimated from specific capacity, which varies from <0.2 to 10 L sec^{-1} m^{-1} (Handy and Stark 1984). Areas within and near SLBE with the greatest specific capacities (as identified by Handy and Stark 1984) are north and northeast of Lime Lake, east of Empire, west of Armstrong Lake, southeast of Glen Lake, northeast of Glen Arbor, and northeast of Otter Lake (Apple and Reeves 2007).

We delineated SLBE's glacial groundwater basins using the watershed tool in ArcGIS 9.2 software (ESRI 2006) and the water table grid maps for Benzie, Leelanau, and Grand Traverse Counties (Michigan Groundwater Inventory and Mapping Project 2005a, b). In SLBE's Mainland-North and Mainland-Central Units, the groundwater divide generally follows the surface water watershed but is offset slightly to the west (Figure 42). In the Mainland-South Unit, the Platte River watershed and groundwater basin generally coincide, except that the part of the Platte River watershed east of Long Lake is not part of SLBE's groundwater basin, and the groundwater basin extends slightly southwest of the delineated surface water basin.

SLBE's potentiometric surface (analogous to water table surface in the unconfined surficial aquifer) is typical of that found in humid areas with high relief (Handy and Stark 1984). Groundwater flows from recharge areas in uplands to discharge areas (streams, lakes, and Lake Michigan) in the lowlands (Figure 43; Michigan Groundwater Inventory and Mapping Project 2005a, b). Watershed analysis shows that in the Mainland-North and Mainland-Central Units, the shallowest groundwater moves toward the Crystal River and Shalda Creek or Lake Michigan, and in the Mainland-South, toward the Platte River and its tributaries, Otter Creek, or Lake Michigan. Within SLBE, the gradient, or slope of the potentiometric surface, varies from 4.7 m/km in outwash plains to 15.2 m/km in moraines (Handy and Stark 1984). Throughout Michigan and in the SLBE vicinity, the surficial aquifer is highly permeable and vulnerable to surface and subsurface contamination (Olcott 1992).

Springs located within SLBE include the Aral Springs complex, near the end of Esch Road in the Otter Creek basin; other springs along Otter Creek; and springs along the Platte and Crystal Rivers. Groundwater is a significant component of streamflow in all these streams. Springs found on North Manitou Island include The Spring, Angell Spring, and an unnamed spring (Handy and Stark 1984).

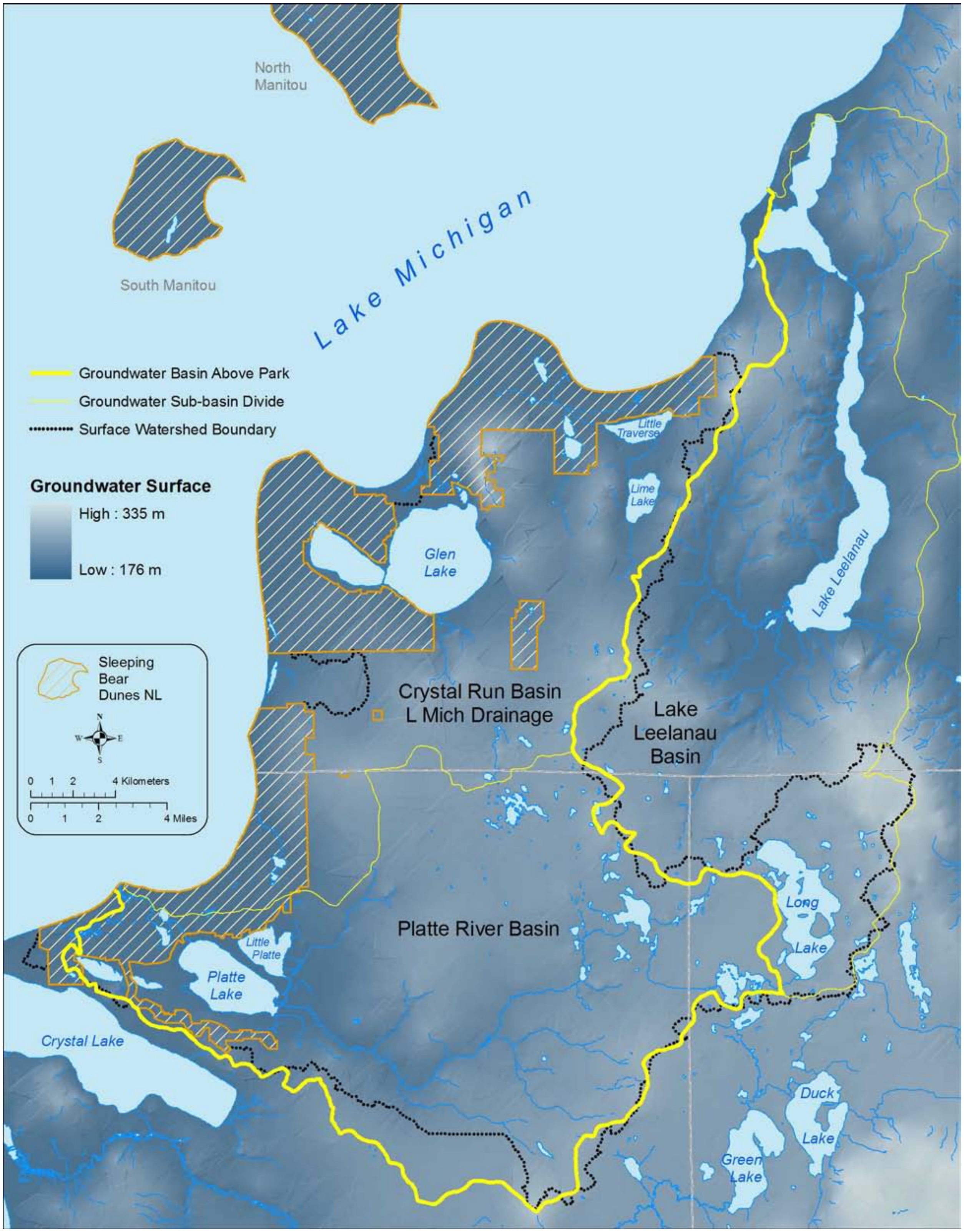

Figure 42. Groundwater basin and sub-basins for Sleeping Bear Dunes National Lakeshore (Michigan Groundwater Inventory and Mapping Project 2005a).

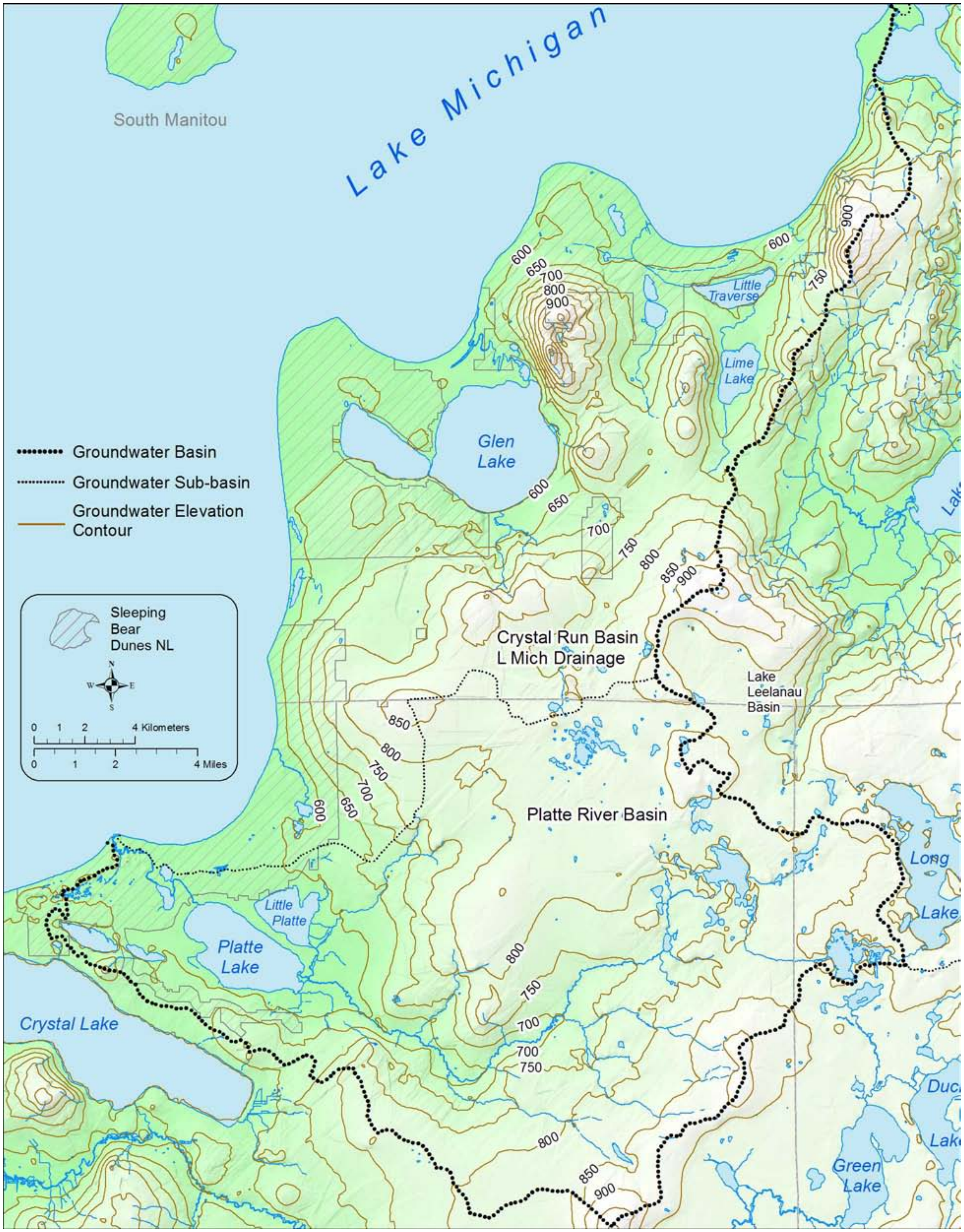

Figure 43. Water table contours for the surficial aquifer in the vicinity of Sleeping Bear Dunes National Lakeshore (Michigan Groundwater Inventory and Mapping Project 2005b).

Groundwater Quality within SLBE

Groundwater quality can be evaluated using specially constructed monitoring wells usually designed to intercept contaminated water if it exists or by using drinking water wells. Drinking water wells are generally constructed to exclude or minimize contaminants, so using them for groundwater quality monitoring normally results in an underestimate of groundwater quality problems. No ambient groundwater quality monitoring wells are known to be in use in SLBE, although several contaminant site monitoring wells are on North Manitou Island and at Tucker Lake, the Platte River Fish Cleaning Station, and the Homestead Resort wastewater area (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). Fifteen transient public non-community water supplies in SLBE (Table 42) are monitored for a limited number of contaminants on a schedule determined by state and federal regulations. No violations of drinking water standards have occurred since a coliform bacteria detection at the Coast Guard station in 1998 (USEPA 2007a).

Table 42. Transient non-community public water supplies, Sleeping Bear Dunes National Lakeshore (USEPA 2007a).

Name	Location	Michigan Water Supply Serial Number	Population Served
Village Utilities	North Manitou	2013345	50
School House	South Manitou	2012845	25
Village Utilities 2	South Manitou	2013245	50
Weatherstation CG	South Manitou	2012545	50
Coast Guard Station	Mainland-Central	2011645	200
Glen Haven Store	Mainland-Central	2011745	200
D.H. Day Campground	Mainland-Central	2010745	300
Outpost Campground	Mainland-Central	2010845	25
Dune Stand	Mainland-Central	2011145	200
Stocking Picnic Mtn.	Mainland-Central	2011345	100
Scenic Drive Kiosk	Mainland-Central	2023945	100
Empire Maintenance Shop	Mainland-South	2011445	30
Platte River CG	Mainland-South	2005510	500
Loon Lake Boat Launch	Mainland-South	2009710	50
Platte Bay	Mainland-South	2014710	100
Total			1,980

From 1979-1982, groundwater quality samples were collected from 10 wells and two springs on the mainland, nine wells on South Manitou Island, and two wells and three springs on North Manitou Island. Most locations were sampled only once (Handy and Stark 1984). Water was mainly of a calcium bicarbonate type and was moderately hard to hard (130-370 mg/L total hardness as $CaCO_3$). One well had an elevated sulfate level (150 mg/L as SO_4), less than the 250 mg/L drinking water standard. Five wells on the mainland had elevated chloride levels (36-170 mg/L) which might indicate human influence, since saline waters are not known to exist in this portion of the Michigan Basin (Westjohn and Weaver 1998). Nitrate-N levels were below 1 mg/L with the exception of three mainland wells (1.4-2.4 mg/L as N), which contained less than the drinking water standard of 10 mg/L. Only one well exceeded a drinking water standard; 0.44 mg/L of iron compared to the secondary (aesthetic) standard of 0.3 mg/L (Handy and Stark 1984).

Elevated nitrate-N levels averaging 0.38 mg/L were reported in springs in the Otter Creek drainage basin in 1999 (Vana-Miller 2002). The elevated levels may have existed for some time; a single spring sample taken in the basin by Handy and Stark (1984) in 1979 had a nitrate-N concentration of 0.65 mg/L. The reference criterion for total nitrogen for rivers and streams in level III subecoregion 51 of ecoregion VII, in which SLBE is located, is 0.81 mg/L (USEPA 2001a). Although the nitrate-N levels observed are below the criterion, total-N levels are not known. Further, the levels observed are higher than those for other streams in SLBE. Therefore, it is unclear whether the observed values in the Otter Creek drainage basin are natural or anthropogenic.

Regional Groundwater Quality

Coliform Bacteria

One hundred thirty-two public water supplies in Leelanau County and 94 in Benzie County are monitored for a limited number of contaminants on a schedule determined by state and federal regulations. From 2004-2006, three public noncommunity water supplies in Benzie County and two in Leelanau County had violations of the drinking water standard for total coliform (MDEQ 2007h). However, coliform bacteria in water wells in a glacial aquifer is most often caused by some sanitary or maintenance defect of the well and not by groundwater contamination.

Nitrate-Nitrogen

Nitrate-N can generally be used as an indicator of the extent of human influence on groundwater quality, especially in areas of coarse, well-aerated soils. Eighty percent of nitrate-N inputs to Wisconsin's groundwater originate from manure spreading, agricultural fertilizers, and legume cropping systems (Shaw 1994). Onsite wastewater disposal systems can also be a significant local nitrate source in densely populated areas or areas with coarse-textured soils. In the western Lake Michigan drainage basin, groundwater in areas with agricultural or agricultural/forest land uses had higher concentrations of nitrate-N than in urban or forest areas (Saad 1994).

The MDEQ provided shapefiles for nitrate-N data for both private and public wells in Benzie and Leelanau Counties from 1983-2003 from their WaterChem database (MDEQ 2005b; MDEQ, Joe Lovato, Chief, Ground Water Mapping and Contamination Investigation Unit, pers. comm., 2008). We combined these shapefiles with additional MDEQ data from 2004-2007 for public water supplies only because the private well data provided would have required significant work in address mapping. Nitrate-N levels exceeded the drinking water standard of 10 mg/L at numerous locations in the two counties, although mostly outside the SLBE watershed (Figure 44). The map provides a useful illustration of the overall vulnerability of the area's groundwater to human contamination. However, it has the limitation of being heavily weighted toward public water supplies, which are required by law to mitigate high nitrate levels, and so may not provide an accurate picture of private well water quality or groundwater quality. Statistics were not calculated for these data because it was not possible to identify and eliminate duplicate samples for a single well, and the data are thus heavily weighted toward public water supplies and probably strongly underestimate the actual nitrate-N levels in shallow groundwater in the area.

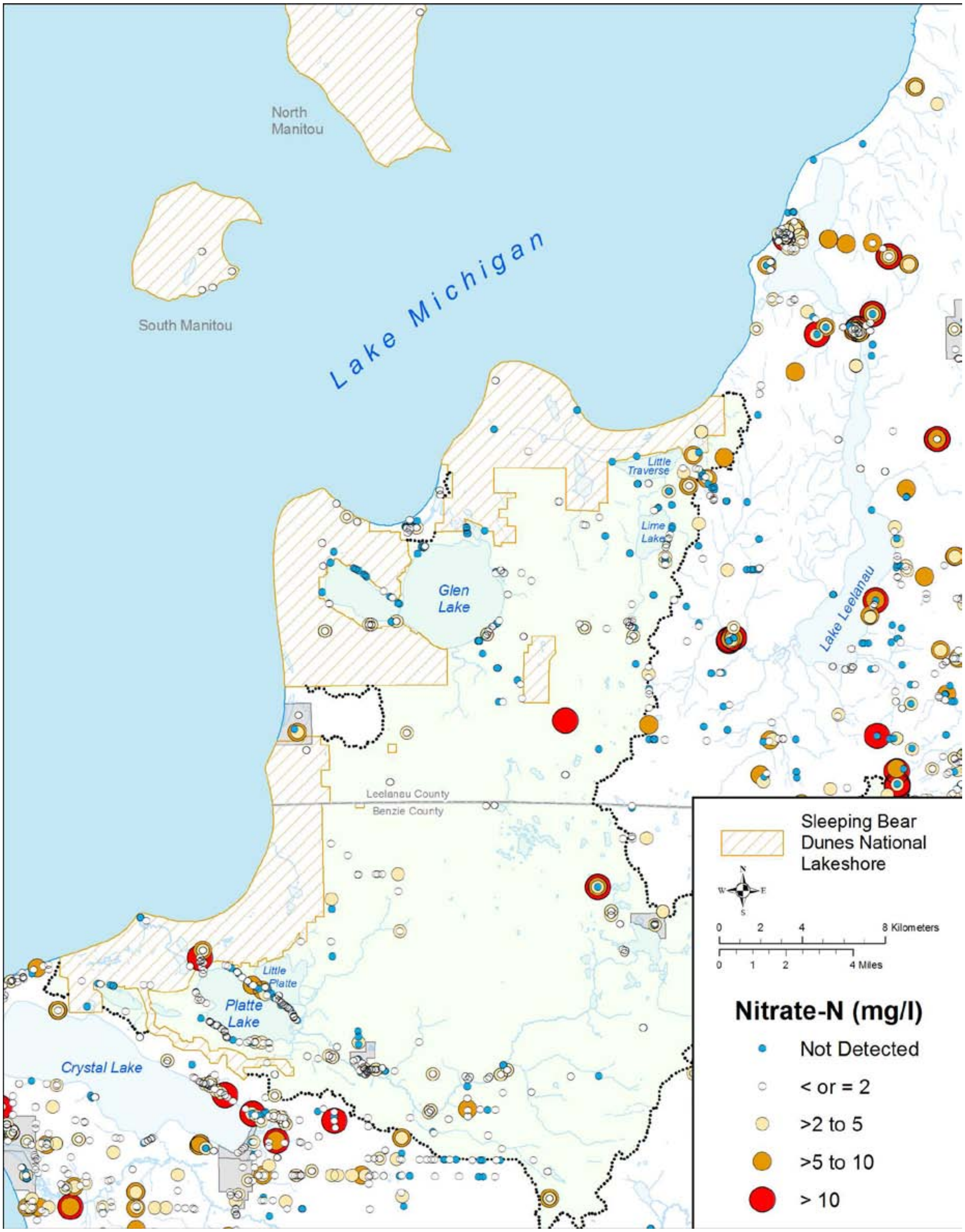

Figure 44. Nitrate-N values for private and public drinking water wells in the vicinity of Sleeping Bear Dunes National Lakeshore (MDEQ 2005b; MDEQ, Joe Lovato, Chief, Ground Water Mapping and Contamination Investigation Unit, pers. comm., 2008).

Arsenic

Arsenic at levels of human health concern is naturally occurring in groundwater in the 'thumb' area of Michigan, likely because of sulfite minerals in the Marshall Sandstone of Mississippian age (Welch et al. 2000). The MDEQ WaterChem database contains 19 arsenic samples for wells within SLBE and 37 well water arsenic samples outside the park but in the SLBE watershed from 1983-2003 (MDEQ 2005b). Of these, 45 contained <1 µg/L arsenic; six within the park and four in the watershed contained between 1 and 5 µg/L, and one in the watershed contained 7 µg/L. All were below the 10 µg/L USEPA drinking water standard for arsenic and the Michigan chronic aquatic maximum value for protection of aquatic life in ambient waters of 150 µg/L (Ledder 2005).

Upland Resources

The upland forests of SLBE are divided into eight forest types based on the data and criteria in Michigan's IFMAP program (MDNR 2003; Table 3); three lowland forest types are also recognized. One important and useful benchmark for assessing the current status and condition of ecosystems is to compare them to the systems that existed pre-European settlement. Though relevant and useful, the pre-settlement condition(s) should not be viewed as a rigid criterion that must be met because it occurred at one point in time, and conditions may fluctuate naturally (Millar and Woolfenden 1999). In the eastern United States, the pre-settlement landscape has been frequently characterized by use of the General Land Office (GLO) survey notes. This source of information has a long history of use in ecology (e.g., Curtis 1959; Goebel et al. 2005) and has been used to produce a detailed map of Michigan community types in approximately 1850 (Comer et al. 1995).

The only published articles found on the vegetation of SLBE were Hazlett (1991) and Goebel et al. (2005). This information was complemented by the unpublished reports of Hazlett (1983, 1986). Corace et al. (2003) recently performed a landscape-scale analysis of SLBE focused on the determination of possible reference ecosystem conditions and the potential for restoration. As part of the analysis, the authors examined pre-settlement vegetation and disturbance regimes. Their determinations of the changes in major plant community extent are included below, by forest type. However, the majority of the plant community characteristics, beyond simple composition and qualitative descriptions, had to be extrapolated from studies in other parts of the LP, state-wide characterizations of community types, and from studies in other parts of the region.

For the portion of the park that was in forest cover at the time of European settlement, we can be reasonably confident, due to the lack of virgin stands and the moderately intense land use history, that the age structure of the forests of SLBE parallels those throughout Michigan and the Great Lakes region. The example for the 'commercial' northern hardwood forests (Table 7 in Frelich 1995) of the western end of Michigan's Upper Peninsula (UP) is probably representative for the northern hardwood forests at SLBE, but with less representation in the oldest age class (120+ years). This age structure probably also matches fairly well other forests at SLBE with a significant component of basswood, white pine, or northern red oak. The proportional allocation by age class would be similar, though shifted to an even younger maximum age class, for aspen, birch, mixed deciduous, pine, and pine-oak forests. The average diameters reported by Hazlett (1986) are consistent with these conclusions.

Northern Hardwood Association

This is the dominant plant community in SLBE, covering approximately 11,500 ha, making it five times more abundant than all other upland deciduous forest types (Table 3). It is especially prevalent in the Mainland-Central Unit; within the Mainland-South, it is largely confined to the northern end, and in the Mainland-North, it is concentrated in the southern half of the Unit. This forest type is primarily found on moraines some distance inland from the Lake Michigan shore. It is the dominant vegetation type on both islands, especially North Manitou (Figure 45).

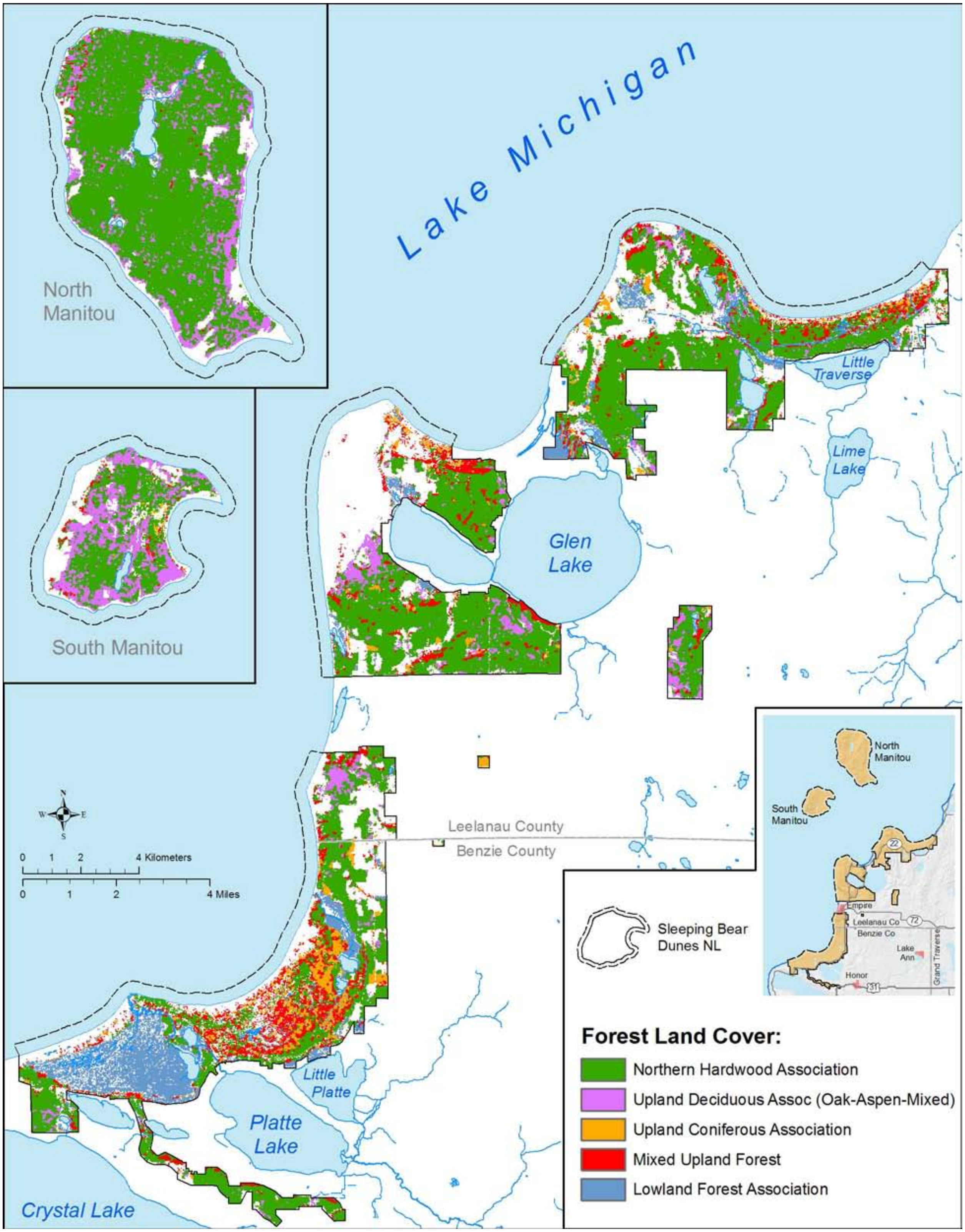

Figure 45. IFMAP forest land cover types for Sleeping Bear Dunes National Lakeshore (MDNR 2003).

The age structure of the northern hardwood type reported for the 'commercial' forests in the UP (Frelich 1995) in 1992 was as follows: less than 10% was 120+ years, approximately 30-35% was >80 but <120 years, 41-46% is >40 but <80 years old, and 15% was 40 years old or less. Balancing the passage of time with the more intense and recent use of forest land in the LP, these categories would probably apply to SLBE if the age ranges were reduced 10-15 years.

It should be noted that the northern hardwood forest type is a loosely defined ecosystem and can have one or more of at least 12 different arboreal species in the overstory (Tubbs 1977; Stearns 1986). Sugar maple (*Acer saccharum*), or sugar maple and beech (*Fagus grandifolia*), are usually considered the "key" arboreal indicators of this type (Tubbs 1978 in Stearns 1986). However, depending on the successional stage, site conditions, and site history, the tree layer could contain no sugar maple, all sugar maple, or varying amounts of eastern hemlock (*Tsuga canadensis*; hereafter, simply 'hemlock'), beech, white ash (*Fraxinus americana*), yellow birch (*Betula alleghaniensis*), northern red oak (*Quercus rubra*), basswood (*Tilia americana*), red maple (*Acer rubrum*), black cherry (*Prunus serotina*), American elm (*Ulmus americana*), eastern white pine ('white pine'), aspen (*Populus* spp.), or white birch (Hazlett 1986, 1991; Stearns 1986). Occasionally, white cedar, balsam fir, or white spruce (*Picea glauca*) might be present. Some aspen/white birch forests are simply an early successional stage of this forest type. For structural descriptions (density, tree size, basal area) of this forest type, see Table 1 of Appendix B in Hazlett (1986), Metzger and Schultz (1981, 1984), and Crow et al. (2002).

Northern hardwood is a classic mesic forest type (Delcourt and Delcourt 2000), and the plants must have access to adequate moisture for essentially the entire growing season. Thus, it is located where surface soils are sandy loam to silty loam (Henne et al. 2007), or where sub-surface conditions (e.g., a perched water table) or topography provide greater-than-average moisture and/or reduce evapotranspiration. Around the Great Lakes, a special dimension of this is the strong gradient in snowfall as a function of distance from the Lake Michigan shore. Henne et al. (2007) found the amount of snowfall was the single most important predictor of the abundance of mesic forests (essentially the northern hardwood type) in the northern LP. They also found that distance from shore significantly affected the abundance of sugar maple relative to hemlock.

The analysis by Goebel et al. (2005) indicates an approximate 25% decrease in the extent of the northern hardwood forest type since the mid-1800s, when it occupied approximately 70% of the landscape. An additional 5% was occupied by hemlock-white pine before European settlement (Corace et al. 2003). The current deficit would be largely offset if all of the current openlands, such as old fields and abandoned agricultural lands were allowed to succeed without interference (Goebel et al. 2005). The magnitude of the decline in this forest type is smaller at SLBE than in the two counties (Crawford and Roscommon) studied by Whitney (1987).

In some classifications of forest types, this would be called the "beech-maple" type (Cain 1935; Braun 1950 in Delcourt and Delcourt 2000). To the north, it grades into the hemlock-white pine-northern hardwood type (Nichols 1935; Delcourt and Delcourt 2000). It was common historically for northern hardwood forests in the Lake States to have scattered hemlock, or hemlock as a secondary dominant (e.g., Whitney 1987; Frelich and Lorimer 1991; Leahy and Pregitzer 2003), and numerous stands at SLBE exhibit this characteristic (Hazlett 1991).

However, SLBE also has areas from the scale of a patch (< 1 ha) up to large stands in which hemlock is the clear dominant, and yellow birch, sugar maple, red maple, and/or white pine are secondary associates (e.g., Hix and Barnes 1984; Whitney 1987; Corace et al. 2003). SLBE also has patches and small stands that are clearly hemlock dominated (Hazlett 1991), but the extent of larger hemlock stands is not inventoried. Because of differences in understory composition and cover, and often in soil characteristics, hemlock is considered a distinct, unique forest type, described below in the Upland Conifer Association section.

The structure of the northern hardwood forest is typically rather simple. A 'suppressed' layer and/or midstory is sometimes present and comprised of ironwood (*Ostrya virginiana*) and one or more of the very shade tolerant overstory species (sugar maple, beech, and/or hemlock). A well-developed shrub layer is seldom present among the stands on the mainland or on North Manitou Island; on South Manitou Island yew is still present and sometimes forms a shrub layer in conjunction with red elderberry (*Sambucus racemosa* subs *pubens* var. *pubens*), wild gooseberry (*Ribes cynosbati*), and maple-leaf viburnum (*Viburnum acerifolium*) (Hazlett 1991).

The understory of the northern hardwood forest can be rather diverse, and includes species with different phenologies; the two most speciose groups are spring ephemerals and summer deciduous (Rogers 1982). Metzger and Schultz (1981) studied four stands of northern hardwoods, each with a different management history, in the UP. They found 30 different taxa in the spring, with a high degree of similarity among stands. Metzger and Schultz (1984) reported the late season understory composition of the same four stands and found a slightly more diverse (36 taxa) understory. The "best" examples of this community type in SLBE are on the Empire Bluffs and in the Bow Lake Unit (Hazlett 1991). Hazlett (1991) lists at least 22 herb species for the community on Empire Bluff, some of which (spring beauty [*Claytonia caroliniana*] and wild leek [*Allium tricoccum*]) are examples of spring ephemerals. The version of the northern hardwood type found in the Bow Lake Unit is notably different than the rest of the Lakeshore in that the shrub layer is better developed. The dominant species are witch hazel (*Hamamelis virginiana*), wild gooseberry, and eastern leatherwood (*Dirca palustris*). Despite the more abundant shrub layer, the herb layer in this region is quite diverse (Hazlett 1991). The northern hardwood forest in the Round Lake area (west of Hwy M-22) contains the only known location for broad beech fern (*Phegopteris hexagonoptera*) in SLBE. In the Mainland-Central Unit, Hazlett (1991) noted that the understory became more luxuriant with increasing elevation on the moraines. The northern hardwood forest in the Alligator Hill area contains the state-threatened three-birds orchid (*Triphora trianthophora*). However, the northern hardwood forest type occurs on slightly drier sites in both the Mainland-Central and the Mainland-North Units. Correspondingly, the herb layer is notably less diverse.

The richness values from Hazlett (1991) probably underestimate the total richness of this forest type. Even the values from Metzger and Schultz (1981, 1984) are low due to the resolution of identification in some genera. In one year of sampling vegetation less than 0.5 m tall, Kern et al. (2006) found 94 species (spring and summer combined) in a sugar maple-dominated northern hardwood forest in northeastern Wisconsin. Other studies of the northern hardwood type in the region generally also found higher richness (e.g., Cain 1935; Rogers 1982; Scheller and Mladenoff 2002).

Upland Deciduous Association

This general category of forest types is largely aspen-dominated (primarily big-tooth aspen [*Populus grandidentata*)]). According to IFMAP (MDNR 2003), an aspen association occupies approximately 7.5% of the current SLBE landscape (Table 3). A very small portion (approximately 0.1%) is oak-dominated, and mixed-species forests (which often have a small amount of oak and/or aspen) are found on a little over 400 ha (1.7%). Corace et al. (2003) estimated that the aspen-birch forest type occupied only 0.1% of the landscape prior to European settlement. As noted in the northern hardwood association, aspen and white birch are classic pioneer tree species and often dominate early successional communities on sites that can support a northern hardwood forest. Thus, given the extent and degree of human alteration of the region in about the past 140 years and the information available on the vegetation along the western edge of the LP (e.g., Olson 1958; Hazlett 1986, 1991), it is not surprising that aspen occupies a much greater portion today. In the aspen and aspen mixed hardwood types, the shrub layer varies from sparse to moderately well developed; it is typically comprised of witch hazel, striped maple (*Acer pensylvanicum*) and maple-leaf viburnum (Hazlett 1991).

Upland deciduous forests are scattered about SLBE in small patches in all three mainland units. Typically they are an intermediate distance from the Lake Michigan shore on an old dune complex or relict beach ridge (Hazlett 1986), or on outwash sand and gravel (Figure 45). In the case of aspen (and aspen-birch), some patches are also found on sites that have the potential to support a northern hardwood forest (Figure 8, Figure 45). Hazlett (1986) noted that the oak-aspen vegetation type can occur on moraines due to “delayed secondary succession.” This has been an explanation for the abundance of oak-dominated forests on old sand dunes in southern Michigan since the turn of the 20th century (Cowles 1899). In the mid-20th century, a thorough exploration of the possible successional pathways in this landscape concluded that these oak-dominated forests were a final stage of succession (Olson 1958). An analysis based on fire-scars, GLO survey notes, and stand structure of two black oak (*Quercus velutina*)-dominated forests in northwestern Indiana at Indiana Dunes National Lakeshore (INDU) suggests that this forest type is fire-maintained (Henderson and Long 1984). Olson (1958) surveyed a large number of sites in INDU, including dunes ranging in age from 90 to 12,000 years. Jack pine (*Pinus banksiana*) and white pine dominated the tree component through an age of approximately 150 years, and then black oak became the dominant tree species. On very old dunes (>7500 years), white oak (*Quercus alba*) was sometimes a co-dominant species. It is probable that some of the oak and oak-pine forests at SLBE are ecologically similar to the black oak type at INDU. However, the oak forest type seems to be less common in SLBE than farther south.

Northern red oak is the dominant oak in SLBE; both scarlet (*Quercus coccinea*) and black oak occur but are very rare (Hazlett 1991) because they are reaching their northern range limit. A little white oak occurs in the “coastal forests” (Hazlett 1991). Across the range of the two species, northern red oak is not as drought tolerant as black oak (Wuenscher and Kozlowski 1971), and the distribution of the two species by soil type reflects this (e.g., Peet and Loucks 1977). However, the two species share many autecologic characteristics, including adaptation to fire (Abrams 1992; Brose et al. 2001). At SLBE, northern red oak occurs under two rather contrasting conditions: on more mesic sites that can or do support a northern hardwood association (Hazlett 1986, 1991) and on older dunes, often with one or more species of pine. The latter sites are clearly sandy and thus have low water-holding capacity—an atypical site for northern red oak in general—but some populations at SLBE appear to have adapted to these conditions. Olson (1958) similarly noted that northern red oak "may take the place of black oak on some dry dunes" north of INDU.

Several of the forest types that fit in the upland deciduous association can intergrade with other vegetation types. Most common would be the white pine and/or red pine (*Pinus resinosa*) vegetation types. In these mixed conifer-deciduous forests are found the bulk of the northern red oak, white pine, and red pine. The oak-pine type is one of the dominant communities in the IFMAP "upland mixed forests" category; collectively, they occupy a slightly smaller area (6.9%) than aspen. The site conditions that are most suited to this mixed forest type can qualitatively be described as intermediate. Young dunes, or coarse sands with little organic matter and soil development, are too harsh for this type. However, once vegetation has been present for 100-200 years, the increased organic matter and corresponding nutrient/water holding capacity can often support a mixed upland forest (Olson 1958).

The general forest type oak-pine encompasses a wide range of site conditions, though most examples of this general type are on the more xeric end of the moisture gradient. Consequently, a large number of subordinate and shrub-layer species can occur with these forests. These shrub and mid-layer species range from a more 'mesic' group, including chokecherry (*Prunus virginiana*), serviceberry (*Amelanchier* spp.), red maple, witch-hazel, and balsam fir, to more xeric-adapted species such as sweet low blueberry (*Vaccinium angustifolium*), black huckleberry, and creeping juniper.

The more mesic version of the aspen-oak type, which may have scattered stems of beech, red maple, or white pine, may grade into the northern hardwood type; this is noted by Hazlett (1991) on the south-and west-facing slopes of the Mainland-North Unit. He further reported that the GLO survey records from 1850 for this area indicate a northern hardwood forest type dominated by sugar maple, beech, and hemlock. The "mixed forest" type can include a surprising group of species in varying mixtures, including some common members of the northern hardwood type. A good example is present on the east side of South Manitou Island, where a series of concentric ridges formed as Lake Michigan receded. In some of the troughs between the ridges, where moisture is available throughout the year, the conifer component can include hemlock, white cedar, white pine, or balsam fir. Beech, sugar maple, aspen, and northern red oak are among the deciduous species present (Hazlett 1991).

Upland Conifer Association

The upland conifer association comprises 2.8% of the SLBE landscape (Table 3). At a small spatial scale such as a patch, an upland conifer type could be dominated by jack pine, red pine, white pine, hemlock, or balsam fir. Only three upland conifer association types were abundant historically: jack pine with either red or white pine; red and white pines co-dominating, and hemlock-white pine. The red and white pine type was moderately abundant historically (6.3%), as was the hemlock and white pine type (5.0%). In contrast, the jack pine type was notable and clearly less common (1.2%) (Corace et al. 2003).

Pine Forest Type

As noted above, the pines often occur as part of the first “tree-stage” in primary succession and come after disturbances of various intensities during secondary succession (Olson 1958; Barnes et al. 1998). As a group, they occupy the more xeric, nutrient poor substrates in the park (Whitney 1986; Hazlett 1991; Leahy and Pregitzer 2003). An example of the mixed pine type is the forest on the Aral Dunes (Hazlett 1991). In jack pine forests on younger dunes, the most xeric of the pine forests, the shrub layer has a strong dune affiliation. In these locations, the shrub layer often contains beach heather (*Hudsonia tomentosa* var. *tomentosa*), sand cherry, and bearberry (*Arctostaphylos uva-ursi*). White pine, in contrast, occurs on a wider variety of soil types (Stearns 1992) and sometimes functions as a mid-seral (shade-intolerant) species in the northern hardwood type (Hazlett 1986, 1991; Leahy and Pregitzer 2003).

Eastern Hemlock Forest Type

Hemlock was not recognized as a distinct forest type in the assessments by Goebel et al. (2005) or in the cover type mapping we looked at. Hence, we did not find SLBE-specific estimates of areal changes in this forest type since European settlement. However, it has been repeatedly documented in various parts of the region, and for the Great Lakes region as a whole, that there have been extensive and large reductions in the amount of hemlock over the past approximately 130 years (Frelich 1995; Leahy and Pregitzer 2003). The GLO survey records cited by Hazlett (1991) for the morainal hills in the Good Harbor Bay area suggest a similar decline in hemlock abundance in this specific area.

Hemlock typically grows on sites that are moist to very moist, but with good drainage (Rogers 1978; Godman and Lancaster 1990). In the Lake States the species grows on upland sandy loams, loamy sands, and silt loams, often with an abundance of ground or coarse rocky material throughout the upper profile deposited from glacial or fluvial material (Godman and Lancaster 1990). Hence, many of the sites that support a northern hardwood forest are suitable for hemlock. However, it also grows in the low-lying sandy lake plains (Goebel et al. 2005), the sloughs between older dunes (Hazlett 1991), and in the lower-lying areas between ridges on South Manitou Island (Hazlett 1991).

The hemlock type is more likely than a maple-beech forest to have white cedar or balsam fire as an uncommon component. The most common tree associates are yellow birch and white pine. Because it is the most shade tolerant tree species (Godman and Lancaster 1990), it can readily regenerate under its own canopy if forest floor conditions are suitable. Consequently, it often has an uneven-age, multi-storied structure. The shrub and herb layer are notably sparse in both richness and cover due to the forest floor and soil conditions (Rogers 1978; Hazlett 1991). Godman and Lancaster (1990) listed Canada mayflower, American starflower, wood fern, mountain wood-sorrel (*Oxalis montana*), goldthread, clubmoss (*Lycopodium* spp.), and sedges as the most common herbs under hemlock.

In areas where hemlock has dominated for an extended period of time, the forest system is clearly different functionally. These differences (relative to a typical northern hardwood forest) include deeper litter and duff (Oi + Oe) layers, lower radiation levels near the forest floor, lower soil pH, lower rates of decomposition and mineralization, lower macronutrient availability, and higher levels of precipitation interception and ground water recharge (Rogers 1978; Hix and

Barnes 1984, Ellison et al. 2005). The ecosystem process-related traits influenced by hemlock are so important that hemlock is considered a 'foundational' species by Ellison et al. (2005).

Openlands

The openlands at SLBE are predominantly, if not entirely, of cultural origin (Corace et al. 2003), resulting from timber harvesting and agricultural conversion around the turn of the 20th century. When SLBE was established in 1970, a number of small, private farms or areas formerly in agriculture were included. Corace et al. (2003) documented a total of 458 fields within SLBE, making up 13.2% of the SLBE land area. None of these openlands represent a natural biotic condition; they would all be some type of upland forest (mostly northern hardwoods) in the absence of human intervention. Consequently, by including some of these in their Historic Properties Management Plan, SLBE has decided to maintain this habitat at the expense of more, and more contiguous, hardwood forest.

However, the openlands play an important conservation role. Most notably, they provide habitat for a significant number of openland bird species, whose populations have been declining for some time-based on the national Breeding Bird Survey (Sauer et al. 2001). Corace et al. (2003) surveyed the openlands of SLBE and encountered 83 bird species, 36 of which are classified as openland species. Furthermore, most of this latter group have declining population trends. According to the MNFI, 19% of the state's bird species of "special concern" are considered grassland species (//web4.msue.msu.edu/mnfi/data/specialanimals.cfm).

Moderately intensive sampling of 12 fields (average size 27 ha) by Corace et al. (2003) showed that the graminoids collectively (grasses and sedges) were the most abundant growth form; the cover of this group ranged from 4% at the forest edge to about 30% cover in the field edges and field interiors. Forbs were the second most common growth form and were less variable across the openland habitat. Forb cover ranged from approximately 8% at the forest edge to 14-18% cover in the field edges and field interiors. Tree seedlings and shrubs each were less than 1% cover, even though woody stems >2.5 cm diameter were found in 22% of the plots surveyed. The invasive forb spotted knapweed (*Centaurea* spp.) was found in all openlands surveyed.

Hazlett (1991) surveyed a couple of old fields in the Empire Bluffs area and several on South Manitou Island. As expected, his species list for one field near the Bluffs (pg. 151) contains many naturalized exotic species. Three species of moonwort (*Botrychium* spp.) were noted in another old field about midway to the bluff along the Empire Bluffs trail; however, each was under a white ash that had invaded the field. Prairie moonwort (*B. campestre*) is a "local variety" (Hazlett 1991); this and the other two species found in the old fields are more typically found on moist, perched dunes. The old fields he surveyed on South Manitou Island differed from those on the mainland in that the dominant woody taxon was *Juniperus*. These fields on the island appear to represent a greater range of successional stages than those on the mainland, and the older ones have a scattering of pin cherry (*Prunus pensylvanica*), chokecherry, white birch, and aspen (in decreasing order of abundance).

Lowland Forest Association

The lowland deciduous and conifer forests comprise 6.3% of the SLBE landscape, with each major type (deciduous vs. conifer) being roughly equal in abundance (approximately 3%), and about 0.5% of the acreage contributed by a mixture of the two (Table 3, Figure 45). The assessment by Corace et al. (2003) indicated that “mixed conifer swamps” covered 7% of the landscape, northern white cedar 1.5%, and mixed hardwood swamps <0.1% in the mid-1800s. Thus, in about the past 150 years, there has been substantial loss of lowland conifer forests and expansion of lowland deciduous associations. The shrub layer of the mixed conifer and northern white cedar types is typically composed of velvet-leaf blueberry, striped maple, speckled alder, and balsam fir (Hazlett 1991).

Physiography, soil characteristics, groundwater and surface water movement, and disturbances collectively determine where the lowland forests occur and which species or groups of species dominate the association. The first four factors interact to determine how much moisture there is on a site, how long the soils stay saturated, the magnitude of annual water fluctuation, and the amount and type of nutrient input (Richardson 2000; Weber et al. 2007). These hydrologic characteristics determine, at a community level, which species are suited for a site. At a smaller scale, the hydrologic conditions are modified by other factors.

Lowland Deciduous Forest

The most common form of this association is “black ash swamps” which usually occur adjacent to lakes on poorly drained soils (Hazlett 1986). On the mainland they are found near Tucker, Shell, Narada, School, and Glen Lakes (Hazlett 1986); significant black ash swamps also occur adjacent to Lake Manitou and Tamarack Lake on North Manitou Island (NPS 1999c). Black ash has an unusual reproductive ecology with a seed dispersal period that extends into the winter and an immature embryo at dispersal (Curtis 1959). Other broad-leaved species that may co-occur include red maple, speckled alder, American elm, quaking aspen (*Populus tremuloides*), and white birch (Hazlett 1986; Weber et al. 2007). Small amounts of conifers occur in these associations, especially balsam fir, hemlock, and white pine.

Lowland Conifer Forest

The two common forest types in this association are white cedar swamps and conifer bogs. The cedar swamps are most commonly found along rivers; the most extensive area lies along Otter Creek. Though cedar defines the type, white pine, balsam fir, and white birch may be present in the overstory. If the canopy is open in spots, other broad-leaved species (red maple, speckled alder, and black ash) may become more abundant (Hazlett 1986).

Bogs are one physiographic feature that commonly support a conifer-dominated overstory. These locations have no drainage outlets and thus have standing water for much of the year. The water and soil have a low pH (are acid to very acid), and peat moss is abundant. Larch and black spruce are the typical dominant trees (Hazlett 1986); lesser amounts of white pine, jack pine, and balsam fir may be present (Weber et al. 2007).

Sleeping Bear Dunes Ecosystem Monitoring and Indicators

Current Water Quality Monitoring Programs

A water quality monitoring program in some form has been conducted by SLBE staff each summer since 1994 (Vana-Miller 2002). In 2008, 13 sites (see Figure 25), were monitored weekly for *E. coli* between the first weeks of May and September. Sampling and testing were performed by SLBE water quality staff. Since 2006, water quality monitoring of SLBE inland lakes has been conducted in conjunction with the GLKN. In 2008, this program was expanded to the following ten lakes: Lake Manitou, Florence, Shell, Tucker, Narada, Bass (Leelanau), Loon, Round, Otter, and North Bar. Each lake, excluding Narada, was sampled three times during the summer. Field measurements included depth profiles of temperature, pH, specific conductance, and DO. Water clarity, water level relative to a benchmark, and other environmental variables were also recorded at the time of sampling. Water samples were collected for laboratory analyses of nutrients (TP, TN, nitrate and nitrite-N, ammonium-N, and dissolved silica), major ions (calcium, sodium, magnesium, potassium, sulfate, and chloride), DOC, alkalinity, and chlorophyll-*a*. Currently, water quality staff are revising sampling and testing protocols for SLBE's additional inland lakes and streams. While the sampling sites and frequency have yet to be determined, sampling procedures, field measurements, and chemical parameters tested will likely follow the GLKN protocol (NPS, Chris Otto, Biological Technician-Water Quality, SLBE, pers. comm., November 2008).

Additional sampling occurred in 2007 at four sites at Aral Springs, two on the Crystal River, two on the Platte River, and at Lake Michigan, Bass Lake (Benzie), Bass Lake (Leelanau), Deer Lake, Florence Lake, Long Lake, Mud Lake, Narada Lake, North Bar Lake, Otter Creek, Shalda Creek, and School Lake. Other secondary sites sampled at times, but not in 2007, were the Aral Road marsh, other sites on Aral Springs, Boekeloo Pond, Day Mill Pond, Little Glen Lake, and Narada Creek (McMahon 2007).

The USEPA monitors 11 Lake Michigan stations twice annually for phosphorus (total and total dissolved), nitrogen (as nitrate plus nitrite), soluble reactive silicon, chloride, total alkalinity, specific conductance, and turbidity (Warren and Kreis 2005). One deep water sampling site in Lake Michigan (MI47), approximately 24 km northwest of South Manitou Island, has been sampled generally twice a year, in March-April and in August-September, since 1996. Michigan's Water Chemistry Monitoring Program does not have monitoring sites in the open water areas of Lake Michigan, but calls for annual water chemistry monitoring on Saginaw and Grand Traverse Bays, as well as selected Michigan streams tributary to the Great Lakes and Great Lakes connecting waters (MDEQ 2008a).

The state of Michigan's water quality monitoring strategy consists of nine interrelated elements: fish contaminants, water chemistry, sediment chemistry, biological integrity, wildlife contaminants, bathing beaches, inland lake quality and eutrophication, stream flow, and volunteer monitoring. Michigan has established water quality standards for bodies of water within SLBE, and it monitors the condition of watersheds in the park and statewide on a rotating five-year basis. The surveys monitor for a combination of biological (benthic invertebrates and/or fish), habitat, water, sediment, and fish tissue indicators in wadable streams. The goal has been to monitor 80% of the river and stream miles in each basin, but the MDEQ is currently looking at a probabilistic design to assess 100% (MDEQ 2008a). In SLBE, the Platte and Crystal Rivers were surveyed in 1998 and 2003 for macroinvertebrates and water chemistry and given a habitat rating. They were scheduled to be resampled in 2008.

During 2005 and 2006, 167 public access lakes (56,468 ha) in Michigan were sampled and reassessed as part of the Lake Water Quality Monitoring Assessment Project. Over 200 lakes were sampled in 2005 and 2006 as part of the voluntary Cooperative Lakes Monitoring Program (MDEQ 2008b). Big and Little Glen Lakes are monitored in this latter program. Monitoring coordinated by the Platte Lake Improvement Association is conducted as part of the Consent Agreement regarding the state's operation of the Platte River Fish Hatchery. Sampling sites are located on Platte Lake, Little Platte Lake, the Platte River and the North Branch, and Brundage, Stanley, Carter, Collison, Featherstone, and Tamarack Creeks (Canale et al. 2006).

One hundred thirty-two public water supplies in Leelanau County and 94 in Benzie County, including 15 transient public non-community water supplies in SLBE (Table 42) are monitored for a limited number of contaminants on a schedule determined by state and federal regulations (USEPA 2007a). This monitoring gives some indication of groundwater quality in the region, as explained in the Groundwater section.

The Grand Traverse Band of Ottawa and Chippewa Indians provides water quality monitoring within the 1855 Reservation boundaries and connecting waters under a USEPA Section 106 Clean Water Act grant. Their activities include surface water quality monitoring, stream habitat assessments, macroinvertebrate collection and identification, road stream crossing surveys, wetlands management plan implementation, soil erosion stormwater runoff control permitting and inspecting, and nonpoint source pollution prevention (Grand Traverse Band Ottawa and Chippewa Indians 2008).

For an overview of past inland water surveys, see the Inland Waters section.

General Indicators

Designations and Protections

All waters within the designated boundaries of SLBE (including Lake Michigan and inland lakes and streams) are designated as "Outstanding State Resource Waters (OSRW)" by the state of Michigan. These waters are protected by applying controls on pollution sources so that existing uses are maintained and water quality is not reduced in the OSRW (State of Michigan 2006). Coastal streams in SLBE that are listed as trout streams are Good Harbor Creek, Shalda Creek (except the Narada Lake outlet), Crystal River (except the portion between Fisher Dam and Glen Lake), Otter Creek, and Platte River (MDNR 2007d).

Violations of Water Quality Standards

During 1997, an NPS contractor reviewed water quality data for SLBE lakes and streams using USEPA's national water quality databases (NPS 1997b). The summary report ('Horizon' report) covered the period 1962-1996 for SLBE and areas within at least 3 miles upstream and at least 1 mile downstream. Data included 149 monitoring stations and 51,317 water quality observations representing 294 water quality variables. Most stations had short term data or intensive data for only one year. Sixty-two stations had data collected before 1985 and are of limited value in determining current water quality conditions (Vana-Miller 2002). Twenty-four stations had data more recent than 1995 and included several multi-year studies (e.g., Boyle and Hoefs 1993a, b; Last et al. 1995) important in tracking water quality trends of SLBE inland waters. Only 12 SLBE lakes had sampling data over the five-year period 1990-1995. Each SLBE stream had one station that was sampled between 1990 and 1995 (Vana-Miller 2002).

The report revealed eight groups of parameters that exceeded screening criteria at least once (NPS 1997b). Twenty-four stations recorded 231 violations of the NPS Water Resources Division (WRD) total coliform criterion for bathing waters (1000 colony-forming units (CFU)/most probable number (MPN)/100 mL) from 1967-1979, mainly in the Platte River. Nine violations of the WRD fecal coliform criterion for bathing waters (200 CFU/MPN/100 mL) were found at three stations from 1967-1981. Since bathing waters are routinely monitored in SLBE, these old violations will not be discussed further here.

Six hundred eighteen observations at 27 stations showed less than or equal to the 4 mg/L USEPA DO criterion for the protection of aquatic life. Sixty-one percent of these violations were at five stations in Platte Lake from 1974-1996 (NPS 1997b). Sixteen observations at seven lake stations exceeded the 9.0 standard units USEPA chronic criterion for pH for freshwater aquatic life from 1962-1996. Drinking water criteria for lead and cadmium, and freshwater criteria for cadmium, copper, and zinc were exceeded at a few locations between 1973 and 1982 (Table 43). These exceedences were in the range of 10-22% over the criterion except for zinc, which was double the criterion. Most of the exceedences did not appear to be targeted for follow-up, but in some cases subsequent samples did not repeat the exceedence.

Impairments, 303(d) Reports, and Fish Consumption Advisories

The federal Water Pollution Control Act (PL92-500, Clean Water Act) requires each state to prepare a biennial report on the quality of its water resources, often called a Section 305(b) report after the pertinent subsection of the Act. Michigan's 2006 report includes the Glen Lakes, Crystal Lake, Lake Michigan north of Frankfort, and an unnamed tributary to Platte Lake in its list of impaired water bodies (often called a Section 303(d) list, again after the pertinent subsection of the Act). These water bodies must have total maximum daily loads of pollution (TMDLs) established for them (Table 44; MDEQ 2006e). In addition to these impairments, all inland lakes, reservoirs, and impoundments in Michigan have an advisory against eating most types of fish more than once a week because of mercury contamination, with additional restrictions for women of childbearing age and children under age 15 (MDCH 2007).

Lake Michigan Indicators

The USEPA and Environment Canada (2007) reported that the overall status of the Great Lakes ecosystem in 2006 was mixed, with some conditions good and others poor, and that ecosystem trends varied from improving to worsening. Assessment is made more difficult by the fact that "for many indicators, ecosystem objectives, endpoints, or benchmarks have not been established" (USEPA and Environment Canada 2007). Numerous authors are currently engaged in developing indices of biological integrity that will allow resource managers to assess the condition of specific parts of the Great Lakes, especially in coastal waters. Indicators used in these indices include invertebrates (Uzarski et al. 2004); diatoms (Reavie et al. 2006); fish (Uzarski et al.

Table 43. Exceedences of freshwater and drinking water criteria for metals in water samples in SLBE and its vicinity, 1962-1996 (Boyle and Hoefs 1993a; NPS 1997b).

Location and number in Horizon report	Within SLBE?	Criterion exceeded or equaled	Value	Month/year	Later sampling dates that met criterion
Glen Lake near Glen Arbor (SLBE 0102)	No	Cadmium freshwater life 3.9 µg/L	4 µg/L	5/1980	10/27/81; <1 µg /L (Handy and Stark 1984)
Glen Lake-North Central Basin (SLBE 0097)	No	Copper freshwater life 18 µg/L	20 µg/L	9/1973	none found
Little Glen Lake-South Central Basin (SLBE 0093)	No	Copper freshwater life 18 µg/L	20 µg/L	9/1973	none found
Lake Michigan (SLBE 0058)	No	Lead drinking water 15 µg/L	18 µg/L	7/1977	none found
Platte River at or near Hwy M-22 bridge (SLBE 0048)	Yes	Cadmium freshwater life 3.9 µg/L; drinking water 5.0 µg/L	5.0 µg/L	5/1980	5/18/93, 6/9/93, 7/13/93, 9/7/93; all <0.2 µg/L (MDEQ data found in USEPA STORET)
Platte River near Hwy 31 bridge (SLBE 0009)	No	Cadmium freshwater life 3.9 µg/L	4 µg/L	either 7/1977 or 9/1982	9/12/78, 9/4/79, 9/2/80, all <2 µg/L (MDEQ data found in USEPA STORET for another site within 250 m)
	No	Lead drinking water 15 µg/L	19 µg/L	7/1977	9/12/78, 14 µg/L; 9/4/79, 5 µg/L; 9/2/80, <5 µg/L (MDEQ data found in USEPA STORET for another site within 250 m)
	No	Zinc freshwater life 120 µg/L	240 µg/L	7/1977; 9/1982	9/12/78, 17 µg/L; 9/4/79, 10 µg/L; 9/2/80, <5 µg/L (MDEQ data found in USEPA STORET for another site within 250 m)
Shalda Creek (none)	Yes	Aluminum freshwater life-chronic 87 µg/L	140 µg/L	12/1990	4/8-9/91, 10 µg/L; 10/10/91, 20 µg/L (Boyle and Hoefs 1993a)

Table 44. Water bodies on Michigan's 303(d) list in the vicinity of Sleeping Bear Dunes National Lakeshore (MDEQ 2008b).

Water Body	Location	Problem	TMDL Date
Crystal Lake	vicinity of Benzonia and Beulah	Polychlorinated biphenyls (PCB) in fish tissue	2010
Glen Lake	south of Glen Arbor	PCB in fish tissue, chlordane Mercury in fish tissue	2010 2011
Lake Michigan	north of Frankfort	Chlordane, DDT, PCB, mercury, and TCDD (dioxins)	2012
Platte Lake	vicinity of Honor	PCB	2010
Unnamed tributary to Platte Lake	confluence upstream of Hwy 31	organic enrichment, bacterial slimes, dissolved oxygen	2013

2005); and rock bass, woolly-fruit sedge (*Carex lasiocarpa*), stephanodiscoid diatoms, spring peepers, and insectivorous birds (Brazner et al. 2007). The status of the Lake Michigan food web is another indicator of the ecosystem's condition; Madenjian et al. (2002) have documented changes, both positive and negative, that occurred in the food web from 1970-2000 as a result of human activities.

NPS has developed conceptual ecosystem models for long-term ecologic monitoring in both Great Lakes nearshore and coastal wetland areas (Gucciardo et al. 2004). Twenty Vital Signs (defined as "…attributes that are determined to be the best indicators of ecological condition, or respond to natural or anthropogenic stresses in a predictable or hypothesized manner, or have high value to the park or the public…") have been identified for the Great Lakes (Route and Elias 2006). Those with a priority ranking greater than 3 on a 5 point scale in the GLKN are, in descending order, plant and animal exotics, core water quality suite, water level fluctuations, advanced water quality suite, aquatic/wetland plant communities, fish communities, land use/land cover fine scale, trophic bioaccumulation, mussels and snails, sediment analysis, and toxic concentrations in sediments.

The GLKN has decided not to pursue water quality monitoring in Lake Michigan for reasons that include the amount of effort needed to adequately monitor this resource, the small amount of park area that extends into the Lake, and limited park jurisdiction over these waters. However, the GLKN hopes to conduct some monitoring of coastal wetlands in the future (GLKN, Joan Elias, Aquatic Ecologist, email, 11/13/07).

For Lake Michigan at SLBE, we have focused on core water quality parameters and fecal bacteria as key water quality indicators. Other key indicators of ecosystem health are the presence of exotic species and their effects on native species and natural ecosystems, and the water chemistry and bioaccumulative effects of atmospheric contaminants.

Inland Waters Indicators

NPS has developed conceptual ecosystem models for long-term ecologic monitoring in inland lakes (Gucciardo et al. 2004). Nineteen Vital Signs have been identified for inland lakes (Route and Elias 2006). Those with a priority ranking greater than 3 on a 5 point scale in the GLKN are, in descending order, plant and animal exotics, core water quality suite, bird communities, threatened and endangered species, water level fluctuations, advanced water quality suite, aquatic and wetland plant communities, amphibians and reptiles, fish communities, land use/land cover fine scale, trophic bioaccumulation, toxic concentrations in sediments, and phenology.

For SLBE inland waters, we have focused on traditional indicators of water quality (clarity, DO, fecal bacteria for lakes and streams with human contact, and other core water quality parameters), native biological indicators (invertebrates, unionids, herptiles, and plant communities), and presence and ecosystem effects of exotic species. Indicators of atmospheric deposition impacts on inland waters include nitrate (Williamson et al. 2008) and base cation (especially calcium and magnesium) (Hedin et al. 1994; Likens et al. 1996) concentrations in streams and rivers.

Wetland and Dune Indicators

Twenty-six Vital Signs have been identified for wetlands (Route and Elias 2006). Those with a priority ranking greater than 3 on a 5 point scale in the GLKN are, in descending order, plant and animal exotics, core water quality suite, bird communities, land use/land cover coarse scale, threatened and endangered species, water level fluctuations, advanced water quality suite, aquatic/wetland plant communities, weather/meteorological data, amphibians and reptiles, mammal communities, fish communities, land use/land cover fine scale, trophic bioaccumulation, sediment analysis, succession, toxic concentrations in sediments, biotic diversity, and stream dynamics.

Vital signs have not been established for dunes. However, in our view, the following wetland vital signs might be logically extended to dunes: plant and animal exotics, bird communities, land use/land cover fine scale, threatened and endangered species, water level fluctuations, aquatic/wetland plant communities, weather/meteorological data, amphibians and reptiles, mammal communities, fish communities, trophic bioaccumulation, succession, and biotic diversity.

Specific indicators of the health of SLBE’s wetlands include their water levels and level fluctuations; populations of native organisms, including invertebrates, unionids, and herptiles; presence of exotic species and their effects on ecosystem functions; bioaccumulation and nutrient enrichment; and physical disturbances in their watersheds that change the amount or timing of water inputs.

For SLBE’s dunes, specific indicators include physical disturbances caused by natural events as well as human use; presence of exotic species and displacement of native species; and nutrient enrichment and bioaccumulation.

Upland Resources Indicators

Seventeen Vital Signs have been identified for Northern Forests (Route and Elias 2006). Those with a priority ranking greater than 3 on a 5 point scale in the GLKN are, in descending order, plant and animal exotics, terrestrial plants, bird communities, problem species (white-tailed deer), threatened and endangered species, mammal communities, land use/land cover fine scale, special habitats, harvested species, terrestrial pests/pathogens, succession, biotic diversity, trophic relations, and phenology. Specific to SLBE, we recommend exotic plant species, atmospheric deposition, white-tailed deer browse pressure, habitat fragmentation, and exotic insects as key indicators for forests, and we add amphibian and reptile populations and aquatic/wetland plant communities for lowland forests.

Key indicators for exotic plant species include 1) new presence or increased abundance of exotics in the northern hardwood community, especially honeysuckles (*Lonicera* spp.), garlic mustard (*Alliaria petiolata*), and buckthorn (*Rhamnus* sp.); 2) abundance in the pine, oak-pine and dune assemblages of spotted knapweed, black locust (*Robinia pseudoacacia*), leafy spurge (*Euphorbia esula*), white sweet clover, and Canada thistle (*Cirsium arvense*); and 3) spread of problem species away from source populations in old fields, trailheads and trails, old home sites, and recreational sites. Atmospheric deposition indicators specific to uplands include the nitrogen content of the understory layer in pine and/or oak-pine forests, and the nitrogen concentration of select understory species.

Indicators for white-tailed deer browse pressure include 1) their level of utilization of sugar maple and browse sensitive species including trillium (*Trillium* spp.), sweetroot (*Osmorhiza* spp.), mayflower, and baneberry (*Actaea* sp.), primarily for the northern hardwood type; 2) their utilization level of the understory, and its temporal change, in the pine/oak-pine types; and 3) increases in deer density as monitored by the MDNR. Finally, the presence of exotic insects should be documented by trapping, visual observation, or other means, and their impact on forest composition must be assessed. Solid inventory data is needed on the composition of 'non-target' species; the single best long term impact indicator is the composition of the subordinate layers (midstory, understory) of the forests.

Sleeping Bear Dunes Ecosystem Stressors

Danz et al. (2007) have developed measures of anthropogenic stress to coastal ecosystems and index value ranges for all 762 watersheds in the US Great Lakes basin. These measures were in five categories (agriculture, atmospheric deposition, human population, land cover, and point source pollution), and ranged from 0 (lowest stress) to 1 (highest stress). For SLBE watersheds (28, Platte and 28L, Lake Michigan drainage) (MDEQ 1998a), index value ranges were highest for atmospheric deposition and lowest for point source pollution (Table 45; Danz et al. 2007). A cumulative stress index was also calculated, with a theoretical range of 0-5. Other stressors have been identified by various researchers, including global climate change (Madenjian et al. 2002) and invasive species, which Jude et al. (2005b) call "arguably the most serious threat to the ecological health of Lake Michigan today." A detailed analysis of the individual stressors we selected as most significant from our experience and reading of the literature follows.

Table 45. Stress measures (range 0-1) by source and cumulative stress measure (range 0-5) for the two major watersheds of Sleeping Bear Dunes National Lakeshore (Danz et al. 2007). (Values were given as ranges on a map; cumulative map was separate, so values are not additive).

Index and five most significant input variables	Range 28L (Lake Michigan drainage)	Range 28 (Platte)
Agriculture		
Phosphorus fertilizer export to streams Nitrogen fertilizer export to streams Phosphorus fertilizer applications Potash applications Phosphorus export from livestock waste	0.2-0.4	0.2-0.4
Atmospheric Deposition		
Inorganic nitrogen Chloride Nitrate Sulfate Sodium	0.4-0.6	0.4-0.6
Human Population		
Human population density Total road density Developed land Distance to nearest Area of Concern Trail density	0.2-0.4	0.2-0.4
Land Cover		
Cultivated cropland Row crops Coniferous forest Hay Mixed forest	0.2-0.4	0-0.2
Point Source Pollution		
Facilities discharging solvents Facilities discharging heavy metals Facilities discharging hydrocarbons Density of sewerage facilities Facilities discharging chlorinated compounds	0-0.2	0-0.2
Cumulative Stress Index	1.1-1.8	1.1-1.8

Atmospheric Deposition

SLBE is designated as a Class II air quality area under the Clean Air Act (CAA), which provides it additional protection against increases in air pollution beyond the general requirements of the CAA. Air pollution is a broad term that includes all forms of compounds, particles, aerosols, gases, and metals that are introduced to a system from the atmosphere. The scope of relevance here are those substances that are either strictly of human origin or entering at rates that clearly exceed the background rates, and have the potential to affect ecosystem structure, function, or composition. Air pollution may affect SLBE water resources through atmospheric deposition of nutrients and contaminants that originate locally or travel long distances from their sources. Terrestrial ecosystems may also be affected through nutrient addition or vegetation damage. Human health and visibility concerns are also related to air quality but not specifically addressed in this report.

Long-range Atmospheric Pollution

Effects of air pollution at regional and larger scales have been well documented for Lake Michigan. The Lake Michigan Mass Balance Project (LMMBP) has examined the loading and cycling of four major categories of pollutants (PCBs, mercury, trans-nonachlor, and atrazine) within Lake Michigan (USEPA 2006a). The lake's largest PCB source is gas phase absorption from the atmosphere to the surface of the lake water, followed by wet and dry atmospheric deposition and tributary loading. Major loss pathways include volatilization to the atmosphere and permanent burial in sediment. PCB concentrations are declining in all media (USEPA 2006a).

Atmospheric deposition is the largest source of mercury to Lake Michigan (LMTC 2006). It is also the largest source of the organochlorine pesticides (chlordane and DDT and its metabolites) to the lake, even though these pesticides are no longer sold or registered in the US or Canada (LMTC 2006). Transport from Mexico and Central America is one potential DDT source, although Bidleman et al. (2006) have shown that continuing emissions from midwestern agricultural soils and urban areas are also important. Southwest winds contribute PCBs, polycyclic aromatic hydrocarbons (PAHs), and mercury from the Chicago area to the lake (LMTC 2006). Atrazine, a corn herbicide, also enters the lake from the atmosphere, mainly in the southern half of the basin, although tributary loading is the greatest source. Atrazine concentrations are projected to continue to increase in the lake, based on 1994-1995 loadings (LMTC 2006). The LMMBP also examined phosphorus loading to the lake; atmospheric deposition accounts for only about 10% of Lake Michigan's phosphorus loading (USEPA 2006a). However, a 1992 USEPA report indicated that 62% of the phosphorus in Glen Lake was attributable to atmospheric deposition (USEPA Region 5 1992 in Lafrancois and Glase 2005). Other SLBE inland waters, wetlands, and uplands are likely affected by deposition of atmospheric contaminants, but except for fish consumption advisories for mercury and pesticides, the effects of atmospheric deposition in SLBE are mainly unstudied.

Local Air Emissions

The USEPA maintains a Toxic Release Inventory (TRI) of facilities (point sources) that discharge toxic materials to the environment, including into the air. For Benzie and Leelanau Counties, the only air release on the TRI came from SLBE itself, which reportedly released 0.14 kg of lead to the air in 2004 (USEPA 2007a). However, in 1999, the most recent year for which reports are available, 1,788,823 kg of toxic air pollutants were released from nonpoint sources in the two counties (663,061 kg in Benzie and 1,125,762 kg in Leelanau). Nonroad mobile sources (a category which includes two- or four-stroke and diesel engines, nonroad vehicles, aircraft, commercial marine vehicles, recreational boats, and locomotives) contributed 78% of the toxic air pollutants, or 1,387,040 kg, in 1999, while onroad vehicles contributed 2%. Area sources such as dry cleaners and gasoline stations contributed another 14% of hazardous releases (144,224 kg) (USEPA 2007b).

Facilities' air releases not categorized as toxic are listed in the USEPA's Aerometric Information Retrieval System Facility Subsystem (AIRS/AFS). Listed facilities release one or more of the criteria air pollutants (those for which numeric standards have been established): nitrogen dioxide (NO_2) (a form of nitrous oxide, NO_x), ozone (O_3), sulfur dioxide (SO_2), particulate matter (PM), and carbon monoxide (CO). In Benzie and Leelanau Counties, AIRS/AFS facilities include a landfill, sawmill, asphalt companies, sand and gravel operations, and petroleum bulk stations and terminals (Table 46, Figure 46; USEPA 2007a).

However, industries are not the primary emitters of at least some of the criteria air pollutants in Benzie and Leelanau Counties. In 2001, the most recent year for which data are available, highway vehicles contributed 58% and 43% of the 1,844 metric tons of NO_x and 18% and 11% of the 236 metric tons of SO_2 emissions released in Benzie and Leelanau Counties, respectively. Off-highway vehicles contributed 33% and 47% of the NO_x and 46% and 52% of the SO_2 emissions in these two counties, respectively. Although specific figures are not available for Benzie and Leelanau Counties, Michigan received nearly 18,000 metric tons of NO_x and 12,000 metric tons of SO_2 emissions from waterborne commerce on Lake Michigan in 1997 (Corbett and Fischbeck 2000). Overall, 34% of the SO_2 emissions, but only 7% of the NO_x emissions, came from fuel consumption in industries and homes (Table 47). These two pollutants are implicated in the formation of acid rain. Vehicles similarly accounted for 88% of carbon

Table 46. Facilities listed on the USEPA AIRS/AFS air release list for Benzie and Leelanau Counties in the vicinity of Sleeping Bear Dunes National Lakeshore (USEPA 2007a).

Facility Name	City	County	Standard Industrial Classification(s) Number and Name
Courville Cartland, Inc.	Frankfort	Benzie	2421 Sawmills and Planing Mills
H.W. Jencks, Inc.	Frankfort	Benzie	3621 Motors and Generators
Koch Material Co.	Elberta	Benzie	2951 Asphalt Paving Mixtures and Blocks 5171 Petroleum Bulk Stations and Terminals
Elmer's Crane and Dozer, Inc. (2 locations)	Maple City	Leelanau	1442 Construction Sand and Gravel 2951 Asphalt Paving Mixtures and Blocks
Elmers Lipman-Duo King PO	Maple City	Leelanau	1442 Construction Sand and Gravel
Glen's Sanitary Landfill	Maple City	Leelanau	4953 Refuse Systems
Kasson Sand and Gravel	Maple City	Leelanau	1442 Construction Sand and Gravel 1422 Crushed and Broken Limestone

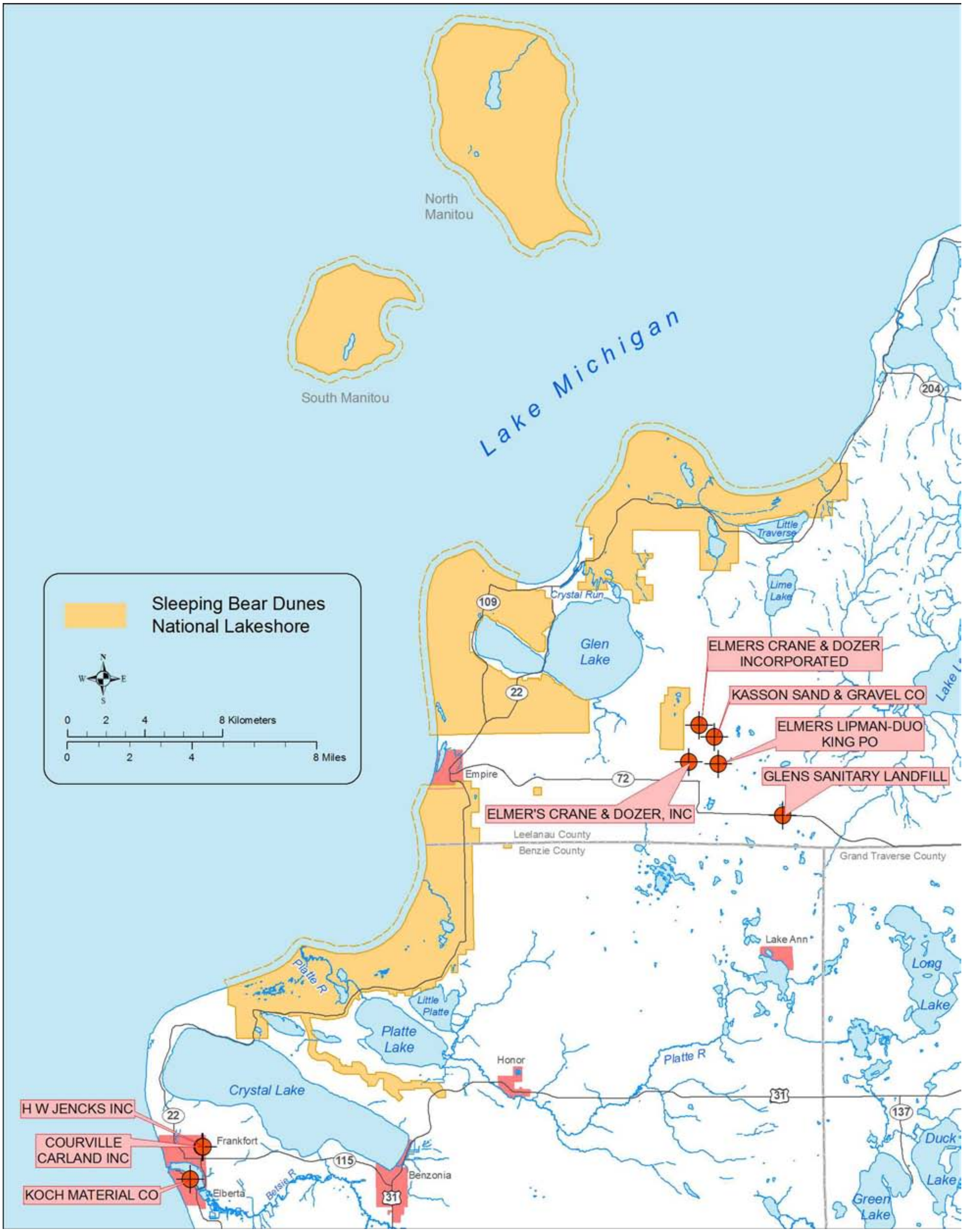

Figure 46. Locations of facilities on the USEPA AIRS/AFS air release list for Benzie and Leelanau Counties near Sleeping Bear Dunes National Lakeshore (USEPA 2007a).

Table 47. Emissions of NO_x and SO_2 by source, Benzie and Leelanau Counties, 2001 (USEPA 2007b).

	Fuel consumption (industry and home heating) (metric tons)	Waste disposal and recycling (metric tons)	Highway vehicles (metric tons)	Off-highway vehicles (metric tons)	Other (metric tons)
NO_x					
Benzie	56 (7%)	20 (2%)	489 (58%)	279 (33%)	1 (<1%)
Leelanau	81 (8%)	20 (2%)	425 (43%)	472 (47%)	2 (<1%)
Total	137 (7%)	40 (2%)	914 (50%)	751 (41%)	3 (<1%)
SO_2					
Benzie	34 (34%)	2 (2%)	18 (18%)	47 (46%)	--
Leelanau	47 (35%)	2 (1%)	15 (11%)	70 (52%)	--
Total	81 (34%)	4 (2%)	33 (14%)	117 (50%)	--

monoxide emissions and 80% of the volatile organic compound emissions in the two counties (USEPA 2007b).

Ozone (O_3), a highly reactive gas that forms from NO_x and oxygen in the presence of high radiation levels, is a criteria air pollutant that affects Benzie County and SLBE mainly from large urban areas along the southern Lake Michigan shoreline (MDEQ 2006c). Due to human activity (primarily use of internal combustion engines) that releases fairly large quantities of NO_x , the concentration of ground-level ozone at mid-to-high latitudes has more than doubled over the last century (Bortier et al. 1999). In 2004, USEPA designated Benzie County as an 8-hour ozone nonattainment area (based on the 2001-2003 monitoring data showing that the three-year average of the 4th highest ozone value [averaged over 8 hours] was above 0.085 ppm). The 2002-2004 and 2003-2005 averages have since shown that the standard was attained, but have remained at 0.083 ppm, close to the standard (MDEQ 2006c). At Peshawbestown, sufficient data were available to calculate a three-year average for the first time in 2005; that average was 0.076 ppm (MDEQ 2006c).

Ground-level ozone does not directly affect water resources, but may affect visitor health and park vegetation (Table 48). Concentrations that affect human health are similar to those at which visible symptoms appear in vegetation (0.08 ppm) (Edmonds et al. 2000). Ozone is generally considered the gaseous pollutant most damaging to vegetation because of its impact on plant tissues, its concentration in the lower atmosphere, and the transport of NO_x by winds (Smith 1985; Bortier et al. 1999). As a gas, ozone readily enters the plant via the stomates and then rapidly disassociates into peroxides and an oxygen molecule. The peroxides damage the membranes of the tissues in the leaf mesophyll, which is where much of the chlorophyll is located; thus, the photosynthetic process is quickly impaired. Photosynthesis is typically impacted prior to any visible symptoms, and thus visible injury often will not correlate well with growth loss.

In addition to chlorosis and lesions seen on foliage, the effects include premature senescence of foliage, reduced allocation of carbohydrate to the roots, loss of stomatal control and thus reduced

Table 48. Plants found in Sleeping Bear Dunes National Lakeshore that are slightly or very sensitive to ozone pollution (Maniero and Pohlman 2003).

Family	Latin Name	Common Name	Ozone Sensitivity
Aceraceae	*Acer negundo*	Boxelder	Slight
	Acer rubrum	Red maple	Slight
Anacardiaceae	*Rhus glabra*	Smooth sumac	Great
	Rhus typhina	Staghorn sumac	Great
	Toxicodendron radicans	Poison-ivy	Great
Apocynaceae	*Apocynum androsaemifolium*	Spreading dogbane	Great
Asclepiadaceae	*Asclepias exaltata*	Tall milkweed	Great
	Asclepias syriaca	Common milkweed	Great
Asteraceae	*Aster macrophyllus*	Big-leaf aster	Great
	Aster puniceus	Purple-stemmed aster	Great
	Rudbeckia hirta	Black-eyed Susan	Great
	Rudbeckia laciniata	Cut-leaf coneflower	Great
Betulaceae	*Betula alleghaniensis*	Yellow birch	Slight
Caprifoliaceae	*Sambucus canadensis*	American elder	Great
	Symphoricarpos albus	Common snowberry	Slight
Fabaceae	*Robinia pseudoacacia*	Black locust	Slight
Lauraceae	*Sassafras albidum*	Sassafras	Great
Hydrangeaceae	*Philadelphus coronarius*	Sweet mock-orange	Great
Oleaceae	*Fraxinus americana*	White ash	Great
	Fraxinus pennsylvanica	Green ash	Great
	Syringa vulgaris	Common lilac	Slight
Pinaceae	*Pinus banksiana*	Jack pine	Slight
	Pinus strobus	Eastern white pine	Great
Poaceae	*Bromus tectorum*	Cheatgrass	Slight
Rosaceae	*Prunus pensylvanica*	Pin cherry	Great
	Prunus serotina	Black cherry	Great
	Rubus allegheniensis	Allegheny blackberry	Great
	Spiraea X *vanhouttei*	Vanhoutte spirea	Slight
Salicaceae	*Populus tremuloides*	Quaking aspen	Great
Simaroubaceae	*Ailanthus altissima*	Tree-of-heaven	Great
Tiliaceae	*Tilia americana*	American basswood	Slight
Vitaceae	*Parthenocissus quinquefolia*	Virginia creeper	Great
	Vitis riparia	Riverbank grape	Slight

water use efficiency, higher rates of foliar leaching of nutrients, and increased incidence of some diseases (MacKenzie and El-Ashry 1988; Bortier et al. 1999; Karnosky et al. 2002). Under semi-controlled conditions (a free air enrichment facility), exposure of *Populus* and *Populus+Betula* to elevated ozone led to less nitrogen in both systems (Zak et al. 2007). Thus, the reduced growth that ozone causes cascades through the system and has the potential for a wide range of effects.

The effect of a given level of ozone in the atmosphere is not a constant. The impact is often influenced by the genotypes of the plants present, the species present, soil moisture, relative humidity, radiation level, and leaf age (Temple and Miller 1998; Bortier et al. 1999). Within a species (e.g., eastern white pine, sugar maple) there is a wide range of sensitivity that has a genetic basis (MacKenzie and El-Ashry 1988; Lehrer et al. 2007). Under controlled or similar ambient conditions, a specific level of ozone can have almost no effect on one species, a modest effect on another, and a severe effect on a third (Lehrer et al. 2007).

Given the levels of ozone recorded in Benzie County and the increasing population density in the northwestern portion of the LP, further impact by ozone is anticipated. On-shore breezes could reduce the impact for the vegetation near the Lake, but the extent of the reduced impact is unknown. Furthermore, even if the winds push the ozone-laden air away from the dunes most of the time, serious impacts could occur because the maximum exposure can be as important as the duration of the exposure (Bortier et al. 1999). Visible symptoms often show up after internal damage has been done and may not be a reliable guide.

Air Monitoring Stations In and Around SLBE

Both state and federal entities maintain air monitoring stations and networks in Michigan. Generally, each network monitors for a specific parameter or suite of parameters. Within SLBE, an Integrated Atmospheric Deposition Network (IADN) station operated by the USEPA and Environment Canada monitors PCBs, organochlorine pesticides, and PAHs (IADN 2002). The nearest ozone monitor, located at Frankfort/Benzonia, 9 km south, is part of the State and Local Air Monitoring Network (SLAMS) in Michigan; another at Peshawbestown, 16 km northeast, is operated by the Grand Traverse Band of Ottawa and Chippewa Indians (MDEQ 2006c).

National Atmospheric Deposition Program (NADP) National Trends Network (NTN) sites monitor wet deposition, which includes pH, sulfate, nitrate, ammonium, chloride, and base cations (calcium, magnesium, potassium, and sodium). One NADP NTN site is located at Peshawbestown, along with a National Mercury Deposition Network (MDN) station; other NADP sites with longer periods of record are found at Wellston, 58 km southeast, and Seney National Wildlife Refuge (NWR), 125 km north. Dry deposition sites, which measure sulfate, nitrate, ammonium, sulfur dioxide, and nitric acid, are operated by the Clean Air Status and Trends Network (CASTNet) at Hoxeyville and Wellston, 65 and 58 km southeast, respectively. Seney NWR is also the site of a $PM_{2.5}$ (particulate matter 2.5 microns or less in size) monitor in the Interagency Monitoring of Protected Visual Environments (IMPROVE) network (Maniero and Pohlman 2003), as well as a State of Michigan Special Purpose Monitoring Station (SPM) for monitoring carbon monoxide, a SLAMS ozone monitor, and an MDN station. A SPM station at Houghton Lake, 103 km southeast, is the nearest location to monitor volatile organic compounds (VOCs) and also monitors metals and speciated $PM_{2.5}$. Finally, SLAMS and SPM sites are found at Grand Rapids, 260 km south, which is the nearest location that monitors PM_{10} (particulate matter 10 microns or less) (Figure 47, Table 49; MDEQ 2006c).

Acid and Nutrient Deposition

Acid deposition is a subset of air pollution that includes all reactive forms of nitrogen and sulfur that do or can form acids when in contact with water. It specifically includes gases, particles, rain, snow, clouds, and fog that are composed of sulfuric acid, nitric acid, and ammonium, derived from SO_2, NO_x, and ammonia (NH_3), respectively. These compounds are emitted primarily by the burning of fossil fuels, but also by agricultural activities (Driscoll et al. 2001).

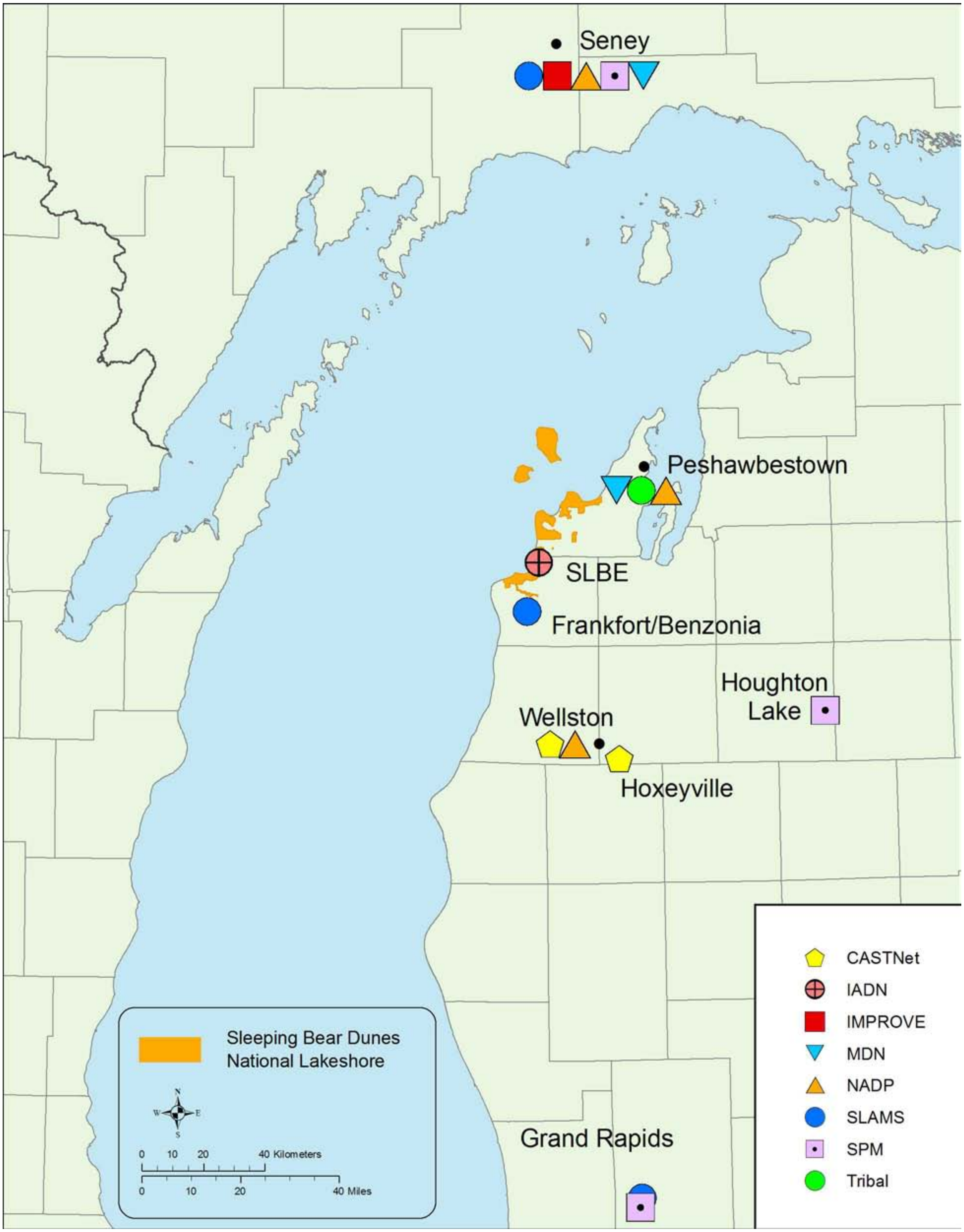

Figure 47. Locations of selected air quality monitoring stations in and around Sleeping Bear Dunes National Lakeshore (Maniero and Pohlmann 2003; MDEQ 2006c).

Table 49. Locations of selected air quality monitoring stations in and around Sleeping Bear Dunes National Lakeshore (Maniero and Pohlmann 2003; MDEQ 2006c).

Location	Distance to SLBE	Network and Operator	Parameters
SLBE	--	IADN, USEPA and Environment Canada	• PCBs • organochlorine pesticides • PAHs
Frankfort/Benzonia	9 km S	SLAMS, State of Michigan	• O_3
Peshawbestown, MI	16 km NW	NADP/NTN, USEPA/ Grand Traverse Band of Ottawa and Chippewa Indians MDN, Grand Traverse Band of Ottawa and Chippewa Indians	• wet deposition • mercury
Peshawbestown, MI	16 km NW	Tribal, Grand Traverse Band of Ottawa and Chippewa Indians	• O_3
Hoxeyville, MI	65 km SE	CASTNet, USEPA	• dry deposition • O_3
Wellston, MI	58 km SE	CASTNet, USEPA NADP/NTN, USDA-Forest Service	• dry deposition • O_3 • wet deposition
Seney National Wildlife Refuge	125 km N	IMPROVE, USFWS NADP/NTN, USFWS SPM, State of Michigan SLAMS, State of Michigan MDN, USFWS	• visibility • $PM_{2.5}$ (particulate matter, 2.5 microns or less) • wet deposition • CO • O_3
Houghton Lake	103 km SE	SPM, State of Michigan	• VOCs • carbonyls • total suspended particulate metals • speciated $PM_{2.5}$ • O_3
Grand Rapids	190 km S	SLAMS, State of Michigan	• PM_{10}

The effect of acid precipitation on aquatic ecosystems is determined largely by the ability of the water and watershed soil to neutralize the acid deposition they receive. Generally, small watersheds with shallow soils and few alkaline minerals are most sensitive to acidification. Watersheds that contain alkaline minerals such as limestone, or those with well-developed riparian zones, generally have a greater capacity to neutralize acids. Low pH levels and higher aluminum levels that result from acidification make it more difficult for fish to reproduce and decrease fish population densities and individual sizes (NAPAP 2005). Lake Michigan and

SLBE inland waters, with alkalinities over the threshold value of 25 mg/L as $CaCO_3$, are not considered particularly vulnerable to acid precipitation (Sheffy 1984; Shaw et al. 1996). However, as will be discussed later, they may be experiencing nitrogen enrichment.

The effects or potential effects of acid deposition on terrestrial ecosystems are dictated by a complex array of factors that may be grouped into four categories: 1) characteristics of the incoming compounds; 2) parent material and soil characteristics; 3) vegetation characteristics; and 4) local and regional weather. For category 1, the salient points are the amount, form (wet or dry, rain or fog, NH_4 or NO_3, etc.), duration of the elevated input, and in some cases, its timing (Johnson et al. 1983; Dittman et al. 2007).

In category 2, all forest soils have at least some capacity to buffer incoming acids. However, once this capacity is exceeded, the increasing acidity may affect system function. Buffering capacity varies by orders of magnitude among forest soils, and is largely a function of five factors (Johnson et al. 1983; Aber et al. 1998):

a) amount and makeup of organic matter from the litter (Oi) layer down
b) surface horizon texture and depth
c) B-horizon texture and depth
d) total cation exchange capacity (CEC) and base saturation, and perhaps
e) abundance of fungi and bacteria in the litter (Oi), duff (Oa, Oe), and upper soil profile.

Generally, buffering capacity is low in systems with coarse, acid soils; soils low in organic matter; and soils that are shallow. Aber et al. (1998) hypothesized that mycorrhizal fungi played an important role in a system's ability to accumulate nitrogen.

In category 3, attributes of the vegetation that can play a role include plant abundance (influencing leaf area and biomass), phenology, longevity, composition (uptake capacity, rooting system type, and depth), and leaf surface characteristics. There are several ways in which vegetation composition can have an effect: 1) throughfall composition, 2) natural acidifying effect during decomposition, and 3) nutrient uptake rates and the portion of the rooting zone from which nutrients are extracted.

Given all the factors involved, it is difficult to establish cause-effect relationships between acid deposition and effects on forest ecosystems (Johnson et al. 1983; Krug and Frink 1983; Aber et al. 2003; Dittman et al. 2007), but the effects may include direct or indirect impacts on plants, changes in forest floor and/or soil chemistry, and altered rates of mineral/nutrient accumulation and loss (Ohman and Grigal 1990; Aber et al. 1998, 2003). Possible direct effects on plants are well known (McLaughlin 1985; Smith 1985) and are all negative with the exception of a fertilization effect that nitrogen may have. This benefit has been noted in high-elevation spruce-fir of the northeastern US, but it is highly unlikely to apply to the conditions in the northern LP. The indirect effects on plants derive largely from changes in forest floor and soil chemistry, and include nutritional, toxic, and altered symbiosis effects (Hedin et al. 1994; Aber et al. 1998; Friedland and Miller 1999; Zaccherio and Finzi 2007). Changes in forest floor/soil chemistry have been intensively studied since the early 1980s (e.g., Johnson et al. 1983; Krug and Frink 1983), but the precise and complete role of acid precipitation alone is still not fully elucidated (Dittman et al. 2007).

The mean pH of rain at the NADP monitoring station at Peshawbestown has varied from 4.76 in 2002 to 4.68 in both 2004 and 2005. A longer period of record at the next nearest NADP site at Wellston, MI, 58 km southeast of SLBE, has shown a generally increasing trend from 1978 to 2005 but a downward trend since 2005 (Figure 48; NADP 2007a, b).

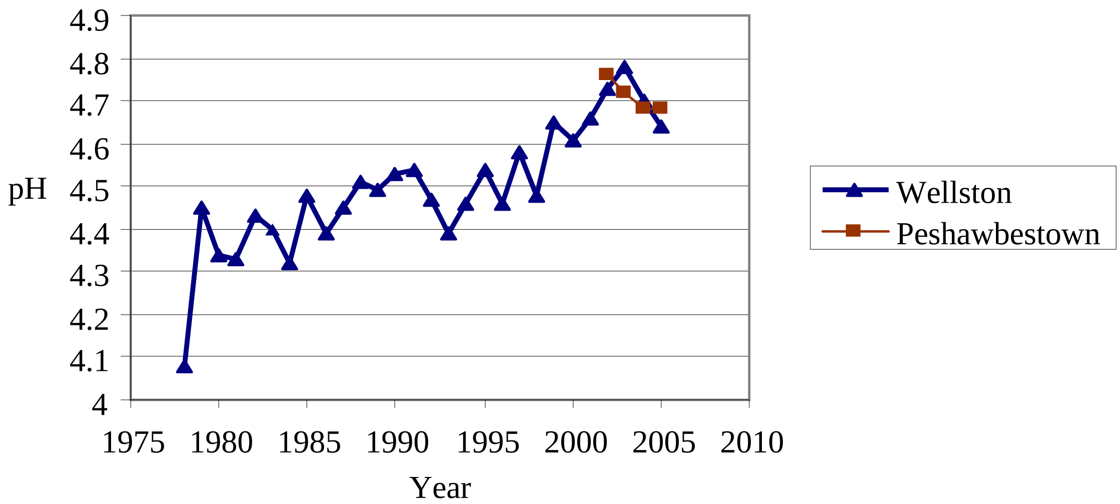

Figure 48. Annual average laboratory pH of precipitation for NADP stations at Wellston and Peshawbestown (NADP 2007a, b).

As a result of the Clean Air Act Amendments (CAAA) of 1990, sulfate wet deposition has decreased in northern Michigan. However, nitrate and ammonia emissions, which have not yet been fully addressed by the CAAA, continue to increase (Driscoll et al. 2001). It is still not clear what the best indicator is of nitrogen saturation in terrestrial ecosystems (Friedland and Miller 1999; Aber et al. 2003), and the composition of the vegetation or the degree of innate nitrogen limitation of the system appear to affect the rate at which saturation may occur (Currie et al. 1999). However, the compilation and analysis by Aber et al. (2003) indicate that some effects on terrestrial and aquatic systems are likely to occur if the nitrogen deposition rate exceeds about 8 kg/ha/yr for an extended period of time. These effects could manifest in soils, vegetation, and/or streams draining the area. A deposition rate of 8 kg/ha nitrate-N will often lead to an increase in N in stream water. Because streams and rivers integrate the deposition on land and deposition directly to the aquatic system, the N concentration in water has been suggested as a suitable sentinel of N deposition problems (Williamson et al. 2008). However, certain processes (e.g., nitrification) do not appear to be affected until the deposition rate reaches $\geq$10 kg/ha/yr.

The deposition monitoring stations near SLBE document that these areas are, and have been, receiving 5-9 kg of N/ha/yr (Figure 49). The mean wet deposition at Wellston from 1979-2005 was 3.8 kg/ha (range 3.1-4.9) NO_3-N; 2.95 kg/ha (range 1.91-3.81) NH_4-N; and 6.79 kg/ha (range 5.62-8.57) inorganic N (NADP 2007a). For Peshawbestown, which is much closer to SLBE but has a shorter period of record (2002-2005), the ranges were 2.6-3.3 kg/ha for NO_3-N, 2.28-3.20 for NH_4-N, and 4.89-6.52 for inorganic N (NADP 2007b). Although levels are variable, they appear to be declining over the period of record.

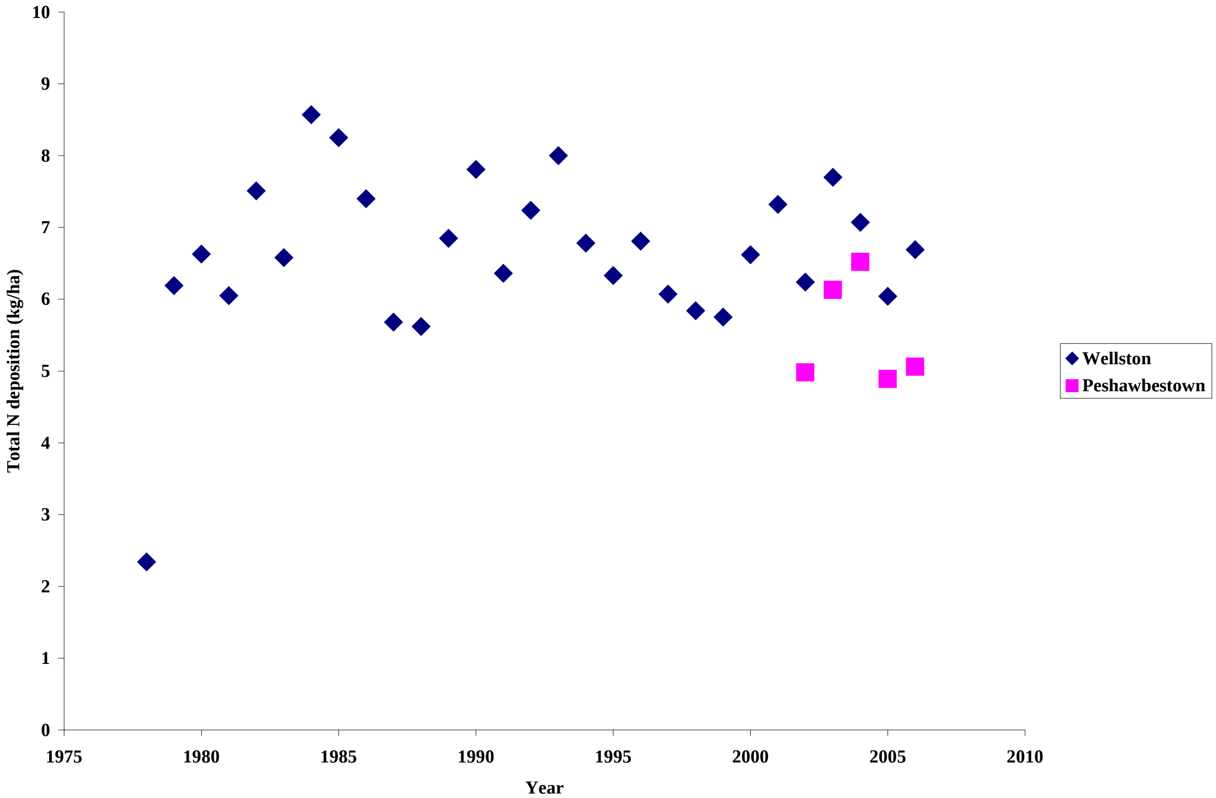

Figure 49. Annual deposition of inorganic N (NH_4-N plus NO_3-N) for NADP stations at Wellston and Peshawbestown (NADP 2007a, b).

Nitrogen form depends on whether the deposition is wet or dry. Wet deposition may include HNO_3, NO_3^-, and NH_4^+. Dry deposition includes HNO_3, particulate NO_3^-, particulate NH_4^+, and NH_3 (NAPAP 2005). Of total nitrogen deposition at Hoxeyville from 2002-2004, 84.8% was wet deposition, while the remaining 15.2% was dry deposition (USEPA 2007c).

Though the data are quite limited, shifts in relative abundance, if not presence, of common understory species could occur. Canada mayflower and starflower moved in opposite directions in response to increasing nitrogen in a red pine forest, and one fern appeared to be at a sharp competitive disadvantage as nitrogen was added (Rainey et al. 1999). Additionally, the high nitrate values noted in some SLBE surface waters (e.g., Otter Creek) may be related to deposition rates; this topic merits further investigation.

In addition, the emission and atmospheric deposition of base cations that help counteract acid deposition have declined significantly since the early 1960s with the enactment of particulate matter pollution controls (Driscoll et al. 2001); a concentration trend of -1.2 µeq/L $year^{-1}$ was observed for 12 stations in the Midwest (including three in Michigan) from 1979-1990 (Hedin et al. 1994). The deposition data from Wellston do not indicate a downward trend in calcium input since 1978, but magnesium has declined 31% since 1990.

Caution should be exercised when extrapolating from one geographic area to another, but the northeastern US has the longest record of data on this issue and thus can highlight possible effects. A decline in base cation input has been documented for the northeastern US and Europe (Hedin et al. 1994; Likens et al. 1996) for more than 40 years. Additionally, large quantities of magnesium and calcium have been lost from the soil in the northeastern US (Likens et al. 1996; Friedland and Miller 1999). Differences in land use and soils clearly exist between the NE and the Lake States, and other relevant factors probably differ. However, it is probable that base cation loss at accelerated rates has been occurring at SLBE. Cations such as calcium, magnesium, and potassium are likely to leach from forests as NO_3^- concentrations increase and percolate through the profile. This is most likely, or likely to occur at a higher rate, on sites that are, or have become, N-saturated. Each of these cations is needed by plants and decomposers in fairly large amounts, and thus have the potential to become a limiting resource. Magnesium, which is necessary for photosynthesis, seems the most likely to become limiting due to the reduced input since 1990, particularly for any of the upland ecosystems on sandy soils.

Phosphorus deposition through gas, particulate matter, and precipitation was monitored as part of the LMMBP (Miller et al. 2000). Volume-weighted mean deposition of TP from 1994-1995 was 6.36 µg/L lakewide and 4.64 µg/L for the SLBE station (Miller et al. 2000), which yields a phosphorus loading rate of 0.05 kg/ha/year.

Great Lakes Shipping

The Great Lakes are an important water highway for the transfer of goods and materials. Cargo ships may affect aquatic ecosystems in numerous ways, including the introduction and transfer of aquatic exotic species; emissions of air pollutants such as oxides of sulfur and nitrogen; accidents that spill cargo or fuel; normal losses of fuel during engine operation; transfer of substances in biocides and antifouling paints to the water; noise and vibration; propeller wash, surge, and wake; groundings and anchoring; wildlife encounters; and discharges of garbage, cargo sweepings, human sewage, dunnage (material placed between cargo during shipping), ballast water, and bilge water (Lewey et al. 2001; Transport Canada et al. 2007). Ballast water and bilge water are described in more detail below.

Many regulations are in place to attempt to prevent water pollution from both recreational boating and commercial shipping activities. The International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) and its amendments is an international treaty that addresses pollution from oil, noxious substances, harmful substances in packaged form, sewage, garbage, and air pollution (International Maritime Organization 1978). The Refuse Act of 1899 prohibits the throwing of any refuse into the waters of the United States (Code of Federal Regulations 1899). The Federal Water Pollution Control Act prohibits the discharge of oil or hazardous substances into US navigable waters (Code of Federal Regulations 1987). All vessels with propulsion capability must have capacity to retain oily materials on board. Coast Guard regulations make it illegal to dump plastics, dunnage, lining and packaging materials, and garbage (except dishwater, greywater, and fresh fish parts) anywhere in the Great Lakes. The discharge of raw sewage from boats is also prohibited in the Great Lakes, and no discharge of treated sewage from marine sanitation devices is permitted in Michigan waters of Lake Michigan (USEPA 2005c). Ballast water rules are discussed in the Ballast Water section below.

Cargo

In 2004, four cargoes accounted for 95% of the weight of cargo carried on the Great Lakes (iron ore, 41.4 million metric tons; limestone, 26.0 million metric tons; coal, 18.1 million metric tons; and cement, 3.6 million metric tons). Other cargoes accounted for an additional 4.9 million metric tons. Indiana Harbor on Lake Michigan is the top port in receipts, receiving 20% of all cargo shipped on the Great Lakes (US Department of Transportation 2005). The Great Lakes-St. Lawrence Seaway System is considered "underutilized" (Transport Canada et al. 2007), and the "Hwy H2O" program has been established to promote marine transportation and attract new shippers. As a result, the St. Lawrence Seaway Management Corporation (SLSMC) reported in 2006 that new cargoes attracted to the system had doubled since the previous year (SLSMC 2006).

The largest cargo vessels on Lake Michigan generally use shipping lanes 8 km or more west of South Manitou Island on southbound routes to deliver coal, grain, or iron ore pellets to ports in Illinois and Indiana (Benn 2004). However, northbound ships are instructed to use the Manitou Passage between the SLBE mainland and the Manitou Islands, coming within 3 km of North Manitou Island and 5 km of South Manitou Island, Pyramid Point, and Sleeping Bear Point (Figure 50; NOAA 2007a). These ships would likely be carrying grain from Milwaukee, Chicago, or Burns Harbor; coal from Calumet; or general cargo from Milwaukee, Chicago, or Indiana Harbor. Other products shipped on Lake Michigan and having the potential to be aboard southbound cargo ships that may choose to use the Manitou Passage include iron ore, limestone, salt, cement, liquid bulk (chemicals or petroleum products), gypsum, potash, coal, and sand and gravel. Numerous ports along the eastern Lake Michigan shoreline receive limestone, including St. Joseph, Holland, Grand Haven, Muskegon, Ludington, and Manistee. Holland, Grand Haven, Muskegon, and Manistee also receive coal (Lake Carriers' Association 2006). Documented discharges from ships using the Manitou Passage include oil spills and human wastes; in addition, medical wastes found on SLBE beaches are suspected to be from passing ships (Vana-Miller 2002). The risk of a shipwreck or accident that could result in a spill of fuel or cargo in the Manitou Passage is not insignificant; sixteen shipwrecks are known in the Manitou Passage underwater preserve (Michigan Underwater Preserve Council 2004). Some of these wrecks periodically leak petroleum products (Vana-Miller 2002).

Fuel and Engine Types

Both oceangoing ships ('salties') and ships confined to the Great Lakes ('lakers') carry cargo on Lake Michigan. Of the 646 trips made by cargo vessels to the port of Burns Harbor, Indiana in 1996, 266 were made by lakers, and the remaining 380 were made by salties (USEPA 1999). These cargo ships are very large vessels that carry large volumes of fuel. A typical 305 m laker carries 689 m^3 of primarily #6 fuel oil (a heavy fuel oil [HFO] also known as residual fuel or bunker C fuel), 167 $m^3$of #2 fuel oil (a lighter diesel fuel), and 72 m^3 of lube and waste oil (US Coast Guard, Greg Schultz, pers. comm. 2005). The vast majority of salties burn HFO, although some use intermediate weight marine distillate oil or lightweight marine gas oil (Corbett and Koehler 2003).

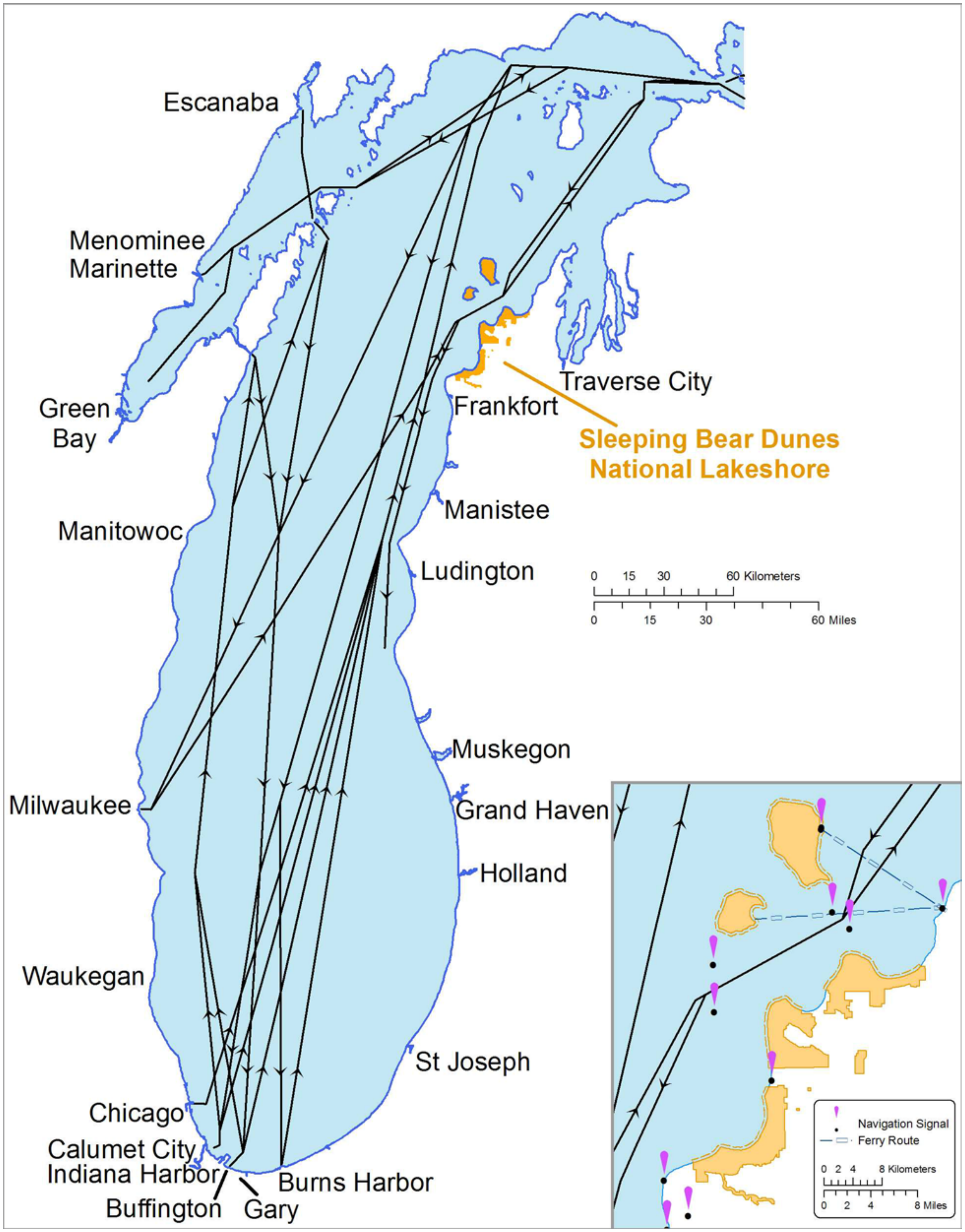

Figure 50. Lake Michigan shipping lanes (NOAA 2007b, c).

The type of fuel burned depends in large part on the speed and type of the engine. A 2003 study of oceangoing transport ships showed that 91% of the bulk carriers and tankers, and 100% of large container vessels, were operated with two-stroke engines, and 95% of low-speed two-stroke engines burn HFO. Seventy percent of four-stroke, medium speed engines also burn HFO, while the remaining 30% burn intermediate weight marine distillate oil or lightweight marine gas oil (Corbett and Koehler 2003). Lakers tend to have USEPA Category 2 engines (USEPA 2002), which have a smaller displacement per cylinder (and are therefore less powerful) than the Category 3 engines in most oceangoing ships (USEPA 2004). At Burns Harbor in 1996, 362 of the trips were made with two-stroke engines, 253 with four-stroke engines, and 31 with steam turbine engines (USEPA 1999). Increased risks of operating two-stroke engines are twofold; they tend to use heavier fuels that would be harder to clean up in a spill, and they operate less efficiently and generate more emissions than four-stroke engines.

The potential harm from an oil spill resulting from a bulk cargo vessel running aground was evaluated for Isle Royale National Park in Lake Superior in a simulation assuming a spill of approximately 100 m^3 of Intermediate Fuel Oil (Rayburn et al. 2004). The researchers concluded that shoreline cleaning methods for freshwaters are not well documented, and that floating platforms would be needed in the nearshore environment for cleanup operations. The greatest risks occurred under the “natural recovery” scenario and included catastrophic losses to coastal wetland macroinvertebrates; shoreline vegetation, herptiles, and birds; and nearshore fish. Critical losses were also anticipated for birds and fish in coastal wetlands, wolves, and shoreline mammals.

In 2000, the USEPA led an interagency effort to develop atlases that showed sensitivity of water resources in its Region 5 to oil spills. The report for Eastern Lake Michigan shows that SLBE has 25.3 km of sand beaches, 61.2 km of mixed sand and gravel beaches, and 5.5 km of gravel beaches, all with low-medium sensitivity (Figure 51, Table 50). In the Mainland-South Unit, 11.4 km of shoreline have not been evaluated and are unclassified (USEPA Region 5 2000). SLBE managers consider these to be some of the park’s most sensitive shoreline; some was previously considered for National Natural Landmark status, and Platte Point is a nesting area for the endangered piping plover. Other particularly sensitive areas according to SLBE managers are North Bar Lake, especially during times of high water, and piping plover nesting sites on North Manitou Island (SLBE, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). SLBE is covered by the Northern Michigan Sub-area Contingency Plan for oil spills (Great Lakes Commission 2001).

Bilge Water

Bilge water is the water that collects at the bottom of the hull of a ship or boat. It is often contaminated with fuel as well as oily materials used to lubricate the boat’s moving parts. Bilge water may also carry solid wastes, and often has a high oxygen demand (Copeland 2005).

Although MARPOL 73/78 specifically forbids the discharge of bilge water that produces a sheen or has an oil content of more than 15 ppm (International Maritime Organization 1978), illegal bilge discharges from ships and boats do occur. Specific data for the Great Lakes were not found, but data on ships’ practices in the ocean may provide some insight into possible risks to Lake Michigan. Currently, 50% of the oil entering the sea from shipping activities comes from bilge

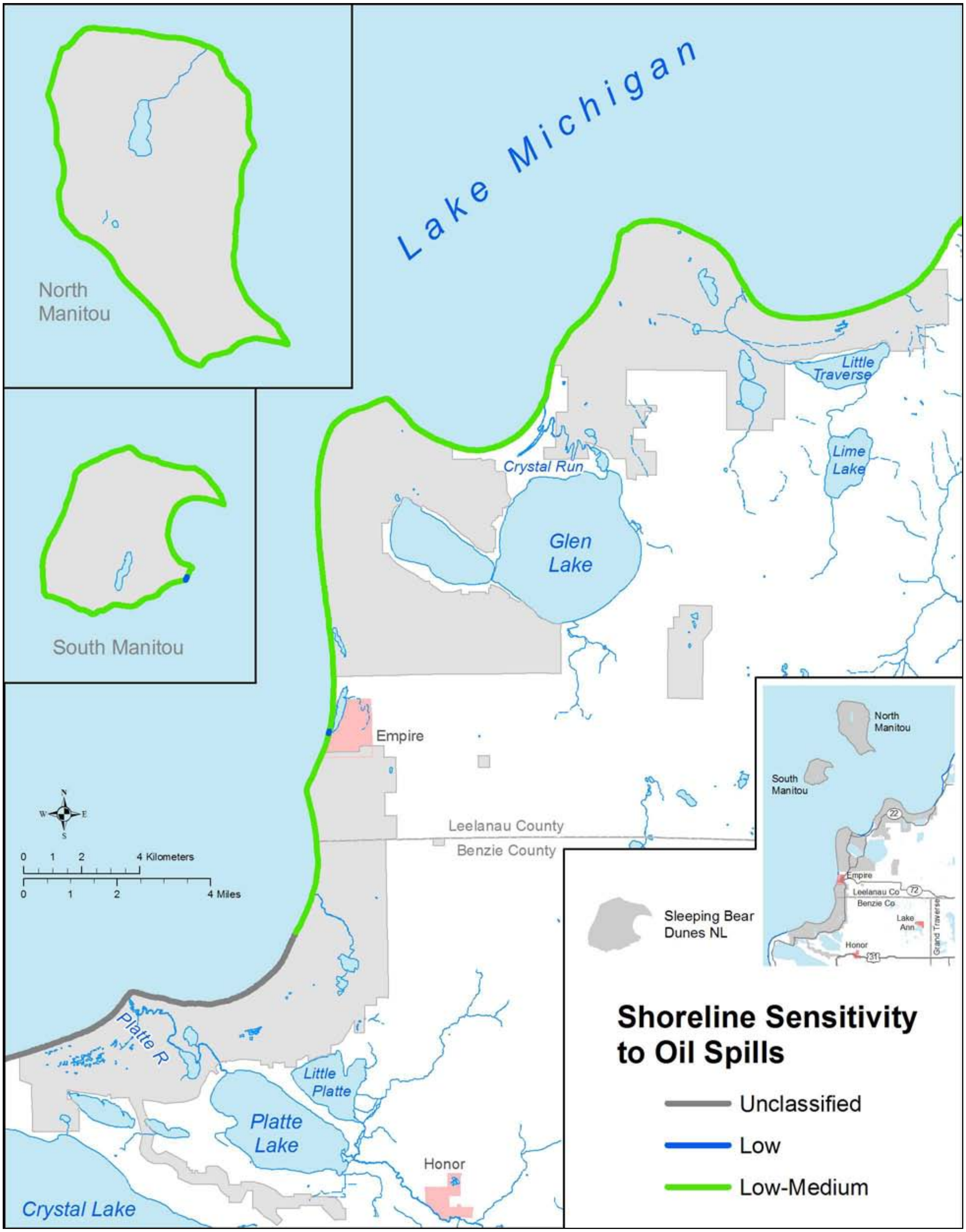

Figure 51. Shoreline sensitivity classifications for Sleeping Bear Dunes National Lakeshore (USEPA Region 5 2000).

Table 50. Shoreline types and sensitivity classifications for Sleeping Bear Dunes National Lakeshore (USEPA Region 5 2000).

	Shoreline Length (km)					
	North Manitou	South Manitou	Mainland-North	Mainland-Central	Mainland-South	Park
Low Sensitivity						
Riprap revetments, groins and jetties		0.1				0.1
Low-Medium Sensitivity						
Eroding scarps in unconsolidated sediments			0.3			0.3
Sand beaches	9.3	6.2	2.3	3.1	4.4	25.3
Mixed sand and gravel beaches	18.8	14.4	15.2	10.6	2.2	61.2
Gravel beaches	5.5					5.5
Unclassified					11.4	11.4
TOTAL	33.6	20.8	17.9	13.8	18.0	104.0

and fuel oil sludges, mainly due to the lack of onshore reception facilities, according to the Ocean Conservancy (2001). A study of foreign-flag cruise ships found 72 cases in which they had discharged oil or oil-based products into US waters between 1993 and 1998 (USGAO 2000). In 2002, the World Wildlife Fund of Canada reported that 300,000 birds are killed each year on Canada's ocean coast because of illegal bilge discharges (Wiese 2002). Bird mortality rates in the US were significantly lower. Fines up to 1000 times higher were thought to dissuade more ships from discharging in US waters.

Ballast Water

Ballast water is water carried in special holding tanks on a ship to allow for trimming and more efficient and safe sailing. Ballast water is usually taken on board when cargo is unloaded and discharged when cargo is loaded. Billions of gallons of ballast water are discharged in the Great Lakes each year. Concerns with ballast water discharges center around the possible introduction of exotic invasive species. Ballast water and residual mud found in empty ballast tanks contain organisms ranging from bacteria and algae to worms and fish. Grigorovich et al. (2003) identified 67% of the 43 aquatic animal and protist species introduced and established in the Great Lakes since 1959 as having originated in ballast water from commercial vessels.

The state of Michigan has established a general permit system for ballast water reporting on the Great Lakes for ships that enter from the Atlantic Ocean. Permit holders must demonstrate that they do not discharge ballast water into state waters or that they have treated the water with hypochlorite or chlorine dioxide, or by deoxygenation or ultraviolet light preceded by suspended solids removal. The permit system does not apply to lakers that move only within the Great Lakes (MDEQ 2006d). However, the MDEQ maintains a list of oceangoing ships that report compliance with the "Code of Best Management Practices for Ballast Water Management" provided by the Shipping Federation of Canada and of nonoceangoing vessels that report compliance with the "Voluntary Management Practices to Reduce the Transfer of Aquatic Nuisance Species within the Great Lakes by United States and Canadian Domestic Shipping," provided by the Lake Carriers' Association and the Canadian Shipowners' Association to the MDEQ (MDEQ 2002).

Recreational Boating

All SLBE waters are closed to personal watercraft (PWC), including the waters of Lake Michigan within 0.4 km of the mainland and island shores and all inland lakes. PWCs are also prohibited from between the closure buoys on Little Glen Lake, and the midpoints of Bass Lake (Leelanau), Crystal River, Shalda Creek, Platte River, Loon Lake, and Otter Creek, to the NPS-owned shorelines. The use of motors at no-wake speeds is permitted on Loon Lake, the Platte River, Bass Lake (Leelanau), the Crystal River, and School Lake, and is either physically impossible or prohibited on other lakes wholly contained within the park (NPS 2006b).

In general, the major impacts of motorized watercraft on aquatic ecosystems may include sediment resuspension, water pollution, disturbance of fish and wildlife, destruction of aquatic plants, and shoreline erosion. The mechanisms by which these impacts occur include propeller contact with plants and animals, turbulence caused by the propulsion system, wakes, noises, and movement that disturbs wildlife (Asplund 2000). Recreational boating may also help to transfer invasive species; this effect is discussed in the Introduction Pathways and Control Strategies subsection of the Exotic Species-Aquatic section.

Conventional two-stroke outboard engines contribute to both air and water pollution because they burn gasoline inefficiently and discharge as much as 30% of their fuel to the environment. Direct-injection two-stroke engines are cleaner than conventional engines, but still not as clean-burning as four-stroke engines. For example, when 90-horsepower gasoline-powered outboard motors are compared, a conventional two-stroke engine creates 164 g of smog-forming pollution per kilowatt-hour, while a direct-injection two-stroke engine creates 45 g and a four-stroke engine creates 11 g (California Environmental Protection Agency Air Resources Board 1999). The primary water and sediment pollutants of concern from marine engines are MTBE (methyl tertiary butyl ether), PAHs, BTEX (benzene, toluene, ethylbenzene, and xylene), and heavy metals such as copper (NPS 2002).

Ferries, Marinas, and Docks

Manitou Island Transit operates ferry service from its dock at Leland to both North and South Manitou Islands daily from mid-June to Labor Day, and less often at other times of the year. Its main ferry is the *Mishe-Mokwa*, which was built in 1966, has a diesel engine, and is 20 m in length. The company also owns the *Manitou Isle*, a 16-m diesel-propelled ferry built in 1946 (LeLievre 2006). The ferries land at docks maintained by NPS; the North Manitou dock is 93 m long with an 87 m 'T' at the end, while the South Manitou dock is 34 m with an 'L' of 29 m at the end. Mooring of private boats at the docks is allowed, but limited to 30 minutes from May 1 to November 20.

Marinas on Lake Michigan in the SLBE vicinity are located at Leland, 8 km north of SLBE, and Frankfort, 8 km south. Public docks constructed at both locations by the Michigan State Waterways Commission provide transient berths, gasoline, diesel fuel, water, electricity, and sewage pump-out (NOAA 2007a). Two private marinas also exist at Frankfort. Three marinas provide services and amenities for boaters on inland lakes around SLBE. One is located along Hwy M-22 in the narrows between Big Glen and Little Glen lakes, another is on Big Glen Lake just outside of Glen Arbor, and the third is on the east side of Fisher Lake just upstream from the Crystal River.

Pollution sources at marinas may include boat washing, repair and maintenance activities, runoff from parking lots and piers, fuel and oil spills, dirty bilge water, improper sewage disposal, and garbage disposal (Ocean Conservancy 2001). Recent research in Isle Royale National Park found clear evidence of PAH contamination in sediments at significant levels near marinas (Clements and Cox 2006).

The North and South Manitou island docks might also be considered ‘marinas’ in the sense that transfers of fuel and human waste occur there. NPS boats transfer fuel oil by trailer to a 3,800 L tank on North Manitou and a 38,000 L tank on South Manitou, and gasoline to a 3,800 L tank on South Manitou. On North Manitou, approximately 1,100 L of gasoline is stored in the trailer-mounted tank. NPS trailers and boats also haul sanitary sewage and garbage to the docks and from the islands. The docks also provide an avenue for exotic species (mainly plant seeds) to reach the islands on visitors’ footwear and equipment (SLBE, Steve Yancho, Chief of Natural Resources, SLBE, email 10/25/07).

Commercial and Sport Fishery

Commercial fishing in Lake Michigan began around 1840, primarily for whitefish, which were very abundant nearshore (Wells and McLain 1973). Other commercially important species in the 1800s were lake sturgeon, lake trout, lake herring, and deepwater ciscoes (Eshenroder et al. 1995). For larger species, such as lake trout, lake whitefish, and lake sturgeon, maximum commercial harvest occurred before 1897 (Table 51; Baldwin et al. 2002).

Before the 1930s, exploitation was the greatest cause of changes in native fish populations in Lake Michigan. Introduction of smelt in the 1930s had some influence, but the impact of the sea lamprey and the alewife outweighed the fisheries impact after their introductions in the 1940s and 1950s, respectively. Accelerated eutrophication and other pollution has been less influential on native fish populations than have exploitation and exotic species introductions (Wells and McLain 1973).

The native fish community has been significantly and perhaps irreversibly altered by the deliberate introduction of salmonines, including pink, Atlantic, coho, and Chinook salmon, and rainbow and brown trout (Eshenroder et al. 1995). The latter four species, along with native lake trout, are major contributors to the sport fishery, and Chinook salmon and lake trout are currently harvested commercially (Holey and Trudeau 2005; NOAA 2007d). Other species, including yellow perch, whitefish, and ciscoes, have also been important as commercially harvested species. Most salmonines except for pink salmon are stocked, but Chinook, coho, and pink salmon and rainbow trout have also naturalized. Populations of yellow perch, smallmouth bass,

Table 51. Commercial harvest of Lake Michigan fish from 1867-2000 (Baldwin et al. 2002) and in 2005 (NOAA 2007d).

Species	Maximum Harvest (kg) 1867-2000	Year	2005 Harvest (kg)	2005 Dollar value
Alewife	21,956,000	1977	19,469	$4,300
Herring and Chubs	12,358,000	1908	--	--
Chubs	5,742,000	1960	820,858	$1,276,079
Lake Whitefish	5,457,000	1879	2,043,958	$2,929,227
Lake Herring	4,396,000	1952	--	--
Smelt	4,129,000	1958	306,574	$338,026
Lake Trout	4,091,000	1896	101,279	$74,680
Round Whitefish	3,415,000	1993	6,079	$2,763
Yellow Perch	2,955,000	1894	10,709	$53,285
Suckers	1,830,000	1917	11,184	$2,732
Lake Sturgeon	1,742,000	1882	--	--
Carp	1,471,000	1974	--	--
Coho Salmon	1,017,000	1970	--	--
Walleye	612,000	1950	8,698	$11,569
Channel Catfish	176,000	1945	48	$11
Burbot	124,000	1975	6,191	$4,788
Northern Pike	116,000	1908	--	--
Bullheads	104,000	1947	145	$0
Sheepshead	63,000	1944	--	--
Chinook Salmon	26,000	1995	2,424	$1,640
Pacific Salmon	24,000	1989	--	--
Freshwater Drum	--	--	1,089	$0
White Bass	--	--	92	$133
White Perch	--	--	568	$635

pike, catfish, and panfish are self-sustaining, but walleye still require stocking. Among benthivores, lake whitefish, round whitefish, suckers, and burbot are self-sustaining, but sturgeon populations are low (Holey and Trudeau 2005).

As of 2007, the status of salmon and trout in Lake Michigan was mixed, with a slightly improving trend. Lake trout have not yet achieved self-sustaining populations. Preyfish population status is also mixed, with a deteriorating trend. Both native and non-native preyfish populations are in decline. Walleye harvests have improved but are below target levels (USEPA and Environment Canada 2007). In 2000, the productive capacity of Lake Michigan fish habitat was considered good (Holey and Trudeau 2005).

The lake whitefish was the most important fish species commercially harvested in Lake Michigan in 2000, with a value of just over $5 million (Kinnunen 2003). Throughout the 1990s, most lake whitefish and lake trout harvested from Lake Michigan were taken from Michigan waters (Kinnunen 2003). In 2005, the most recent year for which data are available, the commercial value of lake whitefish taken from Michigan waters was nearly $3 million. Chub harvest in Michigan waters accounted for another $1.3 million in value (Table 51; NOAA 2007d).

A cursory look at commercial fishing landings in Lake Michigan for the state of Michigan shows a large decline in harvest over the last decade for some species, especially yellow perch, lake trout, lake whitefish, and Chinook salmon (Figure 52). While these declines may be in part due to management changes, they are likely also related to biological changes in the lake (NPS, Jay Glase, Great Lakes Area Fishery Biologist, pers. comm., November 2008). Lake whitefish experienced large declines in fish condition during the 1990s following the invasion of zebra mussels and declines in *Diporeia* in the lake (NOAA 2006b).

In 2006, 12,064 charter angling excursions occurred in the Michigan waters of Lake Michigan and its tributaries (Wesander and Clapp 2007). Nearly 113,000 fish were harvested; 81,675 (72%) were Chinook salmon, and the remainder were lake trout (8,206), rainbow trout (7,385), yellow perch (6,846), coho salmon (6,116), walleye (1,922), brown trout (435), and other fish. Five hundred sixty-nine of these trips left from the port of Leland, 8 km N of SLBE; 5,345 fish were harvested: 4,684 Chinook salmon, 574 lake trout, 84 rainbow trout, two brown trout, and one coho salmon (MDNR 2007b).

Recreational fishing is a popular activity on SLBE inland lakes. Recently, a run on perch during the ice fishing season brought over 70 vehicles to Loon Lake (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., January 2008). Concerns with recreational fishing on inland lakes include trash and human waste disposal, spread of VHS and other aquatic invasives, ingestion of lost lead weights by birds, and release of bait species into inland waters.

In 2007, MDNR, the US government and five Michigan Indian tribes reached an agreement on tribal inland hunting, fishing, and gathering rights in the 1836 Treaty area of Michigan, which includes SLBE. Under the agreement, tribes can establish rules for their members regarding natural resource use, and tribal members may harvest natural resources for their own subsistence use from tribal lands and from lands open to the public. The impact of this agreement on fishing, hunting, and gathering in SLBE is not yet known (NPS 2006e; MDNR 2008a).

Exotic Species-Aquatic

At SLBE, known accidentally introduced exotic fish are the alewife, common carp, sea lamprey (Kelly and Price 1979), and round goby (Michigan Sea Grant 2007a). Rusty crayfish (*Orconectes rusticus*), zebra mussels (Murphy 2004a), and quagga mussels (Quinlan et al. 2007) have also been found.

Exotic aquatic animals considered to be encroaching on SLBE include the ruffe (*Gymnocephalus cernuus*), found in Lake Michigan in Little Bay de Noc and Big Bay de Noc (Czypinski et al. 2007), white perch (*Morone americana*) (NPSpecies 2007), and threespine stickleback (*Gasterosteus aculeatus*) (Quinlan et al. 2007). The fishhook water flea has been found in Lake Michigan (Charlebois et al. 2001). The spiny water flea is in Big Platte Lake near SLBE and may be in Loon Lake in SLBE (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). VHS and bloody red shrimp are relatively new aquatic invasive species in Lake Michigan.

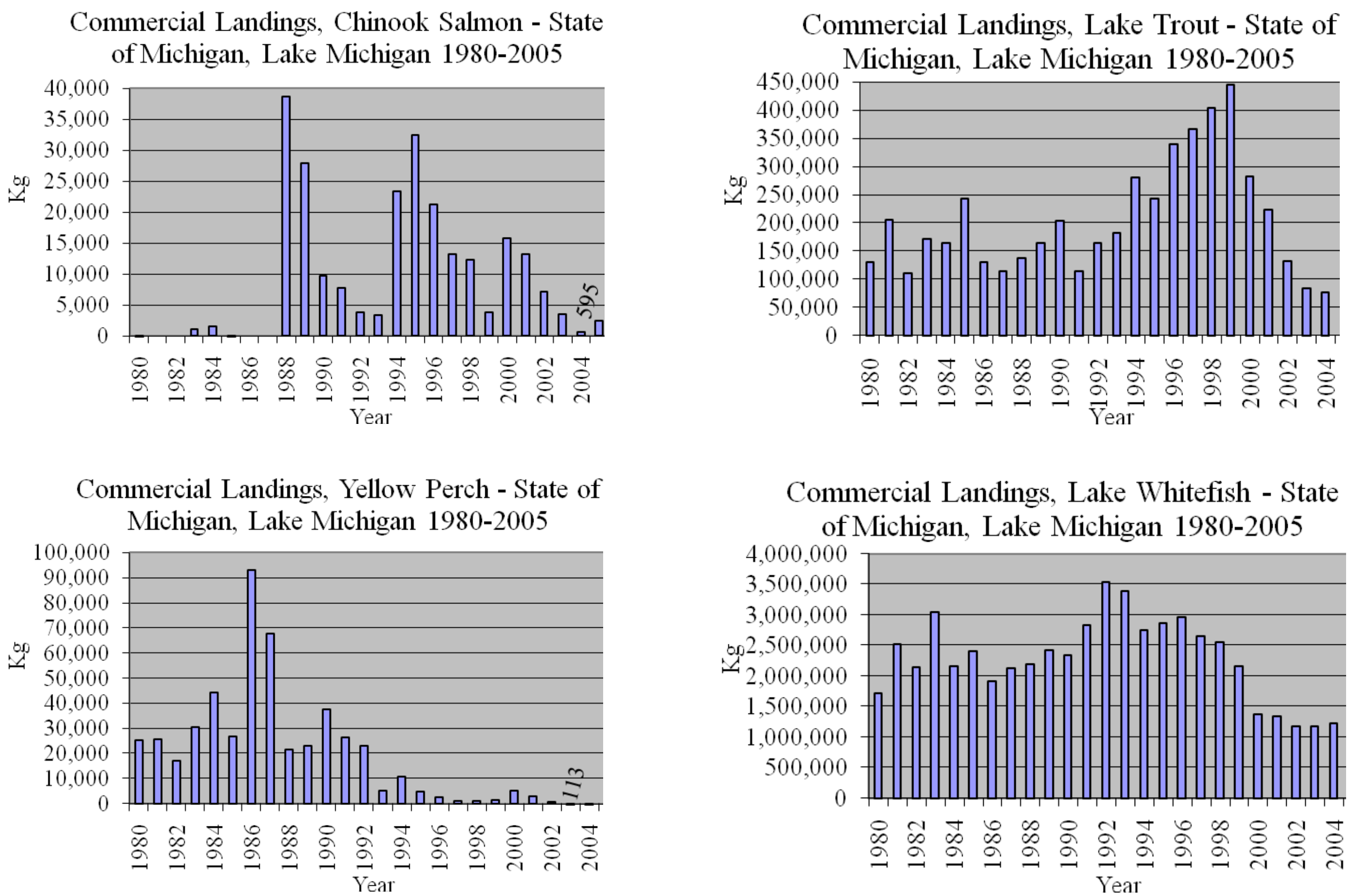

Figure 52. Commercial fishing landings in State of Michigan waters of Lake Michigan for Chinook salmon, yellow perch, lake whitefish and lake trout for the years 1980 – 2005.

Exotic aquatic plants identified within SLBE by Hazlett (1986) are purple loosestrife, curly leaf pondweed, Eurasian water-milfoil, watercress, and brittle naiad (*Najas major*). The common reed was also identified by Pavlovic et al. (2005). A non-native hybrid cattail has been identified at SLBE by Joy Marburger of INDU (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Aquatic Exotics Known in SLBE

Sea Lamprey: Sea lampreys, native to the Atlantic Ocean, were first reported in Lake Michigan near Milwaukee, Wisconsin in 1936 and spread rapidly through the lake in the 1940s and 1950s (Smith and Tibbles 1980). Lamprey predation and fishing pressure are believed responsible for extirpation of Lake Michigan lake trout in the 1950s (Jonas et al. 2005).

Adult lampreys spawn on gravel beds in tributary streams, and immature lampreys grow from 3-7 years before migrating into the lake. Adults parasitize fish, especially lake trout. The number of adult sea lamprey in the Lake declined by 85% after chemical treatment of streams to kill larval lamprey began in the 1960s. Populations have been increasing since then, especially in the northern part of the Lake. However, in 2001, the lakewide population was estimated at only 94,454, only 10% of the 1.1-1.3 million estimated at the peak in the 1950s. In SLBE, the Platte River is categorized as category 1 (highly productive habitat), and Shalda Creek is a category 2 (moderately productive habitat) stream for sea lamprey (Lavis 2005). The sea lamprey has been reported in SLBE in the Platte and Crystal Rivers, Platte Lake, and the mouth of Shalda Creek (Kelly and Price 1979).

Alewife: The alewife is a planktivorous marine member of the herring family, first found in Lake Michigan around 1949 (Smith 1970). Alewife are considered beneficial as prey for salmonines, but are detrimental to zooplankton and the pelagic larvae of native fish species (Jude et al. 2002). In SLBE, alewife have been reported in the Platte and Crystal Rivers, Platte Lake, the mouth of Shalda Creek, Little Traverse Lake, Lime Lake, Narada Lake, and North Bar Lake (Kelly and Price 1979).

Common Carp: Common carp were introduced to the Great Lakes basin in the 1800s as a food fish. They damage shallow habitats used by spawning native fish and waterfowl by rooting around in the substrate, dislodging aquatic macrophytes and increasing turbidity (Jude et al. 2002; USGS 2007a). Carp have been reported in SLBE in the Platte River and Platte Lake (Kelly and Price 1979).

Rusty Crayfish: Rusty crayfish are native to the Ohio River basin, but are considered a threat to Michigan's native crayfish populations (MDNR 2007c). They are easily transported as live fish bait, in bait bucket water, and in live wells, although it is illegal to take, possess, or sell them in Michigan. They inhabit lakes, ponds, and streams (including pools and riffles), and prefer areas that have rocks and/or logs as cover (Gunderson 2006). They are aggressive toward other crayfish (Capelli 1982), destructive of aquatic macrophytes (Lodge and Lorman 1987), and consume twice the food of the similar sized *Orconectes virilis*, a crayfish native to Lake Michigan (Janssen and Quinn 1985; Momot 1992). Rusty crayfish have been reported in Lake Michigan near Traverse City (Quinlan et al. 2007) and in SLBE in Otter Lake (Murphy 2004a).

Zebra and Quagga Mussels: Invasions of zebra mussels and quagga mussels (dreissenids) are a major concern in the Great Lakes because of the resulting catastrophic decline of native mussels. These two species have expanded their ranges at an alarming rate due to their wide environmental tolerances and high reproductive rate (Nichols 1993). They are very mobile and colonize most hard surfaces, including the shells of native mussels (Nichols et al. 2001). They are omnivores as adults, and will feed on algae, zooplankton, their own young, and detritus. Quagga mussels can live in colder water (Snyder et al. 1997) and live at greater depths and on softer substrates than zebra mussels (Dermott and Kerec 1997).

Dreissenids have numerous impacts on ecosystems. They clarify the water and may promote the growth of benthic algae such as *Cladophora* (Stankovich 2004; Jude et al. 2005b). They alter nutrient cycling and availability, and they adversely affect *Diporeia* populations by selectively feeding on diatoms and green algae, and by providing a food source for exotic round gobies (Jude et al. 2005b), which have been implicated in outbreaks of Type E avian botulism in SLBE (NWHC 2007). In 2007 and 2008, NPS staff conducting investigations of botulism related waterfowl die-offs discovered large areas of the Lake Michigan bed in and near SLBE inhabited by quagga mussels (NPS, Jay Glase, Great Lakes Area Fishery Biologist, pers. comm., November 2008). Dreissenids benefit the exotic amphipod *Echinogammarus* as well as the native amphipod *Gammarus* by providing them with substrate (Jude et al. 2005b). Dreissenids have also been implicated in the nutrient enrichment of benthic environments in Lake Michigan (Hecky et al. 2004; Higgins et al. 2008).

Zebra mussels probably entered the Great Lakes in 1985 or 1986 in ballast water in Lake St. Clair (Minnesota Sea Grant 2007). Quagga mussels were first found in Lake Michigan in 1999 (Nalepa et al. 2001) and are beginning to dominate the dreissenids of Lake Michigan (Jude et al. 2005b). They were reported present in SLBE by Quinlan et al. (2007), although an exact location was not specified. They currently cover large nearshore and offshore areas of Lake Michigan in and near SLBE at depths up to 85 m (NPS, Jay Glase, Great Lakes Area Fishery Biologist, pers. comm., November 2008). Zebra mussels, discovered in SLBE in North Bar Lake in 1997, have since spread to Loon Lake, Otter Lake, Bass Lake (Benzie), Glen Lake, and the Platte and Crystal Rivers (Murphy 2004a).

Round Goby: The round goby, originally from the Black and Caspian Sea areas of Eastern Europe, is a small, aggressive bottom-dwelling fish that exhibits prolific spawning and voracious eating behaviors. It was first introduced to Duluth Harbor in western Lake Superior in 1986 via ballast water. In some areas where it has become well-established, it appears to be the only fish species present (USGS 2000). Round gobies were reported by Michigan Sea Grant (2007a) to have been observed off SLBE in the summer of 2007 on the large rocky shoal off the mouth of the Platte River at a density of 10 fish/m^2; however, this work was not intended to be quantitative and may represent an underestimate (NPS, Brenda Moraska Lafrancois, Aquatic Ecologist Great Lakes Area, pers. comm., November 2008). Fessell (2007) reported that it is likely that round gobies exist throughout the Lake Michigan shoreline in SLBE, although observations from SCUBA divers and a remotely operated vehicle (ROV) suggest lower densities near the Manitou Islands than near the mainland (NPS, Brenda Moraska Lafrancois, Aquatic Ecologist Great Lakes Area, pers. comm., November 2008).

Eurasian Water-milfoil: The aquatic macrophyte Eurasian water-milfoil was introduced to North America in the 1940s (Remaley 2005). It is easily transported and spread by boats and waterfowl. This species is found most commonly in the littoral zone of lakes in shallow water where it can attain very high densities and reduce light penetration and shade out native macrophyte species (Weeks and Andrascik 1998). Eurasian water-milfoil has been identified in SLBE in North Bar Lake, Loon Lake, and the Platte River (Hazlett 1986).

Purple Loosestrife: Purple loosestrife is native to Eurasia and was transported to North America in the early 1880s as an ornamental plant (Stackpoole 1997). It is pervasive throughout the upper Midwest, especially in Wisconsin and Michigan. This species is an aggressive plant that prefers wetlands, stream edges, and banks, along with cattails and sedges. Purple loosestrife can have a devastating effect on native plants and animals because it can reduce shelter, niche space, and food for native wildlife such as waterfowl, frogs and toads, salamanders, and some fish with its dense growth and resulting obstruction of normal water flow (Stackpoole 1997). Purple loosestrife has been identified in SLBE in the Platte River, along Hwy M-22, and in School Lake (Hazlett 1986). Biological controls introduced in the late 1990s at SLBE appear to be holding purple loosestrife in check where they were introduced (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Curly Leaf Pondweed: Curly leaf pondweed is an exotic plant, accidentally introduced along with the common carp, which forms surface mats that interfere with aquatic recreation. The plant usually drops to the lake bottom by early July (Minnesota Sea Grant 2006). It has been identified in SLBE in North Bar Lake, Loon Lake, and the Platte River (Hazlett 1986).

Other Identified Exotic Aquatic Plant Species in SLBE: Hazlett (1986) identified watercress in Shalda Creek and brittle naiad within the park at an unspecified location. Pavlovic et al. (2005) identified both native and non-native genotypes of the common reed within SLBE and recommended control of the non-native genotypes. Common reed is expanding quickly, especially in SLBE wetlands. It is now also invading Lake Michigan beaches at Platte Point and North Manitou Island, and the Boekeloo Road wetland (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Aquatic Exotics Believed to Be Encroaching on SLBE

Eurasian Ruffe: Ruffe are a small but aggressive type of exotic percid native to Eurasia, first found in Lake Michigan in 2002 (Jude et al. 2005b). They are highly fecund, feed on a wide assortment of prey, and are able to forage efficiently under reduced light conditions such as in turbid water or at night. They may compete for food with native yellow perch (Gunderson et al. 1998) and have replaced yellow perch in some areas of Lake Superior (NPS, Jay Glase, Great Lakes Area Fishery Biologist, pers. comm., November 2008).

Threespine Stickleback: The threespine stickleback is a small forage fish that was introduced to the Great Lakes either in ballast water, by migration from Hudson Bay, or by accidental bait bucket transfer. They are considered abundant in southern Lake Michigan. They compete with native sticklebacks for food and space and prey on other fishes' eggs. They are known to steal bait and are considered responsible in part for a decline in angling quality in southern Lake Michigan (Quinlan et al. 2007).

Spiny Water Flea: Spiny water flea is a large cladoceran (zooplankter) with a long spine, native to freshwater, oligotrophic lakes of Eurasia, but found in all the Great Lakes by 1987 (Berg 2004). Its spine makes it unattractive as prey for small fish (Lehman and Caceres 1993). Although it is eaten by larger fish such as yellow perch and alewife, it removes many cladocerans needed as food by juvenile fish, and so may be a factor in yellow perch decline in Lake Michigan (Jude et al. 2005b). It is easily introduced into new lakes through fishing and anchor lines, bilge water, and live fish bait. Therefore, lakes that are popular fishing spots are the most susceptible to new invasions of the spiny water flea (Jarnigan 1998). The spiny water flea is found in Long Lake in Grand Traverse County (GLIFWC 2007). Spiny water flea was documented by Dr. C. Kerfoot of Michigan Technological University in Big Platte Lake near SLBE in 2008 (NPS, Brenda Moraska Lafrancois, Aquatic Ecologist Great Lakes Area, pers. comm., November 2008), and spines, but not eggs, have been found in Loon Lake in SLBE (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Fishhook Water Flea: The fishhook water flea is an exotic species from the Caspian Sea. It is similar to the spiny water flea in its size, life history, and habits, although it may eat smaller prey (Jude et al. 2002); however, it does not have a straight caudal spine but rather a spine that is curved at the end. It may compete with larval fish and fish planktivores for small zooplankton (Jude et al. 2005b). As of 2000, it had been found in Grand Traverse Bay, Waukegan Harbor, and Burnham Harbor in Lake Michigan (Charlebois et al. 2001).

White Perch: The white perch, not a perch at all, is a species of the temperate bass family Moronidae. It was first found in Lake Michigan in the 1980s, and is expected to be a beneficiary of climate warming (Jude et al. 2005b). It eats the eggs of walleye and white bass, and could contribute to a decline in the populations of those two species (Wisconsin Sea Grant 2002); its expanding population in Green Bay may be impacting yellow perch populations (Jude et al. 2005b).

VHS: Viral hemorrhagic septicemia (VHS), caused by a rhabdovirus, kills fish by causing both internal and external hemorrhages (Whelan 2007). It was confirmed to exist in the Wisconsin waters of Lake Michigan in 2007 (WDNR 2007). Ballast water was the most likely mechanism by which it entered the Great Lakes, while anglers and recreational boaters are the most likely mechanism for transfer into inland waters. It is expected to spread throughout Lake Michigan in the next 2-4 years (Whelan 2007).

Bloody Red Shrimp: Bloody red shrimp are mysids (as are native opossum shrimp) and were first found in Lake Michigan at Muskegon, MI in November 2006 (Pothoven et al. 2007). In the Netherlands, it was found to reduce cladoceran abundance in reservoirs. It might serve as prey for planktivores, but its overall effects on the food web are uncertain at this time (Pothoven et al. 2007).

Introduction Pathways and Control Strategies
Numerous pathways, both natural and human-made, exist to transfer aquatic species from one location to another. Ludwig and Leitch (1996) list connections between basins at times of high water, animal transport, and extraordinary meteorologic events as natural mechanisms for species transfer. Bossenbroek (2006) also notes the importance of stream connections. These natural events and conditions may be difficult to predict or manage. However, human-initiated mechanisms, including escapes from aquaculture facilities, aquarium release, stocking activities, ballast release, and angler escape or release are more amenable to control through management and public education.

The three most apparent pathways for the further introduction of aquatic invasives at SLBE are ballast water from commercial ships, recreational boating, and bait buckets. Ballast water management in Michigan is described in the Ballast Water section. In the area of recreational boating, Michigan's "Clean Boats, Clean Waters" program uses volunteers to educate the public and to check boats and trailers for invasive species (Michigan Sea Grant 2006). Glen Lake Association employees and volunteers conduct an inspection and/or power-washing operation on boats launched into Glen Lake at the DNR public launch on Little Glen Lake during the summer, and also provide educational materials on invasive species (Glen Lake Association 2009).

Angler education is generally considered to be a critical part of any control program for aquatic invasive species. A 1996 study showed that in Minnesota and North Dakota, the probability of any angler in the Hudson Bay basin releasing live bait that originated in the Mississippi River basin was 1.2/100. Given the 19 million angler days/year in the study area, the probability of bait bucket transfer occurring 10,000 times in one year approached 1.0, which in statistical terms made it nearly a certainty (Ludwig and Leitch 1996). The authors stated that "effective, wide-ranging measures" would be needed to stop bait bucket transfer of species in the study area.

Besides angler education, controlling the problem of bait bucket transfer will require working with industries that deal in live aquatic species. A USFWS study (Sherfy and Thompson 2001) found that from 1998-2000, live aquatic organisms in the categories of live fish, aquatic invertebrates, live worms, and bait other than worms were imported into the United States from 44 countries. Of the seven top ports of entry of these organisms into the United States, Detroit, MI was ranked first, and Port Huron, MI was ranked third (Sherfy and Thompson 2001). The authors suggested that relatively little is known about where these exotic bait species are being used, and what motivates anglers to seek them out.

Michigan's Sea Grant program, in cooperation with Minnesota's Sea Grant Program, has developed a Hazard Analysis and Critical Control Point (HACCP) program for members of the aquaculture, hatchery, and baitfish harvesting and transport industries. A HACCP program involves numerous steps, including evaluation of the hazard (in this case, the accidental establishment of an exotic species in a water body), the critical control points, and the critical limits. Then, a monitoring and recordkeeping program is put in place to address the critical points in the process at which these species might be released (Gunderson and Kinnunen 2004).

Background on Forest Stressors
To fully understand (to the extent we can) what determines the composition, structure, and dynamics of a forest, we must first elucidate the full suite of natural factors that consistently play

a role. These factors operate at a wide variety of spatial and temporal scales (Bobiec et al. 2000); NPS identifies these factors as “drivers and stressors” (Gucciardo et al. 2004). The relevance to this assessment is categorizing them into groups (static vs. dynamic, internal vs. external, and local vs. regional) to determine the time frame at which they operate and how much control the SLBE staff might have. For clarity, ease of communication, and to establish consistency with the ecologic literature, a few points should be made. The static/dynamic distinction is, of course, a matter of the time domain of relevance. For our purposes, the relevant time frame could be a matter of days (e.g., responding to the presence of an exotic species), to the period over which resource management planning is done (years to decades), and ultimately to more than 50 years, the time frame at which certain stressors (air pollution) and drivers (disturbance) operate. The distinction of external/internal is usually, but not always, obvious, and it is useful to separate those forces that are clearly imposed on a community from the outside (e.g., air pollution) versus those that are clearly internal (e.g., competition between plants, or seed predation by an insect that completes its life cycle within the forest). Those factors that are a function of forces and conditions emanating from a spatial scale much, much larger than the community itself (e.g., bedrock composition, climate, an insect moving into the region) are generally beyond direct, proactive influence by the park staff.

The distinction between a driver and a stressor may be subtle and can be dependent on the temporal scale. A factor such as climate, which is a part of the abiotic site conditions, is a natural driver and often an important selective force. It becomes a ‘stressor’ when the condition deviates drastically from the norm for a short period (e.g., a sub-freezing night time temperature in June), or substantially from the norm over an extended period of time (e.g. maximum daytime temperature >30^{o}C for 10 days in a row). Similarly, a substantial and temporally consistent change in weather equates to ‘climate change.’

Potential ‘stressors’ in the uplands at SLBE include: 1) long-term, elevated levels of acid precipitation and nutrient addition; 2) harvesting practices and associated activities around the turn of the 20th century; 3) establishment and spread of exotic plants; 4) fragmentation of the landscape by roads, clearings, right-of-ways, harvesting, agricultural fields, and municipalities; 4) alteration of the disturbance regime, including fire; 5) elevated levels of herbivory on understory plants and tree seedlings; and 6) establishment and spread of exotic animals. Viewing these as stressors has a reasonable, ecologic foundation because they represent forces to which the systems have not been subjected in the past 10,000 years, and they have the potential to substantially alter the richness, diversity, composition, structure, and function of the landscape. Furthermore, 1) and 5) may already be, and all except 2) could potentially become, a novel selective force. However, simply because it is a novel stressor does not inherently and automatically mean that it will cause damage, in an ecologic sense, to the community, ecosystem, or landscape. Populations (species) and by extension, communities, are quite resilient and able to adapt to a surprising variety of outside and novel forces.

All forest types have been significantly influenced over about the past 140 years by a variety of human activities, including many that are disturbances. The distinction is made by ecologists between stress and a disturbance on the basis of the magnitude of the immediate impact and the time frame over which the impact plays out. Thus, a commonly accepted definition of disturbance is “ … any relatively discrete event in time that disrupts ecosystem, community, or population structure, and changes resources, availability of substrates, or the physical environment” (Pickett and White 1985). The more important human disturbances have been extensive and intensive logging around the turn of the 20th century, fires that burned through slash during this same time period, and after about 1925, suppression and exclusion of fire (Leahy and Pregitzer 2003; Goebel et al. 2005; Benzie Conservation District 2006). More recently, exotic insects (e.g., the emerald ash borer) and exotic fungal pathogens (e.g., beech bark disease) have become a serious threat to some species and forest types in the region; these are likely to reach SLBE soon. Exotic earthworms may soon be a stressor in the northern hardwood type forest (Hale et al. 2006).

Altered Disturbance Regimes

No factor is more integral to the short- and long-term dynamics (i.e., on a temporal scale of months to centuries) of a plant community than the disturbances it experiences. Though we cannot fully elucidate the complete historic disturbance regime for any forest type, we must do so to the extent possible to begin to understand the vegetation dynamics of a community or landscape. A complete disturbance regime (DR) is described by the frequency, intensity (force of the event), timing (season), variation in frequency, variation in intensity, and duration of each type of disturbance (White 1979; Sousa 1984; Attiwill 1994).

Insects, pathogens, and abiotic disturbances (wind, ice, fire, floods, etc.) may stress some species in a community, but most are not directly affected (although a flood is probably an exception). Undoubtedly, severe disturbances (where severity describes the impact of a disturbance and intensity describes the disturbance itself) have highly significant and varied impacts on an ecosystem, but the indirect effects may be just as important (Halpern and Franklin 1990). These indirect effects often stress a significantly larger number of organisms, and also create an opportunity for invasion and establishment of novel species. All forest ecosystems that have been studied (and most other types of ecosystems also) can be determined to have been subjected to a suite of disturbances throughout their evolutionary history (White 1979; Sousa 1984). Thus, not only are the disturbances 'natural,' but in some cases necessary for the maintenance of the system (Sousa 1984; Barnes et al. 1998). This statement is just as true for insect and pathogen-induced die-back and mortality as for wind, wave, and fire-induced changes; all of these forces are natural contributors to the dynamism of natural ecosystems, and some have served as selective forces for a few of the species in the system. Some authors have taken this one step further and have concluded that the absence of disturbance, or major alteration of the regime, is in and of itself a stressor (e.g., Barnes et al. 1998). We believe this is warranted and a useful way to view this change.

At SLBE, beaver serve as another biotic disturbance agent (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). This is expected for the region, but no SLBE-specific information was found in published literature. Because beaver activity directly affects areas of 1 ha or more, it will often cause a shift in tree species abundance (Johnston and Naiman 1990), with potential long-term successional implications.

Northern Hardwood Type

The long-term dynamics of the northern hardwood forest type are driven by low-to-moderate intensity disturbances, primarily abiotic, that affect 10-40% of the canopy (Frelich and Lorimer 1991). Based on data from Michigan's UP, a typical forest would have 5.7 to 6.9 % of its canopy die or be killed every decade (Frelich and Lorimer 1991). This translates into a canopy residence time of less than 175 years. In contrast, severe disturbances reoccur on very long intervals (>800 years) (Whitney 1986, 1987; Frelich and Lorimer 1991). Fire return intervals (FRI) for all sites, pre-suppression period, were 566 years for surface fires and 2,797 years for canopy-killing fires (Frelich and Lorimer 1991). Thus, fires of any type were very infrequent in this forest type pre-settlement; return intervals for spreading surface fires range from 300 to 900 years depending on the site and assumptions of the calculation. This equates to a fire regime described by Goebel et al. (2005) as "… very infrequent stand replacing or community maintenance (low intensity surface) fires".

Though all forest types have large numbers of endemic insects and pathogens that can kill trees, the diverse nature of the overstory in the northern hardwood type (Allen 1988), and its spatial variation across the landscape (Tubbs 1977; Hazlett 1986 Appendix B; Allen 1988), result in less impact from outbreak-type insects or pathogens. Due to the traits of the dominant species (maple, beech, birch, basswood), the 'pests' of greatest impact in this system are insect defoliators, decay fungi, and decline/dieback complexes (Houston 1986). Beech is especially susceptible to heart and root rots (Katovich et al. 1998). Several defoliators (e.g., forest tent caterpillar, saddled prominent, maple leaf cutter) have had widespread impacts in the past in areas where sugar maple, or maple in conjunction with yellow birch, beech, or basswood, dominated the forests. Two or more years of severe defoliation are necessary to cause significant mortality; sugar maple is more resilient than the other species. Decline or dieback phenomena have received much attention in the past 40 years, and sugar maple and the birches have been intensively studied. Though the topic is somewhat contentious, the commonality among these phenomena is a plurality of causal factors and the length of time over which effects manifest. Often an abiotic stressor (drought, late freeze in spring, etc.) sets the stage for a series of biotic agents, which in combination cause widespread mortality (Houston 1986; Allen 1988; Castello et al. 1995). Depending on its role in the damage or mortality that results, a factor may be a predisposing factor, an inciting factor, or a contributing factor (Manion 1981; Castello et al. 1995). Both biotic and abiotic factors play all three roles, and it is quite possible for the predisposing factor to occur 1-2 decades prior to plant mortality.

If exotic species are excluded, the recent (post-European settlement) and future (next 25-50 year) DR has not been and will not be significantly different than the pre-European settlement DR. This is due to the highly infrequent and limited extent of fires (Frelich and Lorimer 1991) and the dominance of the regime by localized, small-scale abiotic (wind, ice) and biotic events (endemic insects, pathogens); these small scale and generally low-severity events have largely been unaffected by European settlement. The almost negligible impact of recent land use on the fire regime of northern hardwoods is consistent with assessments of many forest ecosystems in the West that also have long fire return intervals (Keane et al. 2002).

Land use history has potential effects on the DR via two mechanisms. In some forests, fragmentation leads to increased windthrow (Everham and Brokaw 1996). Because windthrow is often the dominant type of disturbance in eastern deciduous forests (Runkle 1982; Cho and Boerner 1991; Clinton et al. 1994), and light to medium intensity disturbances dominate the regime of primary northern hardwood forests of the UP (Frelich and Lorimer 1991), any alteration of windthrow rates or severity could be important. Historic land use (since about 1840) has fragmented the landscape in much of the LP (Leahy and Pregitzer 2003 and citations therein). This has occurred to some extent at SLBE, and the smaller parcel size and resulting increase in edge could result in higher rates of windthrow. We believe, however, that this has occurred to a minimal extent in this forest type at SLBE. Though the type has decreased by about 25% since European settlement, the location and extent is strongly tied to soil characteristics and physiography. Thus, it occurs largely where it did pre-settlement, and only a quarter has been converted to other uses or to an earlier successional stage such as aspen. Some of this conversion has been to agriculture, and this almost certainly has resulted in a small amount of fragmentation of this forest type (see Figure 45). However, most of the upland forests are relatively large blocks, and thus the overall impact of fragmentation on the current DR has been slight.

The second way that land use history could alter the DR is via the age structure of the forests and the different rates of windthrow by forest age. The age structure of northern hardwood forests can be uneven-aged (UEA) or even-aged (EA), but EA is more common in the second growth stands of the Lake States (Crow et al. 2002). The shift from an older, more UEA forest landscape to a younger, more EA forest landscape (Frelich 1995) probably translates into lower rates of canopy turnover today. However, in EA forests, the total canopy area affected by small-scale windthrow follows a predictable trend, with increasing amounts from pole to mature to old-growth forests (Dahir and Lorimer 1996). Therefore, windthrow rates will increase unless the forests are utilized and managed to maintain the general age structure of the type as a whole. The impending impact of beech bark disease probably makes this a moot point, however.

Upland Deciduous Forests

The dominant forest type in this category is aspen or aspen-birch. The three species that may occur as canopy dominants span the intermediate portion of the site condition gradient from moderately dry (big-tooth aspen) to moderately wet (quaking aspen); in the middle range, all three species are common (Curtis 1959; Katovich et al. 1998). As previously noted, this type can be the initial stage of secondary succession on sites that can support the northern hardwood type, but it can also become established in the old dune complex portion of the landscape.

The disturbance history information that is available includes little that is directly and clearly applicable. On mesic sites, the fire regime is probably quite similar to that of the northern hardwoods. Cwyner (1977) examined an 18,600 ha preserve in Ontario dominated by white pine and aspen and found a FRI (for a fire anywhere in the park) of 14 years, an FRI for “major fires” of 45 years, and a rotation of 70 years.

For disturbance types that are largely determined by the autoecology of the species, the change could be quite extensive. These three species (aspens and birch) are all relatively short-lived (Harlow et al. 2001) and will begin to fall out of the canopy due to senescence at about 50-70 years (Katovich et al. 1998). Because they reach physiologic maturity at this age, they begin to suffer higher rates of mortality from insects, disease, and wind. Thus, the decadal rate of canopy mortality accelerates beyond 7% in cohorts over 60-70 years old. Due to the density at which they often occur, their tendency to form monospecific canopies, and their pioneer status (Perry 1994), they are also more likely than the northern hardwood type in general to have epidemic-level insect-caused mortality. Known agents that reach this level of impact include gypsy moth, birch leaf miner, large aspen tortix, and forest tent caterpillar (Katovich et al. 1998). The latter two defoliators, both native, have exhibited major outbreaks in northeastern Wisconsin seven times since 1953 (Katovich et al. 1998), and have also caused major outbreaks at SLBE (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). Fungal-caused impacts, including growth loss and mortality, are more prevalent in aspen-birch than in northern hardwoods, but not necessarily more common in mature stands. The more important agents are *Hypoxylon* canker, a stem and branch disease; *Armillaria* root disease; and white trunk rot. The last disease is typically more common in older stands, and it has been stated that this disease will eventually cause the trunks of all trees in old-growth aspen forests to fail (Katovich et al. 1998).

A pure or almost monotypic oak overstory is uncommon in the park today and was rare historically. Areas dominated by oak are being overtaken by white pine, and oak is not reproducing (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). Thus, the disturbance history and DR of this type will not be discussed separately. On very dry or nutrient-poor sites, where black oak is more likely to occur, the oak type could form a stable successional stage (Abrams 1992), as it appears to do at INDU (Olson 1958; Henderson and Long 1984). Alternatively, on xeric to xeric-mesic sites, succession could proceed very slowly (Olson 1958; Abrams 1992). The pine-oak type, on the other hand, is quite common and is discussed in the following section.

Upland Conifer Forests

Fire is undoubtedly one of the most important types of disturbance for all pine and pine-oak dominated forests in the Great Lakes region (Heinselman 1973; Whitney 1987). Though there is a considerable body of work from the region, including some from the LP, (Whitney 1986, 1987; Leahy and Pregitzer 2003), little specific information was found for SLBE. In a regional level study of "coastal pine forest" fire history, Loope and Anderton (1998) included four SLBE sites. The average FRI for those sites prior to 1910 was 14-32 years. Using survey notes, Whitney (1986) estimated the FRI of high-intensity events for two counties to the east of SLBE (Crawford and Roscommon) as 80-167 years for jack pine (generally <100), 120-260 years for mixed pine, and 172-342 years for pine-oak. Heinselman (1973, 1981) reported FRI of 50 years for jack pine and 180 years for mixed pine in the Boundary Waters Canoe Area region of northern Minnesota. Frissell (1973) reported a similar value of 150 years for a mixed pine forest in central Minnesota. Thus, there is striking agreement among studies for high intensity fires in the mixed pine type in this region; these disturbance events occurred once every 150-200 years. The response of jack pine-dominated forests to severe disturbance has been detailed (Abrams et al. 1985); however, no details are provided here due to the scarcity of this type at SLBE. As previously noted, Cwyner (1977) examined an 18,600 ha preserve in Ontario dominated by white pine and aspen and found a FRI (for a fire anywhere in the park) of 14 years, an FRI for "major fires" of 45 years, and a rotation of 70 years.

It should be noted that jack pine (Abrams 1984) and white pine (Quinby 1991) are occasionally successionally stable in the absence of fire. This pattern is more likely in the southern and eastern parts of the range of jack pine because the level of serotiny is substantially lower there (Barnes et al. 1998). SLBE jack pine cones have been noted to open, and jack pine to reproduce, in the absence of fire (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

The pre-settlement fire regime of the pine-oak type almost undoubtedly included lower intensity fires that occurred more frequently (e.g., Loope and Anderton 1998; Barton 1999) than the high intensity events documented by Whitney (1986). Henderson and Long (1984) found FRIs of 5 and 11 years for two black oak forests at INDU. Fire histories of dry oak forests in other regions have found a FRI as short as 3 years (Cutter and Guyette 1994). Thus, the probable fire regime of the pine-oak forest type was a mixed regime; i.e., it included fairly frequent, low intensity events and then an occasional high intensity event (but not necessarily a crown fire).

Very limited information on the historic role of wind, high water table, ice storms, insects, or diseases is available and must be extrapolated from roughly similar ecosystems in other parts of the country. For example, in a xeric-mesic oak forest in the Southern Appalachians, the extent of canopy gaps was similar to other mature deciduous forests of the eastern US. The arboreal composition of the gaps (red maple and four species of oak) is not surprising (Clinton et al. 1993, 1994). These patterns suggest that oaks are able to maintain their presence over long periods of time (i.e., a relatively stable successional stage) if gap occurrence is frequent and large enough. However, when drought was a major contributor to gap formation, it interacted with the *Armillaria* fungus to reduce oak abundance. In the same region, a study of the effects of ice storms on succession suggested that a xeric pine type and a xeric-mesic oak forest were successionally stable when disturbed by this abiotic agent. In contrast, a mesic oak forest (white oak-dominant) was sent back to an earlier successional stage by an ice storm (Whitney and Johnson 1984). A severe ice storm in Missouri did not appear to lead to a significant shift in composition or structure of an old-growth oak-hickory forest, but if the return interval were as low as 20 years, this would probably direct succession to a different stage (Rebertus et al. 1997).

The alteration of fire regimes has been implicated as a major (though not sole) factor contributing to compositional and structural changes in many forest types of the region, especially pine-dominated forests (Whitney 1987; Leahy and Pregitzer 2003). This alteration took two forms. During the logging era, the pines were typically the first to be harvested, and it was common for fires to occur in the slash left behind (Whitney 1987). Thus, during this period there were more fires, which often further reduced the pine seed source, and so favored oak, aspen, or birch. Some authors believe that the slash fires had a more pervasive impact than the logging (Whitney 1987 and citations therein). However, after the logging era, the "protection period" began around 1920, in which fires were not often set and suppression began in earnest (the "suppression era") (Whitney 1987 and citations therein). Thus, fire occurrence dropped dramatically in all forest types with moderately frequent fire. Other than fires, no information on the current disturbance regime of the upland pine and oak-pine forests was found. It is probably safe to conclude, as was done for the northern hardwood type, that wind-related disturbance has not changed much.

For those forest types that had frequent fire historically, the effects of fire exclusion probably cannot be overstated. As has been noted repeatedly in western pine forests (Keane et al. 2002), the forests of Michigan today are composed of many more, but smaller, trees than in pre-European settlement times (Zhang et al. 2000; Leahy and Pregitzer 2003). In other forest types, there have concurrently been changes in forest structure, canopy closure, tree composition, and understory richness and composition (Keane et al. 2002). It is unknown but likely that some or all of these changes have occurred, or are occurring, at SLBE. At INDU, two black oak-dominated forests differed in structure and composition with only an approximately 6 year difference in fire frequency (Henderson and Long 1984). The forest with the longer FRI had fewer but larger overstory trees, less shrub cover of three species, more blueberry cover, more arboreal seedlings/seedling sprouts, and more graminoid cover. If a modest difference in fire regime can result in this array of changes, complete exclusion of fire for 70+ years most likely has had even more pervasive effects. The compositional and structural changes listed above are not all that may change; several important ecosystem properties are also often affected (Keane et al. 2002). But a change brought about by fire exclusion is not always undesirable. A study in a xeric oak savanna in Minnesota documented an immense increase (approximately 100 Mg/ha) of carbon storage on sites from which fire was excluded for 35 years (Tilman et al. 2000).

An important factor, whose influence is impossible to pin down precisely, is the heterogeneous physiography of the area in which most of these forest types occur. The old dune-and-swale topography results in large changes in soil water over short distances. This usually translates into changes in overstory and/or understory differences (Olson 1958; Hazlett 1986), which could result in some differences in disturbance regime. The fire regime could change due to fuel combustibility and structure (Graham et al. 2004), and wind damage often varies by slope, species, and canopy position (Clinton et al. 1993; Foster 1988; Canham et al. 2001). A rather unique disturbance occurs at SLBE, mainly in areas with swale topography, when the water table rises to a level that causes significant plant mortality. This disturbance is due to the park's proximity to Lake Michigan, and the frequency of such events is undocumented.

Gap-related dynamics probably apply to the forests on coarser soils in which northern red oak is a significant component at SLBE, and the oak component will probably persist after ice storms. It is unknown if root diseases such as *Armillaria* interact with the abiotic disturbances, but it seems likely in the case of drought, because northern red oak is not a drought adapted species.

Lowland Forests

Windthrow is the primary form of disturbance in lowland forests, collectively determined by physiography, soil characteristics, water movement, and tree characteristics. Saturated soils, organic soils, and shallow roots make trees susceptible to windthrow. When a tree is windthrown, micro-topographic heterogeneity in the form of 'pit-n-mound' topography is created. The pit part of this provides a micro-site that is considerably wetter than the area in general. The bole of the downed tree also provides surface heterogeneity that is important for the regeneration of some plant species (e.g., white cedar [Rooney et al. 2002] and conifers in general [St. Hilaire and Leopold 1995]). As might be expected, the return interval for high-severity fire is quite long in lowland forests of the LP (Whitney 1986). Since the dominant species (especially white cedar) exhibit natural resistance to pests, it is presumed that wind-related disturbance was the dominant type of disturbance in these communities historically.

Settlement Period Effects

As noted in the section above, human activity between approximately 1850 and 1920 added new disturbances to the landscape and affected disturbance regimes directly and indirectly. Other anthropogenic effects manifested across the landscape or at the community (site) level. Both scales merit consideration. It is often difficult to isolate individual, cause-effect relationships. For example, harvesting, clearing for agriculture, clearing for roads, and increasing population density can all contribute to losses of biodiversity and the introduction of exotic species.

A variety of human activities contributed to the most widespread and obvious effect of the settlement period: fragmentation of the landscape (Palik and Murphy 1990; Leahy and Pregitzer 2003). This process leads to smaller, more isolated units of natural vegetation (remnants or fragments) that are surrounded by agriculture, developed land, or recently/heavily disturbed areas in early successional stages. It has also greatly reduced the amount of old-growth and mature forest (Frelich 1995). Due to the extent of human modification of the landscape, the remnant vegetation is often poorly connected to other similar units on the landscape; the most common (though not universal) outcome is reduced dispersal among habitats and thus increased likelihood of local extirpation and reduced diversity. Hence, the structure of the landscape and degree of connectivity may be as important as the characteristics of the remnants themselves (Saunders et al. 1991; Boulinier et al. 2001). The reduced size of plant communities and the concurrent increase in the edge/area ratio have a variety of direct and cascading effects on the composition and structure of the communities and on the biological diversity of the landscape (Saunders et al. 1991). The so-called "edge effects" associated with fragmentation have been intensely studied with respect to avian species, avian communities, and the abundance of different species (see reviews by Debinski and Holt 2000; Boulinier et al. 2001; Parker et al. 2005) and will not be reviewed further here. All roads, utility rights-of-way, railroad tracks, and even trails can also create a narrow break in the canopy and thus have some edge effects. In addition to breaking up extensive areas of one habitat type, these human-created breaks and corridors can serve as 'conduits' for exotic plants (Gelbard and Belnap 2003; Watkins et al. 2003). See the section below on Exotic Plants for more detail on this.

Changes in remnant communities can be either physical or biological. Where there is open land or agriculture next to a forest, a sharp edge is created. At these sharp edges, the exposure results in modifications of the environment, including increases in radiation, wind, and temperature and a reduction in relative humidity for a considerable distance into the forest. In the eastern US, these effects are not likely to extend more than 50 m into the forest interior (Palik and Murphy 1990; Matlack 1994). These physical changes result in biotic changes, often including different species showing up in the edge-affected area, different abundances of overstory and understory plants, and invasion by alien species (Palik and Murphy 1990; Saunders et al. 1991; Brothers and Spingarn 1992). Though the edge effects generally decrease fairly rapidly if a forest develops, some of the patterns were still noted after 55 years of succession (Matlack 1994). The landscape at SLBE has not been fragmented to the same extent as in the southern LP (Leahy and Pregitzer 2003). Currently, approximately 13% of the area is in agriculture, openland and developed areas; "herbaceous openland" is the dominant category at 8% (Table 3). We have estimated that approximately 73% of the landscape is in forest; thus, this impact has probably been modest. It is presumed that the greatest impact at SLBE has occurred in the northern hardwood forest type because of the magnitude of the areal reduction of the type and its proximity to agricultural lands.

Harvesting during the settlement period and subsequent forest management have had pronounced impacts on most forest types. One obvious and well-documented effect is the shift in relative abundance of many forest types. The specific changes at SLBE were noted in the Upland Resources section; similar changes have been documented across the LP (Frelich 1995; Zhang et al. 2000; Leahy and Pregitzer 2003). Other important changes due to harvesting and forest management are reduced tree size, increased stem density, and a reduction in old-growth and multi-aged forests. Other structural changes have been documented in northern hardwood (Crow et al. 2002) and red pine (Duval and Grigal 1999) forests in the Lake States. In comparison to unmanaged old-growth, Crow et al. (2002) found that second growth forests had fewer large trees, fewer snags, and a less well-developed (or absent) sub-canopy. A key structural and functional difference between second growth stands and old-growth is the volume and variety of stages of decaying coarse woody debris (Hardt and Swank 1997; Shifley et al. 1997). This pattern applies to red pine forests in the region up to the mature stage of stand development; from that point on, the total woody biomass was equal in managed and unmanaged stands (Duval and Grigal 1999).

The evidence with respect to tree diversity is mixed. Crow et al. (2002) found a reduction in the number of tree species in managed stands in the UP, whereas Niese and Strong (1992) found all forms of uneven-aged management to result in greater tree diversity than non-managed units.

The direct and indirect impacts of logging on the understory are an important and valid concern in most parts of the eastern US (Gilliam and Roberts 2003). The vast majority of plant species are found in this layer, and the abundance and composition of the ground layer has impacts on ecosystem function (Roberts 2004). The more severe the disturbance, such as logging with heavy machinery, or partial logging followed by an intense fire, the greater the potential for a reduction in diversity, the initiation of a novel successional pathway, and/or the establishment of invasive species. Studies in the region assessed the impacts of four different silvicultural systems (different levels of harvesting and numbers of cutting events) in the UP on both spring and summer vegetation. The spring flora was more dense but slightly less diverse on the clearcut compared to the selectively and repeatedly (3-4 times) harvested areas (Metzger and Schultz 1981). The lower richness in the clearcut areas was due to more arboreal and shrub species. In fact, these authors concluded "… ground layer species typically associated with northern hardwood forests apparently persisted in the earlier seral communities … and is unlikely that they were eliminated ... by either harvesting or the postharvest environment." (Metzger and Schultz 1981, pg. 48). For the summer plant assemblage, the composition of three selection harvesting treatments and two clearcuts was very similar to the original composition (Metzger and Schultz 1984). Also, on the basis of "forest taxa," the clearcut with the larger minimum diameter and the individual tree selection areas had greater richnesses than the "reserve." Note, however, that there was not a truly undisturbed or old-growth forest to serve as a baseline. These studies suggest a moderately high degree of resilience in this system.

These considerations raise the question as to whether the understory of mesophytic forests ever fully recovers from clearcutting. Duffy and Meier (1992) and Ruben et al. (1999) evaluated mesophytic forests in the Southern Appalachians and New England, respectively, and suggested that the understory may regain the composition of a mature second growth stand, but not a true old growth stand, in 70-80 years. A recent analysis of sites in Europe and North America concluded that the greater the loss of "ancient" forest during settlement, the greater the loss of diversity and the longer it takes for forests to recover—the time to re-establish the full complement of diversity may take centuries (Vellend 2003). Given the very small amount of old-growth, or primary forest, in the LP, it is probable that well over 100 years are needed for complete compositional recovery.

A similar study from northeast Wisconsin compared EA and UEA silviculture systems to a control. The authors determined various attributes of the "ground layer plant community," and after 49 years found no difference in species density, richness, or diversity (Kern et al. 2006). They attributed the lack of impact to winter logging and lack of soil disturbance. A very recent study in northern Wisconsin found that summer logging led to a reduction of species associated with mature forest conditions, whereas winter logging did not (Wolf et al. 2008). These two studies strongly suggest that it is the degree of forest floor disturbance, not overstory removal, that largely determines the magnitude of the impact on the ground flora.

Undesirable site effects may occur along trails and roads. In a study of six Midwestern forest sites at three nature preserves, Adkison and Jackson (1996) found that areas along the trails had reduced litter cover at five of six sites, and significant soil compaction at all six, compared to sites 10 m away from the trails.

Understory Herbivory

Herbivory, the consumption of live vegetative material by animals, is a common interaction in all plant communities (Perry 1994). In some communities (e.g., grasslands with ungulates) it is a dominant structuring and selective force. In forest communities, an endemic level of herbivory is carried out by hundreds of herbivores, primarily insects. The vast majority of the herbivores have no noticeable impact on the forest community, and, in fact, the total effect of this endemic herbivory may be trivial in terms of community structure, composition, and plant succession (Mattson and Addy 1975). Nonetheless, the interactions between herbivores and plants are a vital part of the ecologic dynamics of a community. Many examples of co-evolution between plants and herbivores are documented (Perry 1994), and many traits in plant populations are due in part to the selective pressure of herbivores. A key factor in this interaction is the genetic variation within (and among) plant population(s); variation among plants (i.e., genotypes) within a population can result in differences in resistance and induced defenses (Dimock et al. 1976; Hunter and Schultz 1995), and thus preferential selection and differential impact. The amount and content of the genetic variation are also vital in determining if and how a plant population might evolve in response to this selective pressure. Populations and species vary widely in their tolerance of low-to-moderate levels of herbivory, but in many, a 10-30% loss of vegetative matter does not have a negative impact if the plant is healthy (Mattson and Addy 1975).

Some forest insects, however, do reach a level of impact well beyond this background level. Obvious examples of relevance to Michigan are the gypsy moth, which has profoundly affected oak and oak-hardwood forests of the Middle Atlantic region for decades (USDA-Forest Service 2003), and the forest tent caterpillar, which occasionally defoliates large amounts of aspen in the Lake States (Katovich et al. 1998). These herbivores have a pronounced impact on community structure, composition, succession, and ecosystem processes such as nutrient cycling.

Mammalian herbivores are another important group, and of special concern is the white-tailed deer (WTD) (*Odocoileus virginianus*). This concern is primarily a function of population densities that are much higher than historic levels (Russell et al. 2001; Cote et al. 2004). It should be noted that the WTD is native to this entire area (Rudolph 2005) and thus has been part of the communities for thousands of years. Consequently, browsing of plants by WTD is a natural part of the interactions and dynamics of the ecosystems in the northern LP.

The issue is whether there have been unnaturally high levels (i.e., increased intensity) of herbivory by WTD at a specific time of the year, and over a long enough period of time, to cause permanent to semi-permanent change in one or more community attributes (Russell et al. 2001). In SLBE, the forest communities for which there is most likely to be a concern are the lowland conifer forests (Van Deelen et al. 1996), areas where hemlock occurs, and the northern hardwood forests. However, the drier forest types have not been as well studied, and thus it should not be assumed that the impact of WTD in these forest types is minimal (Russell et al. 2001).

Concerns have been raised for more than 50 years (e.g., Swift 1948) in the Lake States region about “damage” caused by WTD herbivory. Until the 1980s, these concerns were largely focused on commercially important tree species, with American yew (*Taxus canadensis*) an exception (Beals et al. 1960). White cedar, yew, and hemlock have been studied in great detail because they are three of the more susceptible woody species in the region. Since the 1980s, interest has expanded to understory cover and structure, understory diversity, plant population structure, plant succession, threatened and endangered species, and taxa that may be especially vulnerable

(Alverson et al. 1988; Miller et al. 1992; Stromayer and Warren 1997; Augustine and Frelich 1998; Russell et al. 2001).

Though it is impossible to know with complete assurance what the deer densities were pre-European settlement, there is almost universal agreement that they were much lower than today (Rogers et al. 1981; Alverson et al. 1988; Mladenoff and Stearns 1993; Van Deelen et al. 1996; Stromayer and Warren 1997). The higher WTD densities of the 20th and 21st centuries have come about due to landscape-level changes associated with settlement that have provided almost ideal habitat for WTD—abundant food sources interspersed with high quality hiding and thermal cover (Rogers et al. 1981; Van Deelen et al. 1996; Rudolph 2005). A clear indication of this "landscape" effect is demonstrated by the work of Augustine and Jordan (1998) who showed that WTD grazing intensity is strongly and significantly associated with the amount and type of agriculture within 1.5 km of a forest.

Landscape changes as well as hunting laws and predator control have changed WTD population trends in the "northern" part of Michigan (Augustine and Jordan 1998; Rudolph 2005). WTD increased from about 1850 to 1890, then declined precipitously and stayed low until the 1930s. Another rapid increase for about 20 years was followed by a significant decline (about 66%) until about 1970. Since then, populations increased until shortly before the turn of the 21st century (Rudolph 2005, Figure 2). The WTD population around 1995 was approximately 650,000 and 350,000 higher than the populations in 1930 and 1950, respectively. Though the deer herd declined for a few years after around 1995, the deer harvest statewide in 2007 was 484,000, an increase of about 6% over 2006 (Frawley 2008); thus, there is no indication of a decline in WTD populations that would lead to significant shift in deer pressure on vegetation.

There is disagreement over the WTD density at which damage is likely to occur. Russell et al. (2001) surveyed a large amount of literature and concluded that all studies that documented reduced adult tree recruitment had a density of at least 8.5 deer/km^2. Alverson et al. (1988) suggest densities as low as 4 deer/km^2 may be enough to have impacts on yew, hemlock, and white cedar. Augustine and Frelich (1998) did not find any noticeable impacts on trillium (*Trillium* spp.) until density reached 25 deer/km^2. The results of Frelich and Lorimer (1985) in Michigan's Porcupine Mountains (in the UP) indicate that hemlock is impacted at a density between 2 and 10 deer/km^2. In one of the very few controlled deer density studies, Horsley et al. (2003) found that most understory attributes were negatively affected at between 4 and 8 deer/km^2. The results (thresholds) vary because density is not the whole equation. As noted before, the landscape structure influences how much deer are concentrated, and in some winters, deer will not yard up for any appreciable length of time. Other factors that will determine how much impact and which species are affected include snow depth, plant height, plant growth rate, plant abundance by species, and total browse abundance (Curtis 1959; Rogers et al. 1981; Russell et al. 2001). Studies outside of Michigan have shown that micro-topography, especially tip-up mounds (Long et al. 1998) and the density of balsam fir saplings (Borgmann et al. 1999), can also influence browse intensity on hemlock. It seems reasonable to expect that these types of influences would manifest in a variety of forest types. In these two studies, hemlock on mounds and in the middle of dense fir patches suffered less herbivory. Despite the variation in conclusions regarding a WTD threshold, it seems prudent to become concerned and monitor closely if the density equals or exceeds 4 deer/km^2 for any length of time.

In isolated forest fragments, the WTD density can exceed 30 deer/km^2 (Augustine and Frelich 1998), which is at least 10 times higher than pre-European settlement levels. This density level occurred on North Manitou Island during the mid-20th century (Hurley and Flaspohler 2005). Communities in these locations are especially susceptible to long-term changes driven by intense (and probably unnatural) herbivory.

In 2007, 1,650 deer were harvested in Benzie County and 1,751 in Leelanau County (Frawley 2008). Population estimates for 2008 for the two counties were 10,000 and 7,700, respectively. Deer are not evenly distributed throughout the counties, so a density estimate would be "meaningless" (MDNR, Rodney Clute, Big Game Specialist, email, February 9, 2009).

Given the population trends since the late 1800s and the current population densities, it is quite reasonable to raise the question, "Are current WTD densities causing unacceptable ecologic impacts?" The effects from high WTD densities are not restricted to plant composition and form. Cote et al. (2004) concluded that the effects can cascade through the system and affect insects, birds, and other organisms. There has been very little study of ecosystem-level effects from WTD herbivory (Russell et al. 2001), but Cote et al. (2004) concluded that both carbon and nitrogen cycling can be altered. However, the analyses of Mladenoff and Stearns (1993), Rooney et al. (2000), and Russell et al. (2001), and the findings of Stromayer and Warren (1997) should be carefully considered to avoid assigning unwarranted influence to WTD browsing.

Lowland Forests

If for any reason (winter severity, landscape structure, etc.) the deer in an area concentrate for part of the year, the potential for negative impacts increases as the period lengthens. This 'yarding' behavior is normal, and the likely impact increases as the deer density in an area goes up and the availability of cover decreases (Habeck 1960; Van Deelen et al. 1996). The primary species of concern are the woody species that can serve as a food source when there is snow cover, especially those that are preferred or those that are least able to tolerate heavy browsing. White cedar, hemlock, and yew are in these categories, and the last species is no longer abundant at SLBE due to browsing. Red and mountain maple are other highly preferred species (Habeck 1960). Hemlock is not a typical species of the lowland forests, but does occur with black ash along the periphery of, and on the slopes just above, other lowlands; hence, it is in close enough proximity to be heavily utilized. The non-woody understory can be heavily impacted if deer concentrate in yards for thermal cover at times when snow cover is sparse (Habeck 1960). Rogers et al. (1981) stated that deer will not dig through more than 10-30 cm of snow to reach food. Habeck (1960) provides a list of "decreaser" species among the understory assemblage; these are the species most likely to decline in abundance due to heavy browsing.

The probable impacts on species and populations that are heavily browsed are a bushier growth form (black ash, red maple, hemlock) (Curtis 1959; Russell et al. 2001), reduced recruitment to the "large seedling size class" (approximately 0.3 to 1.0 m) (Rooney et al. 2002), and reduced seedling survival. The long term effect is a population structure skewed toward larger/older individuals (Frelich and Lorimer 1985; Russell et al. 2001). Simulations show that hemlock could shift from a dominant to a minor species in less than 150 years (Frelich and Lorimer 1985). For species that have a well-developed sprouting capacity (e.g., beaked hazelnut [*Corylus cornuta*], red maple, and mountain maple [*Acer spicatum*] [Habeck 1960]), browsing may result in an increase in stem density but smaller average size. However, given the prevalence of windthrow in these forest types (see previous section), small-scale refugia are likely.

Understory – Northern Hardwood Forest

The understory of northern hardwood forests early in the growing season represents an assemblage of concern. In spring, deer are moving around the landscape looking for food sources that are more nutritious than the woody browse they rely on during winter (Rogers et al. 1981). This forest type has a greater abundance than other upland forests of plants and species that leaf out early. A few even begin to grow under the snow, such as sugar maple and adder's tongue (*Erythronium americanum*). The new growth is lush and nutritious, and thus highly preferred. The non-woody species, and some shrubs, cannot grow out of the reach of deer, and thus may be browsed their entire life cycle, increasing the likelihood of long-term negative impacts. The condition of the understory (sparse cover, very limited understory layer giving a "park-like" appearance) as observed on North Manitou Island by Hazlett (1991) is testament to the change that WTD herbivory can cause in this assemblage. The presence of a browse line at about 1.7 m around old-fields and near the shore, and the vegetation structure of an exclosure near Pole Bridge, document the extent of alteration caused by deer since the 1920s (Hazlett 1991). A comparison of the understory on North Manitou with that on South Manitou Island, which has no deer, documents the precise nature of long-term, fairly intense browsing (Hurley and Flaspoler 2005). WTD density peaked in the mid-1980s at around 30 deer/km^2 on North Manitou and has since declined to about 3 deer/km^2. North Manitou, in comparison to South Manitou, had: 1) more tree seedlings and a shift to much greater relative abundance of beech; 2) strong domination of small saplings (<5 cm diameter at breast height) by beech and greater overall density; 3) approximately 1/6 as much herb cover in mid-summer; 4) much less fern, shrub, and yew cover; but 5) more grass cover mid-summer. The spring ephemeral cover on North Manitou is about half that on South Manitou. These authors note that there are minor signs of recovery in the 20 years since browsing pressure started to decline, but that it was proceeding very slowly.

Yew was historically fairly common in the understory of this forest type; however, it was severely browsed, and few vigorous populations persist. The population in the northern hardwoods on Empire Bluffs was reported as an exception by Hazlett (1991), but is now nearly gone (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Several taxa that commonly occur in the northern hardwood forest type have been studied in some detail; all of these are relatively common at SLBE (Hazlett 1986). These studies documented lower cover and smaller plant size for trillium, sweetroot, jack-in-the-pulpit, mayflower, and baneberry in areas of high deer density (Rooney 1997; Augustine and Frelich 1998; Webster and Parker 2000), although it should be noted that these effects were largely restricted to sites with densities of 25 deer/km^2. A 50% reduction in flowering by trillium was also noted (Augustine and Frelich 1998).

Exotic Species-Terrestrial

The NPSpecies (2007) database for SLBE includes four non-native mammals; the Virginia opossum (*Didelphis virginiana*), feral cat (*Felis catus*), house mouse (*Mus musculus*), and European rabbit (*Oryctolagus cuniculus*). Seven non-native bird species are known at SLBE (NPSpecies 2007); the most problematic of these are considered to be the mute swan (*Cygnus olor*), house sparrow (*Passer domesticus*), and European starling (*Sturnus vulgaris*) because of their displacement of native birds; the mute swan is also destructive of habitat (NPS 2006c). The brown-headed cowbird (*Molothrus ater*) also displaces native birds; there is some uncertainty about whether the cowbird should be listed as a native or non-native species. Land clearing following settlement likely caused the population to greatly expand into areas of Michigan that had previously been unbroken forest (Sullivan 1995; NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., January 2009)

Exotic Plants

Two hundred seventeen non-native plants (including both terrestrial and aquatic plants) are known at SLBE (NPSpecies 2007). The latest additions are Jimson-weed (*Datura stramonium*) and yellow archangel (*Lamiastrum galeobdolon*), which were found in a 2003 survey (Pavlovic et al. 2005). Herbaceous species of particular concern to park managers include baby's breath (*Gypsophila paniculata*), garlic mustard, spotted knapweed, blue lyme grass (*Leymus arenarius*), leafy spurge, Canada thistle, bladder campion (*Silene latifolia* ssp. *alba*), bouncing-bet (*Saponaria officinalis*), and periwinkle (*Vinca minor*). Woody species of particular concern include tree of heaven (*Ailanthus altissima*), lombardy poplar (*Populus nigra*), black locust, Scots pine (*Pinus sylvestris*), autumn olive (*Elaeagnus umbellata*), and the bush honeysuckles (Morrow's honeysuckle [*Lonicera morrowii*], Tatarian honeysuckle [*L. taterica*], showy fly honeysuckle [*L.* x *bella*], and European fly honeysuckle [*L. xylosteum*]) (NPS 2006c). In addition, 149 non-native plants are considered to be encroaching on SLBE (NPSpecies 2007).

Collectively, the exotic plants represent an important economic and ecologic threat (DiTomaso 2000; Ehrenfeld 2003; Heneghan et al. 2006). In the recent past, the eastern US has experienced a rapidly increasing number of established exotic plants. Concurrent widespread effects have included, at a minimum: 1) alteration of community structure (Heneghan et al. 2006), 2) reduction of native richness, 3) alteration of ecosystem process such as decomposition, mineralization, and primary productivity (DiTomaso 2000; Ehrenfeld 2003; Heneghan et al. 2006), and 4) altered fire regimes (DiTomaso 2000; Brooks et al. 2004). Many, if not all, of these outcomes apply to SLBE, given the extent and number of alien species present. Some effects have already been documented at both SLBE and INDU (Pavlovic et al. 2005; NPS, Ken Hyde, Wildlife Biologist, SLBE, pers. comm., September 2008). It is also probable that in areas in which one or more native plant species have been locally extirpated, the presence or abundance of other groups of organisms such as insects and fungi have been affected (Ellison et al. 2005).

The introduction of alien species began with, if not before, the arrival of European settlers (DiTomaso 2000). It was not unusual for immigrants to bring useful plants or seeds with them from their native lands. More recently the horticultural trade has been a prime source of naturalized exotics (see Cultivated List in Hazlett 1986; Brothers and Spingarn 1992), and the number of accidental introductions has increased in the past two decades or so as intercontinental trade has increased (Crall et al. 2006). Another source of exotic species, now on the decline, is intentional introduction for a resource management purpose, such as black locust, barberry (*Berberis* spp.), autumn olive, and Scots pine. Early restoration efforts by NPS managers brought in native plant species, but they were likely of the wrong genotype (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). The widespread and severe disturbance of much of the landscape around the turn of the 20th century set the stage for easy invasion (Hobbs and Huenneke 1992). That is, many (though not all by any means) of the problem exotic species are especially adept at invading recently disturbed areas (e.g., black locust, spotted knapweed).

This threat is a major issue, as indicated by the number of species, but its importance varies tremendously across the landscape. Since the mid-20th century, the insertion of roads (Gelbard and Belnap 2003; Watkins et al. 2003); creation of hiking, biking, and all-terrain vehicle trails

(Adkison and Jackson 1996; Dickens et al. 2005); and timber harvesting have provided the disturbed areas for exotics to establish and migrate across the landscape. Forest roads have lesser impacts than edges created by agriculture or recent clearcuts, but still influence the abundance and spread of exotic species. In a northeastern Wisconsin landscape dominated by hardwood forests, exotic species were most prevalent within 15 m of roads; however, native richness and diversity were equal to interior conditions within 5 m of the roads (Watkins et al. 2003). Brothers and Spingarn (1992) found a similar pattern in old-growth remnants in Indiana.

The number of "weeds" of European origin along the roads (Hazlett 1986, pg. 15-16) and restored home sites (NPS, Ken Hyde, Wildlife Biologist, SLBE, pers. comm., September 2008) in SLBE is ample testament to the role of humans in facilitating exotic invasion and spread. The establishment of a park by no means guards it against further exotic invasion. A recent study of a small (19 km^2), newly-established national park in Quebec found that the proportion of exotics increased from 16 to 25% in just 21 years from 1984-2005 (Lavoie and Saint-Louis 2008). Furthermore, even in largely unfragmented landscapes, more subtle human manipulation of the landscape and accidental introduction can lead to steady increases in the number and dominance of exotics in the flora; this was recently documented for a 50 year period in upland forests of northern Wisconsin (Rooney et al. 2004). The increase in exotics led to an 18.5% decrease in native species density at a 20 m^2 scale.

The systems with the greatest number of exotic species in SLBE are, in decreasing order, grasslands and former agricultural fields (Hazlett 1991; Corace et al. 2003), early successional dune assemblages, open-to-moderately open pine/pine-oak forests on older dunes, forest wetlands, and northern hardwood forests (Hazlett 1986, 1991). Though exotics are not trivial in forests, we are reasonably confident that the impact in forest ecosystems has been less extensive than in aquatic, dune, and grassland ecosystems.

The works of Hazlett (1986, 1991) and Corace et al. (2003) and the documentation by Ken Hyde (NPS, Ken Hyde, Wildlife Biologist, SLBE, pers. comm., September 2008) detail the large number of alien species in the "open lands." For example, Hazlett (1991) lists the species present in the old field along Empire Bluff trail, and more than half are alien. In addition, a significant number of known invasive aliens are present in many different fields; Corace et al. (2003) found spotted knapweed in all 12 fields they studied. In his documentation of the mainland flora, Hazlett (1986) included a list of "Cultivated and Persisting Species," almost all of which are found near old home sites, buildings, and old fields. Sixty-one taxa are listed, which indicates the extent of alien species brought in for landscaping and personal use as well as the role of human disturbance. A few of these taxa are exotic trees established as plantations (Douglas-fir [*Pseudotsuga* spp.], Scots pine, blue spruce [*Picea pungens*], Norway spruce [*Picea abies*], and Austrian pine [*Pinus nigra*]), which collectively total 234 ha (NPS 2006c). In addition, there is a white spruce plantation in Benzie County and a small black walnut plantation in the Mainland-South Unit (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Common exotics on and around the dunes are white sweet clover (*Melilotus alba*), bladder campion, Jimson-weed, spotted knapweed, bouncing-bet, and baby's breath (Hazlett 1991; NPS, Ken Hyde, Wildlife Biologist, SLBE, pers. comm., June 2007). The open nature of this system, the amount of traffic it receives, and its frequent disturbance by humans make it highly susceptible to continued invasion and impacts from the exotics after invasion. The SLBE website (NPS 2006c) indicates that the park has a "long history" of spotted knapweed presence; the open sandy areas of older dunes are prime for further invasion by this aggressive, stress-tolerant species (WDNR 2008). Spotted knapweed can also invade forested sites on the drier end of the gradient, and is one of the most extensive exotic plant species at INDU (Pavlovic et al. 2005). The species has the capacity to eliminate native species via spatial competition, allelopathy, and disruption of below-ground mutualisms (Callaway and Aschehoug 2000; Czarapata 2005; Stinson et al. 2006). Leafy spurge, the teasels (*Dipsacus* sp.), Canada thistle, sweet clovers, and wild parsnip (*Pastinaca sativa*) (Czarapata 2005) are all serious pests of grasslands, right-of-ways, and other disturbed areas. For example, spurge is legally classified as a noxious weed in 19 states, including Iowa, Minnesota and Wisconsin (Czarapata 2005), is established on at least 2.5 million ha, and increased its area by 67% from 1999 to 2004 (Cornett et al. 2006). This species is clearly a serious concern for SLBE.

Black locust deserves careful scrutiny because of the range of effects it can have on a system. At INDU, it was shown to reduce herbaceous diversity, facilitate an exotic grass, and increase available nitrogen (Peloquin and Hiebert 1999). It can invade both disturbed and relatively intact communities, so many areas are susceptible. All of the coastal forests are probably susceptible, especially those with a partially open canopy. Because it is a nitrogen-fixer, locust can have strong cascading effects on the systems it invades by facilitating species that compete better at higher nitrogen levels. The observation by park staff (NPS, Ken Hyde, Wildlife Biologist, SLBE, pers. comm., September 2008) that the exotic honeysuckles come in under black locust is particularly troublesome.

For forests in general, other exotic taxa of serious concern, based on results in other areas, are garlic mustard, the alien buckthorns, Oriental bittersweet (*Celastrus orbiculatus*) and the honeysuckles (Nuzzo 1991; Woods 1993; Czarapata 2005). These species can invade intact communities and reduce the number and/or diversity of native species. The oak, oak-pine, and oak-aspen forests are probably the most likely to be impacted, though one or more of the honeysuckles and the buckthorns can thrive in richer soils and thus could invade birch, or aspen-northern hardwood type forests. Garlic mustard is a relatively new threat that grows in the shade of the densest forest, crowding out native flowering plants and ferns (NPS 2006c).

Albert (1992) surveyed two wooded dune and swale complexes in the Platte River basin and found two exotic species in their transects (cattails and reeds). Kost et al. (2007) list eight exotic species as threats to wooded lowlands in Michigan: reed canary grass, reed, autumn olive, glossy buckthorn (*Rhamnus frangula*), narrow-leaved cattail, hybrid cattail (*Typha* x *glauca*), purple loosestrife, and European marsh thistle (*Cirsium palustre*). Autumn olive has begun to appear in coastal forests such as the Otter Creek area, and appears to be somewhat shade tolerant (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

An excellent source for the basic biology and control options for the important exotics is the book by Czarapata (2005). The range of control efforts tried and being used by park staff (NPS, Ken Hyde, Wildlife Biologist, SLBE, pers. comm., September 2008) indicates a high level of awareness of control options. Resources are the primary limiting factor to increasing the reduction of exotic plants in SLBE. For more detailed studies on the control and efficacy of control of garlic mustard, see Nuzzo (1991) and Blossey et al. (2001). On-line resources are extensive and expanding rapidly. The NPS Great Lakes Exotic Plant Management Team has a website at http://www.nature.nps.gov/biology/invasivespecies/presentations/GL_EPMT.pdf. The state of Wisconsin has an extensive list of problem species and fact sheets on many of them at www.dnr.state.wi.us/invasives/plants; this site is the best all-around for the Upper Great Lakes.

The Minnesota Department of Agriculture has primary responsibility for terrestrial weed plants in Minnesota, and they provide a valuable resource to all interested parties in the form of an interactive mapping site (www.mda.state.us/plants/weedcontrol).

Exotic Pests

Because the NPS, and SLBE in particular, would like to be able to anticipate the impacts of new biotic agents (such as the hemlock woolly adelgid), a framework for assessing the importance of predicted changes would be useful. A recently-proposed framework seems to meet the needs of SLBE nicely. Lovett et al. (2006) stated that six key features "regulate" the effects of exotic pests and pathogens on forest ecosystems: 1) mode of action of the organism (how does it affect the plant?), 2) host-specificity of the organism (restricted to one species or does it affect many?), 3) virulence of the organism (actual severity of impact), 4) importance of the host (ecologic, aesthetic, cultural, etc.), 5) uniqueness of host (does the host provide habitat or some condition(s) that no other plant can provide?), and 6) phytosociology of host (does it occur in small scattered groups or does it occupy tens to hundreds of hectares, and where in the successional sequence does it occur?).

Beech Bark Disease Complex (BBD): The two primary causal agents of this complex, *Cryptococcus fagisuga* (scale insect) and *Nectria coccinea* var. *faginata* (beech bark disease) are both non-native organisms introduced from Europe. The scale was first documented in North America in Halifax, Canada in 1890 but did not start causing significant mortality until the 1920s (Houston 2005). The two agents have been in the US since 1919. One of two native species of *Nectria* typically invades first, and then the non-native (*N.c*. var. *faginata*) infects the tree later (Houston 2005; Witter et al. 2005). The non-native *Nectria* appears to cause significantly more damage than the native ones. The scale insect feeds on the parenchyma tissue of bark (Wainhouse and Gate 1988 in Latty 2005), typically causing the bark near the attacked area to dry and crack. This provides an entry point for the fungus, which is not capable of invading intact bark.

The scale, which is followed by the fungus, has spread south and west from its initial point of introduction at an annual rate of 6-16 km yr^{-1}. The complex was documented to have made it to Michigan by 2000; however, given the extent of the infestation in both the UP and LP, it was probably present at least 15 years before detection (Witter et al. 2005). There is no known barrier to prevent the complex from spreading throughout the range of beech, and natural predators do not have an impact on the course of the disease at the stand or landscape level (Houston 2005). How rapidly it spreads across a landscape is influenced by the proximity of one beech stand to another because the insect spreads passively. The stage of the insect known as the 'crawler' is the primary dispersal stage, though eggs can also spread. Both are blown by the wind, and thus the number generally decreases rapidly from the source tree; >95% disperse less than 10 m (Witter et al. 2005). The insect is almost bound to be moved by birds and mammals, though the importance of this dispersal method is unknown.

A number of tree characteristics affect the distribution and abundance of the scale; traits facilitating greater abundance include 1) older trees, 2) larger diameter, 3) the amount (surface area) of live bark, 4) higher than average N concentration in the bark, 5) "susceptible" genotype (=vast majority), and 6) poor crown health (Griffin et al. 2003; Witter et al. 2005). It should be noted that 1-4 often occur in tandem, such that large, old trees have a much higher likelihood of succumbing to BBD. Studies to date indicate that only <1% of the trees in a stand are naturally resistant, and the direct causal features for resistance identified are the thickness, continuity, and proximity to the surface of sclerophyll cells in the bark and lower amino acid-N and TN in the bark (Houston 2005).

The first invasion of BBD generally causes about 50% mortality of the overstory (McCullough et al. 2001), though this impact is typically spread over several years. Furthermore, an additional 25% will be infected and exhibit slower growth (Witter et al. 2005). Numerous studies, many spanning 15+ years in the New England region, provide good indications of the types and level of impact that can be expected in SLBE and the Great Lakes region in general. Though the larger beech have a high infection and mortality rate, the total level of infection among all sizes and the impacts of the complex on the forest ecosystem are surprisingly variable. For example, it is not unusual for beech to remain stable or even increase in a forest long affected (Forrester et al. 2003; McNulty and Masters 2005), though the opposite is also found (Twery and Patterson 1984). Typically, beech density does not decrease because of the species' high capacity for root sprouting (Houston 2005) and steady or increased recruitment in the face of stand invasion by BBD (Forrester et al. 2003). In New Hampshire, a five-fold increase in beech density since 1965 was documented (Hane 2003); however, no change in beech density was found across 62 forests in Michigan (Kearney et al. 2005). For reasons that are unclear, other species (sugar maple, yellow birch) may decline concurrently with the beech (Twery and Patterson 1984; Forrester et al. 2003; Kearney et al. 2005). However, in some forests, sugar maple has responded positively. Latty (2005) speculated that these different outcomes might be related to competition and the crown class of the maple prior to loss of the beech. In the Catskill Mountains of New York, Griffin et al. (2003) found BBD present in virtually all beech >10cm. In contrast, Forrester et al. (2003) found that 58% of beech stems in second growth stands in the Adirondacks exhibited no or minor signs of BBD, 28% had a moderate degree of infection, and 13% had a high level when tracked over a 15-year period.

The short-to-intermediate term (roughly 10-30 year) presence of BBD could potentially affect many forest and ecosystem properties directly (e.g., greater radiation and precipitation reaching the forest floor) or indirectly by allowing other species, with substantially different traits, to increase in importance. For example, beech has a higher-than-average lignin level in its leaves (Page and Mitchell 2008), and if it were replaced by species with lower lignin concentrations, then rates of decomposition and mineralization are likely to increase (Barnes et al. 1998; Finzi et al. 1998). However, this has not been studied, and more research in this area is needed (Latty 2005). The most obvious and pervasive change is the change in forest structure (diameter and height) due to greater levels of mortality among larger trees (Latty 2005). The study by Forrester et al. (2003) documented that red maple was the "winner," whereas Twery and Patterson (1984) found that hemlock benefited the most from beech mortality. If these patterns of relative abundance persist for extended periods of time, they could affect nutrient cycling as noted above. The differences between hemlock and broad-leaf dominated forests are detailed below.

Ecosystem function-related properties that have been studied, and their trend in affected forests, include no change in litterfall rate (Forrester et al. 2003); no substantial change in understory (Twery and Patterson 1984); shrub layer richness and abundance increased (McNulty and Masters 2005); total amount of coarse woody debris increased, but average size went down (McNulty and Masters 2005); total above-ground biomass decreased (Forrester et al. 2003); and lignin content of litter did not change (Forrester et al. 2003).

BBD has been reported in both Benzie and Leelanau Counties (MDNR 2008b). The reported rate of spread (6-16 km yr^{-1}) suggests it will reach areas within SLBE boundaries within five years. BBD should be considered present, and impacts should be anticipated soon.

Emerald Ash Borer (EAB): This bark boring, phloem-feeding exotic beetle (*Agrilus planipennis*, Buprestidae) was found and identified in southeastern Michigan and adjacent parts of Ontario in July, 2002 (Muirhead et al. 2006; Poland and McCullough 2006). Since then, it has spread throughout the LP, much of Ohio and Indiana, and parts of Illinois. It has also been transported on nursery stock to Maryland. In just five years, it has killed at least 12 million trees (probably 15 million if all urban trees are included) (Poland and McCullough 2006) in the Midwest.

The basic life cycle of the beetle is as follows. Adults emerge in June-July and live 3-6 weeks. They are active during the day, especially under warm, sunny conditions. The adults take refuge in bark crevices or on foliage under inclement conditions. Adults use the foliage of ash as a food source. Females may mate several times and lay 50-90 eggs, typically in bark crevices. The eggs hatch in 7-10 days, and the resulting larvae chew through the bark and into the cambial region. The larvae feed on the phloem and outer sapwood for several weeks. The extensive galleries created by the larvae effectively girdle the tree. Typically, the late stage (pre-pupal) larvae overwinter in shallow excavations in the outer sapwood or bark. However, in a few cases, earlier stage (younger) larvae will overwinter and thus require two years to complete the life cycle. Pupation begins in late April, but the incompletely formed adult remains in the pupal chamber for 1-2 weeks. Upon emerging, the adult creates a D-shaped exit hole in the bark (McCullough and Katovich 2004; Poland and McCullough 2006).

The EAB is native to Asia and feeds on a variety of species, including several in other genera (e.g., *Ulmus*, *Juglans*). However, in North America it has successfully completed its development only on ash trees, although its eggs have been found on a few other species (Agius et al. 2005). It appears to attack all native species, as well as several horticultural varieties; the insect appears to show less preference for blue ash, but blue ash is attacked as neighboring ash trees die (Poland and McCullough 2006). In its native range, it is not considered a serious pest; in contrast, its impact in North America has been catastrophic. Unlike some beetles, EAB will attack trees as small as 1 inch in diameter (McCullough and Katovich 2004). Saplings may die within one year, but it typically takes 3-4 years for large trees to succumb (Poland and McCullough 2006). The beetle is fully capable of killing vigorous, healthy trees—even those receiving optimal water and nutrients (McCullough and Katovich 2004). Monitoring to date has found a very high level of mortality in stands containing the beetle.

Spread of the beetle to every county in Michigan is inevitable given the flight capabilities of the adult and other means by which the species disperses (Taylor et al. 2005; Muirhead et al. 2006). The beetle has made it to black ash swamps in the northern LP even though they are surrounded by forests containing no ash (Siegert et al. 2005). The spread rate from low density, outlier populations has been less than 1 km yr^{-1} (Poland and McCullough 2006); this appears to be the best case scenario, given the extent to which it has spread from its original location in southern Michigan. Smith et al. (2005) found that mortality in 11 stands in southeastern Michigan was unrelated to basal area or canopy cover of ash. Given this history, it seems highly likely that more than 95% of the ash trees on the mainland greater than 1-2 inches will die in the near future. The virulence of the beetle does not mean that ash will be completely eliminated in this time frame, as current seedlings and small saplings will escape the first wave of infestation. This next cohort will soon grow into the size class that the beetle utilizes, so the long-term fate of the ash is quite bleak.

EAB is the tree pest of greatest imminent concern to SLBE managers. In 2008, EAB prism traps with lures were deployed in SLBE in areas of heavy visitor use (campgrounds, group campgrounds, concessionaire areas, and areas popular for beach fires), but no EAB were found (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). However, it is reported as present in both Benzie and Leelanau Counties (USDA 2009) and the LP is considered to be "generally infested" (MSU 2009). EAB should be considered as present, and impacts should be anticipated soon.

Hemlock Woolly Adelgid (HWA): The hemlock woolly adelgid (*Adelges tsugae*) was introduced into the eastern US (near Richmond, Virginia) in 1953 or 1954. A native of Asia, it probably came in on nursery stock from Japan (Souto and Shields 2000). This species is a tiny (adult is about 2 mm), aphid-like insect. The species is totally female, and thus reproduction is more certain than it is in other species. It has two generations per year; one is longer-lived than the other and overwinters. The shorter-lived generation completes its full life cycle in late spring. The life cycle consists of egg, nymph ('crawler') and adult stages. The adelgid is dispersed by animals, especially birds (Ward et al. 2004) in the egg and crawler stages, and by wind in the crawler stage. The insect harms its host by sucking nutrients from the tree, which it usually does at the base of needles. The adult and eggs are covered by a woolly, wax-like substance, and hence the common name.

For the first 30 years the species was in the eastern US, there was very little spread, and it was not considered a serious pest. That changed in the early 1980s when the species reached the natural range of eastern hemlock and began to spread rapidly. Originally, the pest spread primarily along a NE-SW axis parallel to the Appalachian Mountain chain. It reached the southern end of the contiguous range of hemlock fairly quickly, but spread more slowly to the north. There was limited spread to the West, though a couple of large leaps were made that established outlying (disjunct) populations in western Pennsylvania and western New York. Cold winter temperatures may result in significant mortality and are thought to limit the spread of the species. For example, up to 99% HWA mortality was noted at a New Hampshire site where a minimum temperature of -24.5^{o}C was recorded (Shields and Cheah 2004). However, short-term warm periods (>1 year) and its ability to complete a life cycle in less than eight weeks probably allow the species to establish in areas which, on average, have winter temperatures that are "too cold."

There is a very significant amount of innate resistance to the adelgid among species of hemlock in the US (Montgomery et al. 2005), partially due to the level of terpenoids in the plant tissues. Though eastern hemlock has lower levels of terpenoids in the leaf cushion (where the insect feeds) than in needles, this provides some anticipation of a mechanistic basis for differential effects (innate resistance) among trees and locations.

Although mortality in infected hemlocks is often high, over 90% defoliation is generally required to produce hemlock mortality (Souto and Shields 2000). In south-central Connecticut, the mortality level was over 60% in four of eight forest stands and was increasing 5-15% per year in 1998-99. Impacts on understory trees were similar (Orwig and Foster 2000). Furthermore, the majority of remaining trees contained less than 25% of their foliage; these authors predicted near-100% mortality within a few years. During this period, several other arboreal taxa regenerated rapidly, and thus it appeared that in south-central Connecticut the forest would rapidly transition to one dominated by black birch (*Betula lenta*), red maple, and oak. In contrast, a detailed study of another forest natural area in Connecticut showed that HWA arrival caused mortality only among the larger stems (Goslee et al. 2005). The resulting canopy gaps have led to an increase in shade-intolerant species in the understory, and thus qualitatively the long-term impact here will be different than the study of Orwig and Foster (2000) in that this site is being set back further in succession.

However, across a landscape the mortality level can vary substantially (Jenkins et al. 1999; Orwig and Foster 2000). Orwig and Foster (2000) found much greater mortality in the southern part (20-100%) of Connecticut than in the northern part (0-20%), and site conditions did not explain much of the variation. In contrast, a study in Maine found greater effects on drier sites, exposed ridges, and wet and poorly drained sites (Souto and Shields 2000); the authors also surmised that partial harvesting may predispose a stand to greater damage, as can prior defoliations (Souto and Shields 2000). Summarizing across a number of stands, Orwig et al. (2002) concluded that mortality occurs among all size classes within 4-15 years of infestation.

Effects of overstory hemlock mortality on the understory were quantified in two declining stands in the Delaware Water Gap National Recreation Area. Coincident with the increased radiation, there was an increase in understory plant cover, tree seedling frequency, and richness of the vascular plants and bryophytes (Eschtruth et al. 2005). Four new exotic species also became established. The authors concluded that the initial response of the community to the loss of hemlock in the overstory is a rapid increase in the abundance of black birch, red maple, and, in the understory, ferns. Jenkins et al. (1999) also found increased seedling densities in southern New England. Characterizing the status of hemlock throughout its range, Ellison et al. (2005) stated " … generally does not re-establish following adelgid-induced mortality, but is replaced throughout its range by hardwood species."

The adelgid-induced mortality of dominant hemlock has pronounced effects on numerous ecosystem characteristics and the connected processes (Ellison et al. 2005). These include lower forest floor carbon: nitrogen ratios, soil organic matter, and soil moisture, but higher levels of radiation. Net nitrification and mineralization, leaf N concentration, and total N pool were higher following adelgid infestation (Jenkins et al. 1999; Yorks et al. 2000; Orwig et al. 2008). Changes in N were likely due to increased decomposition, reduced water and N uptake, and nutrient-enriched throughfall (Jenkins et al. 1999; Stadler et al. 2006; Orwig et al. 2008). Many of these changes were documented before 'substantial overstory mortality' occurred (Orwig et al. 2008). In contrast to the other studies, Jenkins et al. (1999) found no change in soil organic matter, total carbon, or total N as a result of hemlock decline. The change in litter type and quality leads to a shift in the relative abundance of microorganisms and nutrient fluxes from the litter layer. In situations where birch (and possibly maple) come in strongly, more of the limiting nutrients, especially N, are tied up in the litter layer, and thus less percolates down into mineral soil (Stadler et al. 2006). Jenkins et al. (1999) found much higher levels of N availability and nitrification rates, and thus surmised that nitrate leaching is likely. An increase in cation (aluminum, calcium, and magnesium) leaching in soil water was documented in one study, which raises further concerns about forest productivity (Yorks et al. 1999).

HWA was only as far west as the Ohio-Pennsylvania border in early 2008 (USDA-Forest Service 2008). Based on its rate of spread from 1998 to 2008, it will take about two decades for this insect to reach SLBE. However, unintentional human transport could easily shorten this time frame. In areas at SLBE (from the patch scale and up) where hemlock currently dominates the overstory, significant compositional and functional changes may occur as the hemlock die from adelgid herbivory. The compositional change will depend on co-occurring species, especially those in the midstory and understory, and surrounding seed sources. Any species in the lower strata will be released by hemlock mortality and could quickly recruit to the overstory. Sugar maple and/or beech sometimes co-occur with hemlock (e.g., the beech-maple-birch-hemlock association) (Hazlett and Vande Kopple 1983) and are shade tolerant, and thus are most likely to be the species directly favored by the loss of hemlock in SLBE. Red maple and yellow birch have a lower level of shade tolerance but can persist in partially shaded conditions, and thus probably will benefit modestly as well. Any pioneer, widely dispersed trees in the vicinity will likely ‘invade’ the stand as canopy gaps are created; these seeds could come from inside or outside the hemlock patch/forests. White birch and aspen are prime examples of wind-dispersed, pioneer species. Two others likely to increase are white pine and balsam fir, based on their moderate to high shade tolerance, ability to co-occur with hemlock, and fairly wide seed movement.

The majority of nutrient-related changes noted by studies in the Northeast will favor species in SLBE that are more competitive under relatively high levels of nutrient (especially N) availability and high radiation environments. These conditions work strongly against hemlock successfully re-establishing, even when there is a seed source (Mladenoff and Stearns 1993), and will particularly favor birch, aspen, and maple. As other species claim the portion of the canopy vacated by hemlock, some of the changes (moisture, radiation, leaching losses) will disappear. Others, such as carbon: nitrogen ratio and N-mineralization, will persist for decades. Thus, the domination by a group of broad-leaved species sets up a feedback loop that puts hemlock at a competitive disadvantage.

Exotic Earthworms

The scientific consensus is that there are no native earthworms in the hardwood forests of the western Great Lakes region, since they have not migrated back after the retreat of the Wisconsin glacier (Hendrix and Bohlen 2002). However, due to human migration and commerce (e.g., use of worms as fish bait and for composting), at least 45 exotic earthworm species have been introduced to North America. The most common exotics are from Europe, and they spread substantially over the past few decades (Bohlen et al. 2004). The most numerous are members of the family Lumbricidae (Hendrix and Bohlen 2002). As early as the 1960s, it was noted that these species have significant impact on soil properties in areas devoid of native species (Hendrix and Bohlen 2002). More recently, some far-reaching implications for the composition and function of northern hardwood forests in the northern parts of the Great Lakes region have been identified (Hale et al. 2006 and citations therein).

A succession of earthworm species usually occurs at a site, very similar in concept to the changes of plant species composition during succession. Members of the first group to invade typically are smaller, stay in the litter layer, and have a minimal impact on the system. The second and third waves, or stages, include larger species and those that move between the litter/duff layer and mineral soil. Of particular influence seems to be the species *Lumbricus* *rubellus* (Hale et al. 2006). These later-successional species have very notable impacts on the litter and soil (Bohlen et al. 2004) and indirectly on the plant community as a whole. The most immediate impacts of the earthworms are to reduce litter layer depth and to incorporate some litter and duff in the mineral soil. Subsequently, this alters the dynamics of carbon and nitrogen in the soil and the composition of the understory (Bohlen et al. 2004; Hale et al. 2005, 2006). The understory community will typically have reduced species richness, reduced recruitment of sugar maple saplings, and increasing amounts of Pennsylvania sedge (*Carex pensylvanica*) (Hale et al. 2006). It has also been noted that at least one species of concern, little goblin moonwort (*Botrychium mormo*), is negatively correlated with the abundance of *L. rubellus* (Gundale 2002). Although this plant is not reported from SLBE, this finding adds to the threat exotic earthworms may represent.

Agriculture

In 2002, the number of hectares of cropland in Leelanau and Benzie Counties was 15,574 and 4,893 respectively (USDA 2002). Of those, approximately 6,000 ha were in the SLBE watershed and used to grow row crops, forage crops, and orchards (Figure 53; MDNR 2003). Crops grown in Benzie and Leelanau Counties include tart and sweet cherries, apples, corn for grain, forage, and Christmas trees (Table 52). In 2002, Leelanau County was the number one producer of tart cherries in the nation, and Benzie County was 10th (USDA 2002).

Approximately 21% of Benzie County farmland and 40% of Leelanau County farmland was fertilized in 2002 (Table 53). Statistics collected by the USDA National Agricultural Statistics Service indicate that in 2003 (the latest year for which statistics are available), nitrogen and phosphorus fertilizer was applied to 99% and 86%, respectively of Michigan's corn. The average annual application rates were 138 kg/ha and 54 kg/ha respectively. The herbicide atrazine was used on 68% of corn fields at an average annual application rate of 1.3 kg/ha (USDA 2004).

Twenty-four types of fungicides were applied to apples, 12 types were applied to sweet cherries, and 13 types were applied to tart cherries in Michigan in 2003. The most common fungicides applied on apples included an average of 5.2 applications of Captan on 82% of the crop and 4.0 applications of mancozeb on 67% of the crop. Sweet cherries most commonly received applications of sulfur (72%, 4.2 applications) and chlorothalonil (68%, 2.1 applications). Tart cherries most commonly received applications of chlorothalonil (83%, 3.0 applications), sulfur (73%, 4.9 applications), and tebuconazole (70%, 3.3 applications). Fifty-nine percent of sweet cherries and 80% of tart cherries received an application of ethephon to help in removing the cherries from the trees (USDA 2004).

Cherry production also includes the use of insecticides; 68% of sweet cherries and 70% of tart cherries were treated with azinphos-methyl, and 67% of tart cherries were treated with phosmet in 2003 (USDA 2004). Azinphos-methyl is scheduled to be phased out of use on cherries by September 2012 because of the risks to agricultural workers, water quality, and aquatic ecosystems. These risks include cholinesterase inhibition (a precursor to neurological effects) in humans and moderate to high toxicity to freshwater fish (USEPA 2006b). Phosmet use has been restricted on some crops because of risks of cholinesterase inhibition in agricultural workers and ecologic risks (high toxicity to some birds, some fish, and honeybees), but its use on cherries is still allowed with some risk reduction measures (USEPA 2001b).

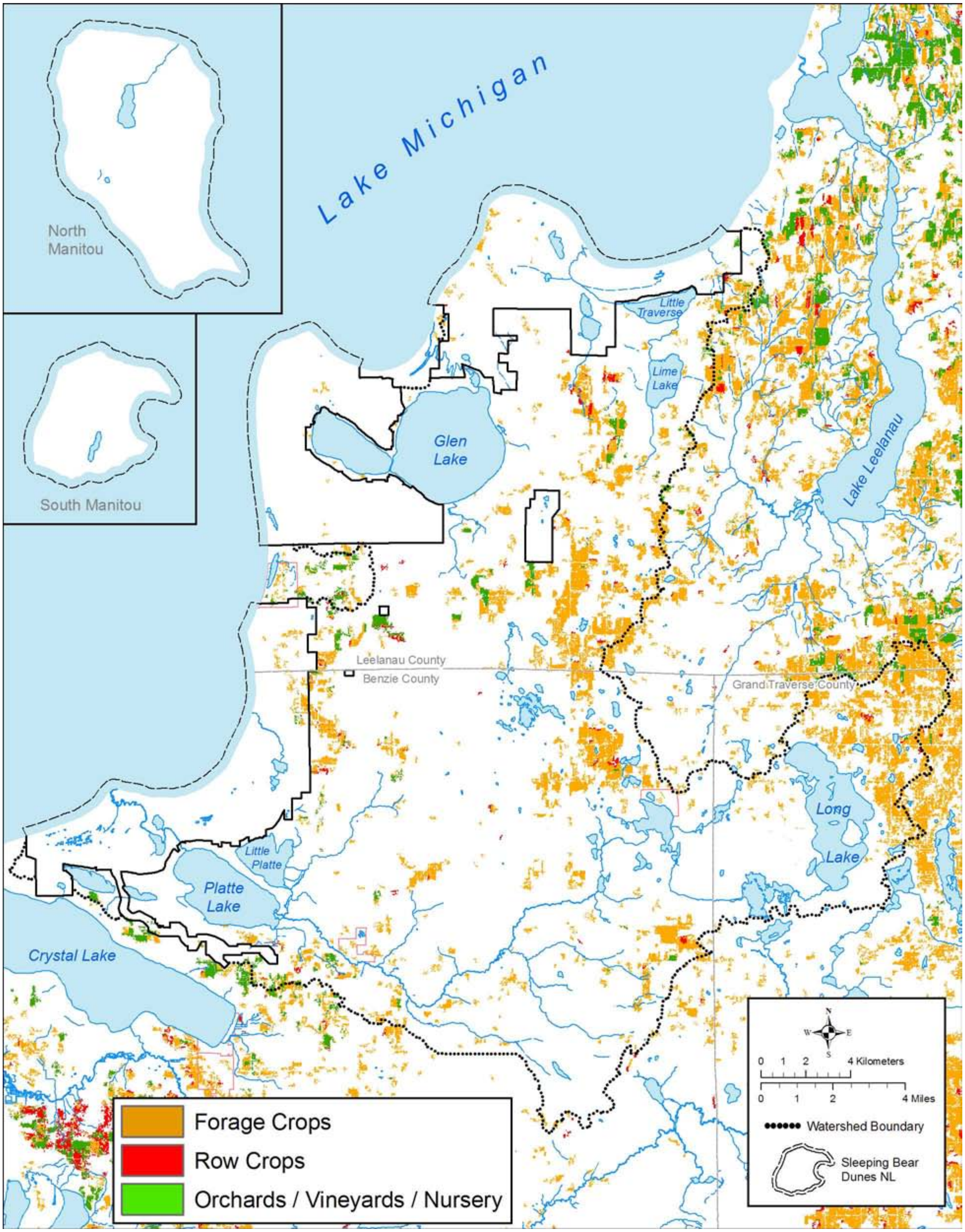

Figure 53. Forage crops, row crops, and orchard/vineyard/nursery crops in the vicinity of Sleeping Bear Dunes National Lakeshore (MDNR 2003).

Table 52. Top five crops and number of hectares in each, Benzie and Leelanau Counties, Michigan (USDA 2002).

Crop	Benzie County (ha)	Leelanau County (ha)
Tart cherries	573	3,668
Forage (hay, haylage, grass silage, greenchop)	1,141	2,232
Sweet cherries	--	1,862
Corn for grain	331	1,170
Apples	439	836
Cut Christmas trees	260	--

Table 53. Number of hectares in Benzie and Leelanau Counties that were treated with fertilizers and chemicals in 2002 (USDA 2002).

Treatment	Benzie County (ha)	Leelanau County (ha)
Cropland fertilized	1,981	10,115
Pastureland and rangeland fertilized	23	386
Manure applied	302	1,883
Insect control	1,238	6,721
Weed, grass or brush control	901	7,307
Nematode control	22	244
Disease in crops and orchards control	1,073	5,948
Chemicals to control growth, thin fruit, or defoliate	305	2,214

Of the agricultural pesticides known to be used in Benzie and Leelanau Counties, three have a high potential for surface water runoff (mancozeb, sulfur, and tebuconazole), four have moderate potential (azinphos-methyl, chlorothalonil, atrazine, and ethephon), and Captan has a low potential (NRCS 2006b). For leaching to groundwater, two have a high potential (atrazine and sulfur), tebuconazole has a moderate potential, and five have low potential (azinphos-methyl, Captan, mancozeb, chlorothalonil, and ethephon) (NRCS 2006b).

Benzie County was also home in 2002 to 1,282 cattle and calves, 1,122 hogs and pigs, and 586 chickens; Leelanau County had 3,290 cattle and calves, 503 horses and ponies, and 928 chickens (USDA 2002). A small feeder pig operation exists in the Platte River watershed and applies its waste within SLBE boundaries in the Otter Creek watershed (Vana-Miller 2002), but is considered to pose little risk of surface water runoff; the risk to groundwater was not evaluated (Michigan Groundwater Stewardship Program, Dan Busby, email, 9/12/07). A small reindeer farm also exists near SLBE (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Golf Courses

At least 17 golf courses are located in the SLBE vicinity, and five of those are within the SLBE watershed (Figure 54). In an extensive literature review, Wheeler and Nauright (2006) have described environmental impacts of golf courses, such as their tendency to be located in the most scenic natural areas, and the impacts of their construction, which may include natural vegetation

Figure 54. Location of golf courses in the vicinity of Sleeping Bear Dunes National Lakeshore (for sources, see Appendix A).

clearing, deforestation, habitat destruction, and changes in local topography and hydrology. Chemical applications, including fertilizers, insecticides, pesticides, and fungicides, are extensive and may equal three to seven times the amount used in "large-scale agriculture" (Wheeler and Nauright 2006). Worldwide, the volume of water used to irrigate the world's golf courses each day (9.5 million m^3) is equal to the amount of water needed to support four-fifths of the world's estimated 2005 population (Worldwatch Institute 2004).

In 1998, construction of a golf course near the village of Arcadia, approximately 26 km from SLBE's southern boundary, resulted in the loss of approximately 6,300 metric tons of soil into Lake Michigan. The state of Michigan stated that this soil was contaminated with DDT and other persistent organic pesticides from the property's previous use as an orchard (MDEQ 2003).

In response to environmental concerns, the Michigan Department of Agriculture, Michigan Turfgrass Foundation, the MDEQ, Michigan State University, Michigan Golf Course Owners Association, and Golf Association of Michigan have established the Michigan's Turfgrass Environmental Stewardship Program (MTESP). The program has two parts. A pollution prevention module addresses site evaluation, wellhead protection, fuel storage, pesticide handling and application, pesticide and fertilizer storage, and pesticide mixing and loading pads. An environmental enhancement module is meant to improve the "green space" value of golf courses through promoting fish and wildlife habitat, indigenous vegetation, and water quality protection through the development of buffer strips (MTESP 1999).

Participants in MTESP in the SLBE vicinity are the Crystal Downs Country Club at Frankfort, the Crystal Mountain Resort at Thompsonville, the King's Challenge Golf Club at Sugar Loaf Resort at Cedar, and the Leelanau Club at Suttons Bay. The Crystal Downs Country Club has also participated in the National Audubon Society program for golf course certification with assistance from SLBE staff (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

In 2004, five golf courses (136 ha) in Benzie County were irrigated with 1,552 m^3day^{-1} of groundwater; seven courses in Leelanau County (135 ha) used 1,098 m^3day^{-1} of water (76 m^3day^{-1} Great Lakes water, 492 m^3day^{-1} other surface water, and 530 m^3day^{-1} groundwater); and seven courses (226 ha) in Grand Traverse County used 1,779 m^3day^{-1} of water (341 m^3day^{-1} surface water and 1,438 m^3day^{-1} groundwater). Within the hydrologic unit that includes SLBE's mainland (HUC 04060104), fifteen courses with a total of 341 irrigated ha used a total of 3,747 m^3day^{-1} of water (719 m^3day^{-1} of surface water and 3,028 m^3day^{-1} of groundwater) (MDEQ 2004b).

Soil and Groundwater Contamination Sites

The MDEQ keeps records of discharges of hazardous materials (ERD sites) and of leaking underground storage tanks (LUST sites) under Parts 201 and 213, respectively, of Michigan's Natural Resources and Environmental Protection Act 451 of 1994 (State of Michigan 1996a, b). Benzie County has 12 Part 201 sites and 18 Part 213 sites; Leelanau County has 34 and 17, respectively (MDEQ 2007b, c). Of these sites, 11 Part 201 sites and 13 Part 213 sites are located within the SLBE watershed or in communities immediately adjacent to SLBE (Table 54, Table 55, Figure 55). Glen's Sanitary Landfill, located in Kasson Township, Leelanau County, is near

Table 54. Part 213 leaking underground storage tank (LUST) sites in the vicinity of Sleeping Bear Dunes National Lakeshore (MDEQ 2007c).

Name	City	County	Substances
Benzie County Road Commission	Honor	Benzie	Diesel
Bud's In Honor	Honor	Benzie	Unknown
Lone Pine Party Store	Honor	Benzie	Unknown
Residential Well	Honor	Benzie	Unknown
Wishing Well Party Store	Honor	Benzie	Unknown
B & M Party Store Inc	Lake Ann	Benzie	Used oil
Sugarloaf Resort	Cedar	Leelanau	Diesel, unknown
Taghon's Service	Empire	Leelanau	Unknown
Lakeview Orchard	Empire	Leelanau	Unknown
Rich's Amoco	Glen Arbor	Leelanau	Unknown
Arts Tavern	Glen Arbor	Leelanau	Gasoline, unknown
B & Z Well Drilling Co	Maple City	Leelanau	Gasoline
Miller Short Stop	Maple City	Leelanau	Unknown

Table 55. Part 201 hazardous material discharge (ERD) sites in the vicinity of Sleeping Bear Dunes National Lakeshore (MDEQ 2007b).

Name	City	County	Substances	Risk Score	Status
Leelanau Co. Road Commission	Maple City	Leelanau	sodium, salt	14/48	no action taken-inactive
Thoreson Rd. Spill	Glen Arbor	Leelanau	gasoline	17/48	interim response in progress
Carter Creek	Thompsonville	Benzie	2,4-dimethlyphenol, naphthalene	19/48	interim response completed
Empire-Front Street	Empire	Leelanau	fuel oil	19/48	delisted
Empire School	Empire	Leelanau	mercury	19/48	no action taken-inactive
Birchway Drive Spill	Glen Arbor	Leelanau	1,2,4 TMB, ethylbenzene, fuel oil	20/48	interim response in progress
*Leelanau Co. Landfill	Kasson Twp	Leelanau	4-chloro-3-methylphenol, arsenic, phenol, toluene	21/48	interim response in progress
Sugar Loaf Resort	Cedar	Leelanau	benzene, ethylbenzene, PCE, toluene, xylenes, PNAs, lead	21/48	interim response in progress
N. Manitou Life Station	Leland	Leelanau	benzene, ethylbenzene, toluene, xylenes, PNAs	26/48	interim response in progress
Fewins Junkyard	Interlochen	Benzie	1,2 DCA, benzene, lead, zinc	27/48	interim response in progress
*Glens Sanitary Landfill	Kasson Twp	Leelanau	arsenic, benzene, zinc, ethylbenzene, lead, methylene chloride, toluene, xylenes	34/48	approved re-medial action plan implement-tation in progress

*outside SLBE watershed

Figure 55. Locations of soil and groundwater contamination (LUST/ERD) sites in the vicinity of Sleeping Bear Dunes National Lakeshore (MDEQ 2007b, c).

the SLBE watershed boundary. A modeling study indicates that contaminants from this landfill may be moving toward Glen Lake (Glen Lake Water Level Committee 2007), but MDEQ says contaminants from this site have been determined to be moving to the east (MDEQ, Philip Roycraft, Cadillac District Supervisor, Waste and Hazardous Materials Division, email, January 17, 2008).

Within SLBE, the old Glen Arbor town dump is located in a wetland adjacent to Tucker Lake. The wetland has been created by beaver dams and/or human activities and was not present when the site was actively used for waste disposal (Vana-Miller 2002). A consultant was hired to evaluate the site and some remediation work was done in the mid 1990s; it was determined that no additional assessment work was needed (Enviroscience 1995, 1996). Trash disposal took place on both North and South Manitou Islands. Three five-gallon cans of DDT were buried in the South Manitou Island dump in the 1970s. “High background levels” of arsenic have been detected in monitoring wells on North Manitou Island (Ozaki 2001). Known underground storage tanks in SLBE have been removed, but some may still exist on older land acquisitions (Vana-Miller 2002), including at several former gas station sites (Ozaki 2001). Other sites in SLBE are still being actively monitored, as on North Manitou Island. Many formerly developed sites contain buried foundations, wells, holding tanks, and other structures whose contents and impacts are often unknown (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Oil and Gas Resource Development and Gravel Extraction

The geologic formation known as the Michigan Basin contains numerous layers that produce oil and natural gas, and permits have been issued for over 56,000 oil and natural gas wells in the state of Michigan (MDEQ 2007f). SLBE lies atop the Devonian-age Antrim Shale and underlying Silurian-age Niagaran formations that have the potential to produce oil and gas (Ozaki 2001). In the SLBE vicinity, Benzie County has 14 currently producing natural gas wells and 10 oil and gas wells, mainly in its southeastern corner. Grand Traverse County has 158 currently producing wells, and Leelanau County has none (MDEQ 2007f). Michigan has issued permits for 13 slant drilling wells that take oil and gas from under Lakes Michigan and Huron, but six of them were dry holes (Clark and Dutzik 2002); such drilling under the Great Lakes was permanently banned in 2005 (USACE 2005). SLBE does not own the mineral rights to the majority of the properties it owns (Ozaki 2001). The park’s 2001 Geoindicators Scoping report recommended an investigation of oil and gas assessments in the SLBE vicinity (Ozaki 2001).

Eleven major sites in SLBE were once gravel and sand extraction pits or topsoil mining operations (Ozaki 2001). Work is ongoing in the park to rehabilitate these sites. Park staff have also expressed concerns about development of new extraction sites along park borders. Mining of sand dunes within two miles of the Lake Michigan shoreline is regulated by the Michigan Geological Survey, but mining of other deposits is controlled by township regulations (MDEQ 2007i). Nine townships in two counties (Lake, Benzonia, and Platte in Benzie County and Empire, Kasson, Glen Arbor, Leland, Cleveland, and Centerville in Leelanau County) have some jurisdiction over lands in or adjacent to SLBE (Figure 3), creating difficulty in monitoring the activities of local governments.

Storm Water

Storm water contains a variety of contaminants washed from parking lots, streets, rooftops, lawns, and other areas. In the 117 ha urban watershed of Marquette, MI, parking lots contributed 30% of the total zinc, 25% of the total cadmium, 22% of the total copper, and 64% of the PAHs that left the basin as a whole. Low-traffic streets contributed 27% of total suspended solids, 21% of nitrate-nitrite-N, and 25% of total cadmium (Steuer et al. 1997).

The communities in the SLBE vicinity are all too small to be covered under the federal and state phase I or II storm water regulations (MDEQ 2007g). The village of Empire did install storm sewers in 2008 (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). A small but potentially significant portion of SLBE (0.8%) is covered by paved roads, including county roads, and parking lots (MDNR 2003). The park's 2001 Geoindicators Scoping report recommended an evaluation of erosion from the county roads that pass through the park (Ozaki 2001).

Wastewater Disposal

Platte River State Fish Hatchery

In 1928, the state of Michigan built a fish hatchery on the Platte River upstream from Platte Lake and the part of the Platte River that flows through SLBE to Lake Michigan. This facility, originally used to raise trout, was replaced in 1967 by the Platte River Anadromous Fish Hatchery and became the state's main salmon hatchery in 1972. Currently, it raises coho and Chinook salmon, and it is the main egg take station for coho salmon in the Upper Great Lakes (MDNR 2007a). It received a National Pollution Discharge Elimination System (NPDES) permit in 1976.

There are two weirs operated by the hatchery on the Platte River, a lower weir off Lake Michigan Road 3.2 km northwest of Hwy M-22 and an upper weir at the hatchery (MDNR 2007a). The purpose of the lower weir is to allow excess salmon harvest to reduce the phosphorus loading that would occur when the salmon died after spawning. This weir also provides some passage to salmon to the upper weir where eggs and sperm are harvested. In 2005, 14,571 adult coho and 571 adult Chinook salmon were allowed to pass the lower weir (Canale et al. 2006). In general, 70-80% of these fish are harvested by anglers as they make their way between the weirs (Whelan 1999). Although egg harvest at the lower weir would prevent the salmon and their phosphorus load from entering Platte Lake, the eggs are not fully mature when the fish reach the lower weir, so a holding facility would have to be built (Vana-Miller 2002).

The water supply for the hatchery in 1999 consisted of surface water from the Platte River (46,000 m^3 day^{-1}) and Brundage Creek (26,500 m^3 day^{-1}) and spring water from Brundage Spring (6,400 m^3 day^{-1}) (Whelan 1999). Recently the hatchery has avoided using Platte River water because of its temperature extremes, the potential for diseases carried by the resident fish populations, and silt which collects in the rearing units (MDNR 2007a). The MDNR also discharges approximately 7.6 m^3 day^{-1} of water from four test wells at the lower weir to attract salmon during their migration; Vana-Miller (2002) recommended an evaluation of the impacts of this pumping on nearby SLBE wetlands.

From 1928-1964, phosphorus loading from the hatchery to the Platte River was relatively constant at about 74 kg year^{-1}, but increased to a maximum of 1,960 kg year^{-1}by 1974 (Canale et al. 2004). The increase was related to increased fish production and its associated food usage as well as a change in food composition. In the late 1960s and early 1970s, the water quality of Platte Lake declined markedly, with reductions in Secchi depth, DO, number of rooted plant species, crayfish, and mayflies, and increases in algal blooms and rough fish (Canale et al. 2004).

Vana-Miller (2002) has described the subsequent history of controversies, conflicting scientific opinions, and lawsuits that began in 1979 and culminated with a Consent Judgment in 2000 which limited the hatchery's total net phosphorus discharge to 102 kg year^{1}until May 31, 2007 and 79 kg year^{-1} thereafter. Under its NPDES permit, the facility's discharge is also monitored for flow volume, total suspended solids, and temperature (MDEQ 2005a). In 2005, the facility was well below its permitted flow volume, but exceeded its annual permitted phosphorus discharge by 0.6 kg (Canale et al. 2006). Although the hatchery is the only point source of phosphorus in the watershed, it is not the largest source overall; tributary phosphorus loads to Platte Lake in 2000 and 2001 were 836 and 898 kg, respectively (Vana-Miller 2002). The MDNR, Platte Lake Improvement Association, and Benzie County Conservation District have therefore developed a comprehensive watershed management plan to reduce non-point phosphorus loading to Platte Lake (Canale et al. 2004). Antibiotics and disinfectants are also used in the hatchery to mark fish and treat infections, but are not monitored under the NPDES permit (MDEQ 2005a; Canale et al. 2006).

The effects of the hatchery on the water quality and biological integrity of the Platte River and Platte Lake are discussed in the Platte River watershed section.

Onsite Sewage Disposal Systems (OSDS)

OSDS can be an efficient and effective means of sewage disposal if they are properly located, designed, constructed, and maintained. However, if these conditions are not met, OSDS have the potential to introduce a variety of contaminants into both groundwater and surface waters, including pathogens, nutrients, pharmaceuticals, and other chemicals (GWPC 2007).

Swann (2001) describes OSDS failures in three categories: hydraulic failures, subsurface failures, and treatment failures. Hydraulic failures are the most commonly known; they occur when the drainfield or distribution system has become so clogged that wastewater ponds at the surface. The system then discharges partially treated wastewater that may have nitrogen, phosphorus, bacteria, and biological oxygen demand characteristics similar to that of untreated wastewater. Hydraulic failures can deliver high pollutant loads to water bodies, especially along lake shores (Swann 2001).

A second type of failure occurs when subsurface plumes of partially treated sewage move through soil macropores or cracks. This type of failure is “fairly common” in sandy soils and can add high nitrogen and phosphorus loads to downstream surface waters (Swann 2001). The third type of failure occurs when nitrogen enters groundwater in the form of nitrate, which contributes to eutrophication in nitrogen-sensitive waters such as estuaries, coastlines, and springs. As much as 75% of this nitrogen may eventually be delivered to surface waters (Swann 2001).

All the major soil series within the SLBE watershed are ranked "very limited" in suitability for septic tank absorption fields (Table 56; NRCS 2007a). Most are limited by rapid seepage from the bottom of the soil profile and poor filtering capacity, which may lead to both subsurface failures and treatment failures. Small areas of organic soils are limited by slow water movement, ponding, shallow depth to the saturated zone, or the possibility of subsidence and are more likely to lead to hydraulic failures.

Private Systems: Over 90% of Benzie and Leelanau County residents utilize private OSDS (BLDHD 2002), which may mean over 23,500 systems are located in these two counties (US Census Bureau 2007). Within the boundaries of SLBE's watershed, we estimate at least 2,900 OSDS, based on the 2,900 household wells in the MDEQ Wellogic database (MDEQ 2007e; Figure 56). (Most homes with private wells also have private sewage systems, but not all private wells are in the Wellogic database. Also, the village of Empire has a public water supply but private sewage systems, so 2,900 is a conservative estimate).

Michigan has no statewide code regulating domestic OSDS (Halvorsen et al. 2004; MEC and MLCVEF 2007), and is the only state in the nation without such a code. In the SLBE vicinity, OSDS are regulated by the Benzie-Leelanau District Health Department (BLDHD). For nine months in 2003, the BLDHD issued 296 sewage permits for Benzie County and 258 for Leelanau County.

A 2004 study found that of 74 regulatory agencies surveyed around the Great Lakes in both the US and Canada, the BLDHD was strongest in the most measures of system management effectiveness (presence of Responsible Management Entities for alternative systems, post-installation inspections, maintenance requirements, homeowner contacts, and the comprehensiveness of its computerized permit database) (Halvorsen et al. 2004). Benzie County was one of the first counties in the nation to require inspection and upgrade of OSDS when property was transferred (Benzie County Board of Commissioners 1989). (Leelanau County does not have such an inspection and upgrade requirement, however.) Benzie County also participated in a National Onsite Demonstration Program project to test advanced phosphorus removal systems on Crystal Lake in the 1990s (NWMOWTF 2006).

Currently, Benzonia and Lake Townships in Benzie County (Figure 57) are applying for assistance through a state of Michigan program (State of Michigan Department of Environmental Quality Clean Water Revolving Funds: Strategic Water Quality Initiative Fund [SWQIF]) to improve OSDS through elimination of holding tanks, installation of some mound systems or advanced phosphorus removal systems, and/or construction of cluster systems for treatment of wastewater (NWMOWTF 2007). This project, if implemented, would likely decrease the discharge of holding tank waste to the ground and replace some systems with hydraulic failures. It would also decrease phosphorus loading. However, it is unclear what, if any, impact it might have on subsurface and treatment failures that result in nitrogen loading to surface water and groundwater.

Table 56. Limitations on suitability of soils in the Sleeping Bear Dunes National Lakeshore watershed for septic tank absorption fields. All the soils are rated as “very limited.” The numeric rankings (from 0.01 to 1.00) indicate the increasing severity of the individual limitation for the specified use (NRCS 2007a).

Soil Series	Slope	Seepage, bottom layer	Slope	Slow water movement	Filtering capacity	Ponding	Depth to saturated zone	Subsidence
Blue Lake	0-6%	1.00		-	-	-	-	-
	6-12%	1.00	0.04	-	-	-	-	-
	12-60%	1.00	1.00	-	-	-	-	-
Cathro	--	-	-	0.72	-	1.00	1.00	-
Deer Park	0-6%	1.00	-	-	1.00	-	-	-
	6-18%	1.00	0.63	-	1.00	-	-	-
	18-45%	1.00	1.00	-	1.00	-	-	-
East Lake	0-6%	1.00	-	-	1.00	-	-	-
	6-12%	1.00	0.04	-	1.00	-	-	-
	12-45%	1.00	1.00	-	1.00	-	-	-
Eastport	0-15%	1.00	0.01	-	1.00	-	-	-
Emmet	2-6%	1.00	-	0.50	-	-	-	-
	6-12%	1.00	0.04	0.50	-	-	-	-
	12-45%	1.00	1.00	0.50	-	-	-	-
Kalkaska	0-6%	1.00	-	-	1.00	-	-	-
	6-12%	1.00	0.04	-	1.00	-	-	-
	12-45%	1.00	1.00	-	1.00	-	-	-
Leelanau	0-6%	1.00	-	-	-	-	-	-
	6-12%	1.00	0.04	-	-	-	-	-
	12-45%	1.00	1.00	-	-	-	-	-
Montcalm	0-6%	1.00	-	-	-	-	-	-
	6-10%	1.00	0.01	-	-	-	-	-
	10-18%	1.00	0.96	-	-	-	-	-
	18%+	1.00	1.00	-	-	-	-	-
Roscommon	--	1.00	-		1.00	1.00	1.00	-
Rubicon	0-6%	1.00	-	-	1.00	-	-	-
	6-18%	1.00	0.63	-	1.00	-	-	-
	1.008-45%	1.00	1.00	-	1.00	-	-	-
Tawas	--	1.00	-	-	-	1.00	1.00	1.00

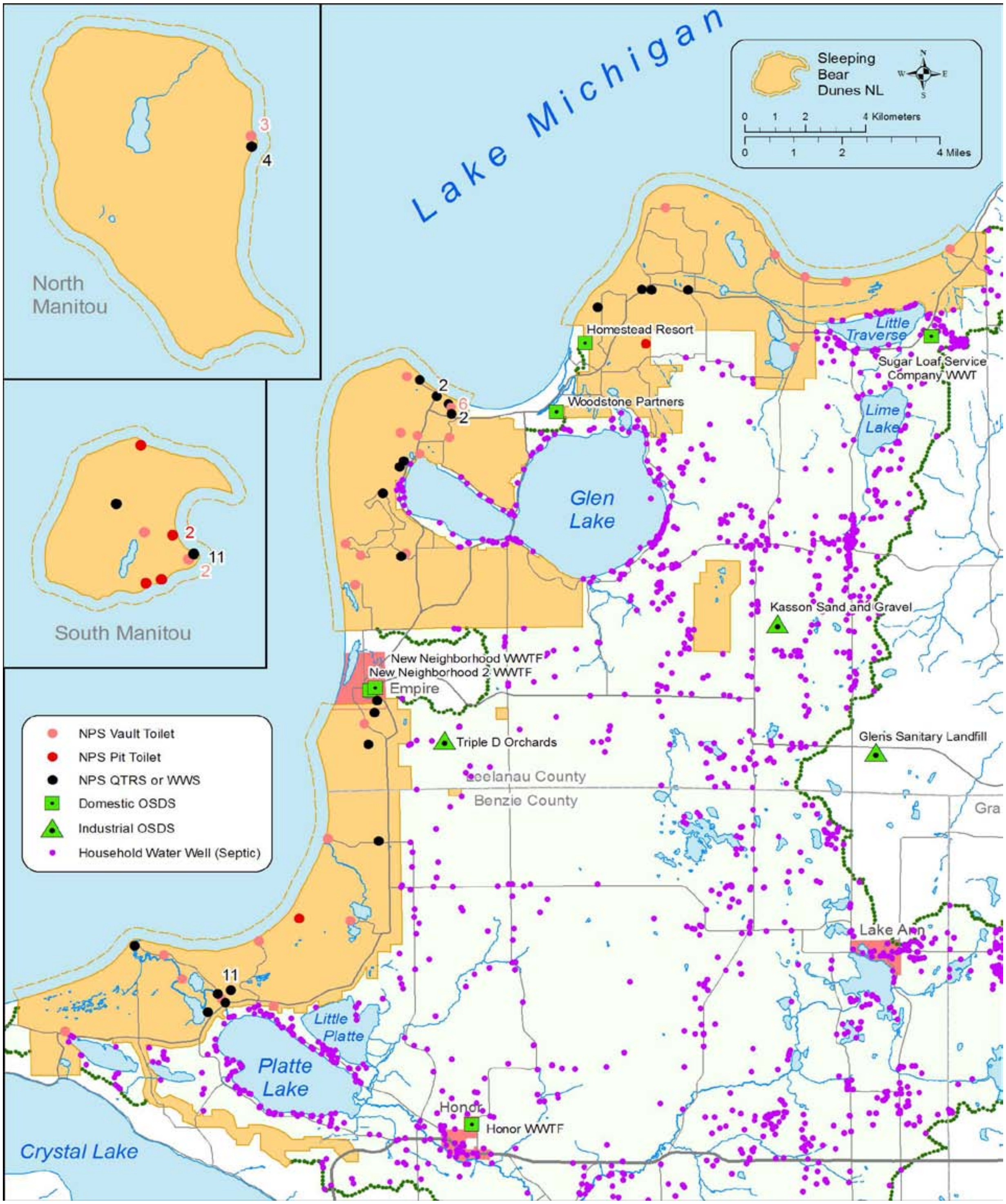

Figure 56. Locations of onsite sewage disposal systems in and around Sleeping Bear Dunes National Lakeshore (MDEQ 2007e; MDEQ, Janice Heuer, Senior Environmental Engineer, email, 11/28/07; NPS, Mark Pressnell, B&U Supervisor, SLBE, pers. comm., December 2007).

Figure 57. Location of proposed SWQIF project in the vicinity of Sleeping Bear Dunes National Lakeshore (NWMOWTF 2007).

Benzie County allows disposal of septage on agricultural fields within the SLBE boundary; the effects of this disposal on groundwater are not being monitored (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Group Systems: In Benzie and Leelanau Counties, the disposal technology of choice for wastewater facilities is discharge to the ground or groundwater. Most streams in the area are small flow cold water trout habitat, and meeting the treatment standards for those would be economically prohibitive. Groundwater discharge facilities do not receive NPDES permits. In Michigan, those discharging more than 22.7 m^3 day^{-1} receive MDEQ groundwater discharge permits and construction permits with detailed engineering reviews. Developments such as condominiums that discharge less than 22.7 m^3 day^{-1} also receive MDEQ engineering reviews. Other developments, such as small resorts and large restaurants, fall under the jurisdiction of the BLDHD if they discharge less than 22.7 m^3 day^{-1} and are wholly owned by a single owner (MDEQ, Janice Heuer, Senior Environmental Engineer, email, 11/28/07).

The Homestead Resort in Glen Arbor Township discharges 45,000-55,000 m^3 $year^{-1}$ of wastewater effluent on two parcels owned by NPS (NPS 2004b). The wastewater is first treated in an aerated lagoon system before being applied by slow rate irrigation to a 3.3 ha wooded parcel of mixed hardwood forest and red pine and a 1.9 ha open parcel from which alfalfa is harvested. In 2004, continuation of this arrangement (the "no-action alternative") was recommended over developing a subsurface irrigation system on adjacent NPS land to prevent damage to cultural landscapes and aesthetics, increases in nitrogen levels in nearby private water wells, and possible increases in nitrogen in Lake Michigan's nearshore environment (NPS 2005b). However, the Homestead plans to clearcut and grade the wooded parcel and plant grasses to increase nutrient uptake. In years prior to 2004, the Homestead "often" exceeded discharge standards for total inorganic nitrogen and fecal coliform bacteria (NPS 2005b).

The Sugar Loaf Service Company provides sewer service to Sugar Loaf Resort and more than 90 other neighboring properties in Cleveland and Centerville townships (Carlson 2007). The wastewater is treated in a sequencing batch reactor before discharge. The system is designed for up to 138,000 m^3 $year^{-1}$, but currently discharges only about 28,000 m^3 $year^{-1}$ (MDEQ, Janice Heuer, Senior Environmental Engineer, email, 11/28/07). Sugar Loaf Resort has been closed for skiing since March 2000 (Carlson 2007).

Two neighborhoods in Empire have group OSDS with drainfields that each discharge less than 14,000 m^3 $year^{-1}$ (MDEQ, Janice Heuer, Senior Environmental Engineer, email, 11/28/07). The village of Empire developed a proposal for a private system to serve up to 87 parcels in the downtown, but was not successful in receiving MDEQ SWQIF funding in August 2007 (Olson 2007). Woodstone Partners operates a wetland and tile field system for its development in the village of Glen Arbor that discharges less than 28,000 $m^3 year^{-1}$. The village of Honor has a lagoon and irrigation system that discharges 49,000 $m^3 year^{-1}$. Large scale industrial dischargers in the watershed are Glens Sanitary Landfill (30,000 $m^3 year^{-1}$), Kasson Sand and Gravel (11,000 m^3 $year^{-1}$), and Triple D Orchards (32,000 m^3 $year^{-1}$) (MDEQ, Janice Heuer, Senior Environmental Engineer, email, 11/28/07).

Groundwater permits generally require monitoring, with the type and extent determined by the facility size and type of wastewater discharged. Facilities discharging less than 14,000 $m^3 year^{-1}$ require flow monitoring only. Medium sized facilities also monitor treated effluent, and the largest facilities monitor flow, effluent quality, and groundwater quality both upgradient and downgradient (within 50 m of the discharge point). Sewage plants monitor nitrate, nitrite and ammonia-N; phosphorus; chloride; sodium; pH; and sometimes BOD (biological oxygen demand). Fecal coliform are monitored if public contact with the effluent may occur. Food processing facilities generally monitor for COD (chemical oxygen demand), sodium, chloride, solids, pH, and sometimes phosphorus. In addition, groundwater monitoring at food facilities usually includes iron and manganese (MDEQ, Janice Heuer, Senior Environmental Engineer, email, 12/03/07).

OSDS and other waste disposal systems within SLBE: The SLBE Facility Management Software System lists seven pit toilets, five of which are on South Manitou Island, and 34 vault toilets (one of which is still in the planning stages) (NPS, Mark Pressnell, B&U Supervisor, SLBE, email, December 2007). Pit toilets discharge human waste directly to the soil, but because no additional water is used, the distance that contaminants can travel from them is limited. Vault toilets have almost no environmental impact (except for installation impacts) in their immediate vicinity. Thirty-three OSDS are found within SLBE at staff quarters, picnic areas, campgrounds, dump stations, and other visitor use areas (
Figure 52), including a fairly new mound system at the headquarters in Empire. A fish cleaning station is located within SLBE on the Platte River. Features of this wastewater treatment system include three septic tanks, a constructed wetland, and a drainfield. Water typically goes to the

drainfield only in September and October during the salmon run (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., March 2009).

Visitor Use

As previously noted, overall SLBE visitor use ranges from 1.2-1.4 million people per year (NPS 2008a). Monthly visitor use is recorded at 20 locations in SLBE and compiled to obtain annual use figures. From 2005-2007, the greatest number of visitors were recorded at the headquarters visitor center (117,000-133,000). Park locations where visitor environmental impacts may be most direct include the dune climb, Platte River below the Hwy M-22 bridge, Stocking scenic drive, campgrounds, the Esch road beach, and the islands (Figure 58; NPS 2007). Number of visitors alone does not determine environmental impact. For example, a relatively small number of visitors travel to the islands, but their impact in transporting invasive species may be more significant than that of a greater number of visitors to a mainland site.

Dune Climb, Lake Michigan Overlook, and Other Dune Sites

The Dune Climb is one of the most visited sites in SLBE, with 83,000-93,000 vehicles counted each year from 2005-2007 (Figure 58). From the 1930s to the 1970s, motorized dune tours were conducted in the Sleeping Bear Dunes area (Karamanski 2000). Although that practice has ended, visitors are still allowed to climb the dunes on foot at both the Dune Climb area and the Lake Michigan Overlook. High foot traffic and social trails at these sites have contributed to acceleration of wind erosion, soil erosion, destabilization of vegetation, alteration of sand supply to biotic systems, and aesthetic damage (Ozaki 2001). The Dune Climb parking lot was paved in 2008, adding a significant area for water runoff.

Pranger (ca. 2005b) evaluated and rated the severity of visitor disturbance (on a scale of 1-6) to SLBE dunes. The most disturbed dunes were found at the Dune Climb and the Cottonwood Trail area, which has access from the Pierce Stocking Scenic Drive. These dunes had some areas of level 6 disturbance (“vegetation eliminated from a wide area and dune form obliteration”). A second tier of dune areas with “local severe disturbances” was the Sleeping Bear Point area, the Lake Michigan Overlook area, and the area just south and across the Platte River from Platte River Point. These areas had limited level 5 disturbances (severely incised or widened trails or denuded areas where vegetative cover was eliminated). Other dunes, including those near Pyramid Point, west of the main Dune Climb, at the southwest corner of South Manitou Island, near Empire Bluffs and Aral, and west of the main disturbed area near Platte River Point, also showed disturbance, but the author reported that “the majority of the dunes at the lakeshore have light to no disturbance from human foot traffic” (Pranger ca. 2005b).

Platte River and Platte River Mouth

The mouth of the Platte River is a popular location for swimming, canoeing, kayaking, and fishing (Vana-Miller 2002). From 2005-2007, 79,000-87,000 vehicles were counted at the Platte River mouth each year (Figure 54; NPS 2007). One canoe livery and one permitee operate on the Platte River. In 2007, 7,059 canoes and 12,407 swimmers were counted (NPS 2007). Fishing pressure varies seasonally; in spring, anglers catch steelhead, and in fall, coho and king salmon (Vana-Miller 2002).

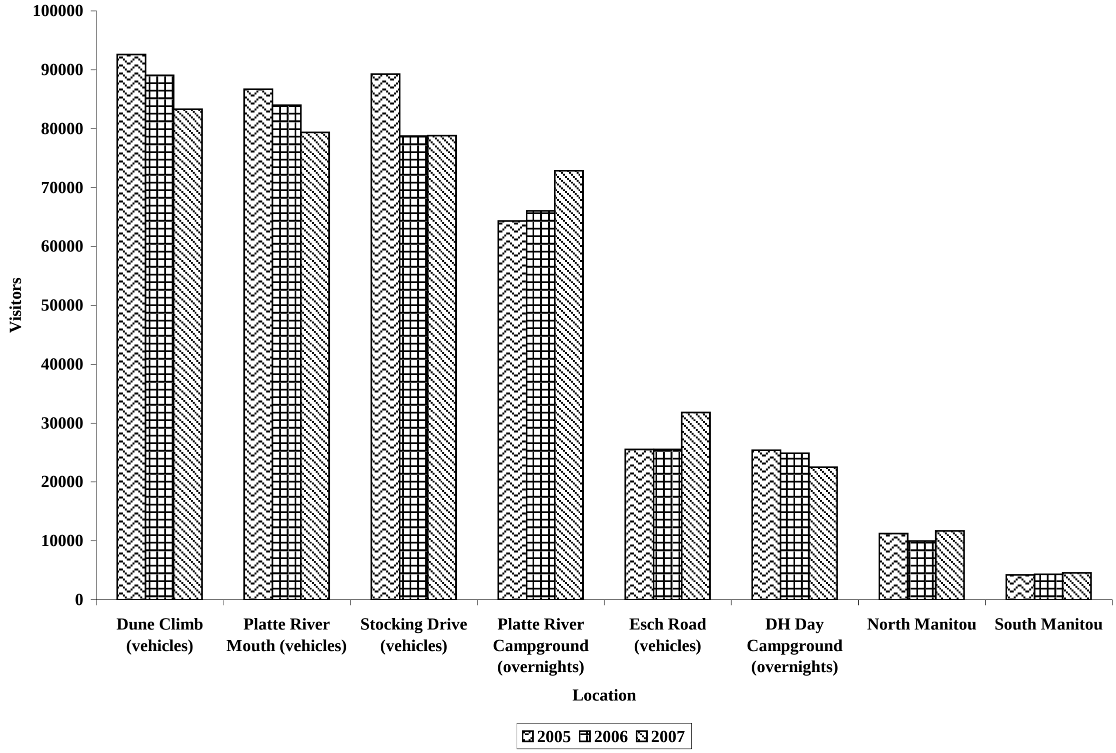

Figure 58. Number of visitors at selected locations for 2005-2007, Sleeping Bear Dunes National Lakeshore (NPS 2007).

The MDEQ conducted a biological and water chemistry survey of the river system in 1998, but only upstream of Platte Lake, and noted that the Platte River and its tributaries are high quality streams that are sustaining a coldwater fishery and meeting Michigan water quality standards (Walker 1999). Little is known about the current or recent chemical or biological condition of the Platte River downstream of Platte Lake and within SLBE. Concerns have been raised about the impacts of kayaks, tubes, and canoes, and about the people who may leave these conveyances and wade in the stream bed. A 2006 report noted that a concessionaire was leaving trash from canoes at Platte Point, and that visitors were climbing on and jumping off the DNR weir, entering DNR harvesting structures, and urinating and defecating in the woods (NPS 2006d). In addition, the biological effects of ongoing management changes at the Platte River Fish Hatchery apparently are not being systematically assessed.

Dredging has occurred to improve boat access at the mouth of the Platte River since 1968, when seven Platte Bay fishermen drowned in a storm (Karamanski 2000). Environmental Resources Management (1985) described the effects of dredging on turbidity, macroinvertebrates, and sand spit morphology, and recommended future monitoring of shoreline processes and recreational impacts. Ozaki (2001) noted that dredging can cause sudden drops in water levels and dewatering of wetlands, and recommended further evaluation. Vana-Miller (2002) noted that dredging may affect key biological processes, such as a loss of marsh refugia for larval or juvenile fish, or the creation of conditions favoring the establishment of exotic or nuisance wetland plants.

The NPS Geological Resources Division (Pranger c.a. 2005a) has noted numerous "logical reasons" to stop dredging the Platte River mouth. These include aesthetic issues for swimmers and beach-goers, safety hazards in bringing boaters and swimmers together, and increased access to recreational fishing in other nearby locations. Pranger (c.a. 2005a) also noted that dredge spoils have significantly altered natural coastal and fluvial processes at the river mouth and may have a role in that site being selected as a nesting site by piping plover. He recommended removing the accumulated dredge spoils, discontinuing dredging, and allowing the river to return to a natural state through natural geomorphic processes.

Crystal River
Issues related to visitor use on the Crystal River are similar to those on the Platte River. Two canoe liveries and three permitees operate there. Annual use statistics are not compiled for the Crystal River, but in 2007, 432 boats were counted on the Crystal River during three days in August; 2,873 boats were counted on the Platte River on three similar August 2007 dates (NPS 2006d). A commercial outfitter puts in canoes either on Glen Lake or in the Crystal River near the intersection of CR 675 and Fisher Road. In 1998, the MDEQ conducted a biological survey of the river below Glen Lake and above the Homestead Resort. Two stations were rated as having good (slightly impaired) habitat (next to CR 675 and north of 675 at Hwy M-22), while the third, farthest downstream at Hwy M-22 south of 675, was rated as fair (moderately impaired). Stations 2 and 3, were noted to be adversely affected by road culvert design which partially dammed the river (Flower and Walker 1999a). The USFWS has determined the dune and swale formations at this location to be globally rare (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

Platte River and D.H. Day Campgrounds
In 2007, nearly 73,000 overnight visits were recorded for the Platte River campground, and over 22,000 for the D.H. Day campground (NPS 2007). Camping impacts on the environment may include littering, water pollution, vegetation damage, track formation, soil compaction and loss, increased weed dispersal, and an increase in fire frequency (Sun and Walsh 1998). Campers' firewood collection affects availability of woody material and density of saplings around campsites (Cole 2004). Foot trampling by campers and hikers reduces plant cover, biomass, and species richness (Cole 2004). In a study conducted in canoe-accessible campsites in low elevation riparian forests in the eastern US, most vegetation had been eliminated, and a shift in the remaining vegetation from forbs to graminoids was observed (Marion and Cole 1996).

Beach Fires
SLBE staff have expressed particular concern about campfires on the Lake Michigan beaches, which are a tradition among some visitors. Concerns include loss of vegetation, dune impacts, wildland fire threats, beach aesthetics, charcoal deposition, trash, and visitor injuries from buried fires (NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008). No literature was found specific to beach fires, but the closely related topic of campfires has been studied in some detail. Many visitors to NPS and USDA-Forest Service campgrounds perceive campfires to be an important aspect of their camping experience, but numerous aesthetic and ecologic impacts have been attributed to campfires (Reid and Marion 2005). In an extensive literature review, Reid and Marion (2005) report that the resource damage attributable to campfires includes "fire site proliferation; overbuilt fire sites and associated seating

arrangements; fuel wood depletion; sterilized soils; charred rocks and tree roots; ash and charcoal buildup; semimelted plastic, glass, and metal trash; chemical contamination of soils; unburned food, which attracts wildlife; tree damage and felling; and vegetation trampling associated with firewood collection."

A study of campfire effects by soil type showed that sandy soils attain higher temperatures and retain heat longer than clayey soils under similar fuel, moisture, and weather conditions. Sandy soils that were initially moist and achieved temperatures of 100-350^{o}C during burning were likely to form a water-repellent layer (Fenn et al. 1976). Temperatures above 400 ^{o}C produce losses of organic matter, nitrogen, sulfur, and phosphorus (Cole and Dalle-Molle 1982). Studies conducted at three National Parks (Great Smoky Mountains, Shenandoah, and Isle Royale) showed that the total number of damaged trees at campsites where fires were allowed ranged from 190-1,128 (Reid and Marion 2005). Trampling in search of firewood causes soil compaction and changes the composition of the understory. The gathering of downed wood for fires may also reduce site productivity, especially on droughty or infertile soils, and habitat for spiders, arthropods, birds, and small mammals (Cole and Dalle-Molle 1982).

Burning garbage in campfires produces toxic metals that remain in the ash and may be washed into the Lake during high water or storms. Plastic cup lids, chip bags, and plastic forks and spoons contribute lead to ash; colored cardboard boxes contribute cadmium; and cigarette and candy wrappers contribute mercury (Davies 2004). Further, campfires lead to visitors transporting firewood into the Lakeshore, increasing the likelihood of forest pest infestations.

Water Use

In 2004, estimated total water use in Benzie, Leelanau, and Grand Traverse Counties was 56,774 m^3day^{-1}. This estimate was obtained by combining the MDEQ annual statistics for water use for public water supplies, industry, agricultural irrigation, golf course irrigation, and thermoelectric power generation (the last of which is zero in the three counties) (MDEQ 2004a, 2006f, 2007d) with an estimate of private well water use. The private well water estimate was based on an average low domestic water use of 300 L/person/day (USGS 2005) times the number of household wells in each county (MDEQ 2007e) times the average number of persons/household/county (US Census Bureau 2007).

In Benzie and Leelanau Counties, over 90% of the water used was taken from groundwater. In Benzie and Grand Traverse Counties, the largest water user is public water supplies (37% and 64% respectively). Leelanau County uses 31% of its water for private wells, followed by 26% for agricultural irrigation and 18% for public water supplies (Table 57). One such public water supply is that of the village of Empire, which serves 378 people; its one-million gallon storage tank is located on SLBE property (USEPA 2007a; NPS, Steve Yancho, Chief of Natural Resources, SLBE, pers. comm., November 2008).

SLBE has 15 transient non-community public water supplies (supplies that serve at least 25 people at least 60 days of the year, but do not serve the same people over six months of the year) (Figure 59, Table 42; USEPA 2007a). These water supplies serve up to 1,980 people per day. In a recreational setting, water use is estimated to be 38-57 L/person/day (Handy and Stark 1984), so peak visitor water use may be 75-113 m^3day^{-1}. By comparison, within SLBE's watershed, the

Table 57. Estimated water use (in m^3day^{-1}) for public water supplies, industry, agricultural irrigation, golf course irrigation, and private wells in Benzie, Leelanau. and Grand Traverse Counties, MI, 2004 (MDEQ 2006f, 2007d, e).

County	Facilities	Hectares	Water Withdrawals (m^3day^{-1})				
			Great Lakes	Surface Water	Groundwater	Total	% of County Total
	Public Water						
Benzie	11		0	0	2,725	2,725	37
Leelanau	16		0	0	1,816	1,816	18
Grand Traverse	24		18,397	0	6,435	24,832	64
	Industrial						
Benzie	4		0	38	1,249	1,287	17
Leelanau	6		0	0	1,514	1,514	15
Grand Traverse	5		0	0	1,249	1,249	3
	Agricultural						
Benzie	9	165	0	76	492	568	8
Leelanau	21	595	0	151	2,574	2,725	26
Grand Traverse	36	681	189	530	2,725	3,444	9
	Golf Courses						
Benzie	5	136	0	0	1,551	1,551	21
Leelanau	7	135	76	492	530	1,098	11
Grand Traverse		226	0	341	1,438	1,779	5
	Private Wells						
Benzie			-	-	1,294	1,294	17
Leelanau			-	-	3,162	3,162	31
Grand Traverse			-	-	7,728	7,728	20
	Total						
Benzie	29		0	114	6,018	7,426	
Leelanau	50		76	643	6,435	10,316	
Grand Traverse	73		18,586	871	11,848	39,032	
Total	152		18,662	1,628	24,301	56,774	

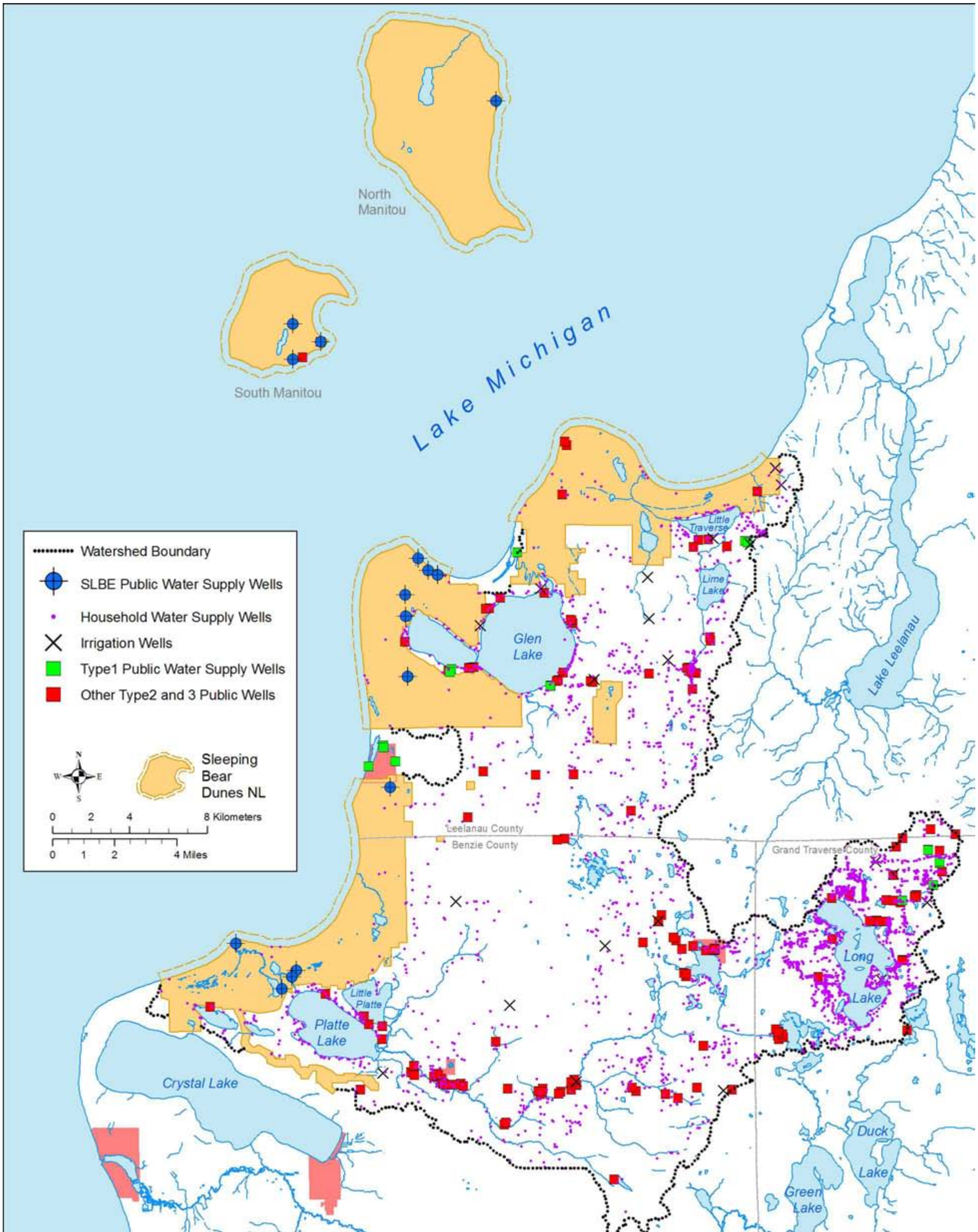

Figure 59. Locations of water supply wells in and around Sleeping Bear Dunes National Lakeshore (MDEQ 2007e).

Michigan Wellogic database lists 2,900 wells (Figure 55; MDEQ 2007e). With an average domestic water use of 300-375 L/person/day (USGS 2005) and an approximated average of 2.45 persons/household (US Census Bureau 2007), private well users in the SLBE watershed withdraw approximately 2,100-2,700 $m^3 day^{-1}$. (We recognize that not all private wells are listed in the Wellogic database, so this is a conservative estimate.) However, in either case, most of that water is returned to the ground through onsite wastewater disposal systems.

With water shortages becoming more prevalent nationwide, concerns have been raised about the possibility that Great Lakes water will be sold or diverted to other parts of the nation or world. The Great Lakes-St. Lawrence River Basin Water Resources Compact of 2005 would prevent new or increased diversions of water from the Great Lakes except under limited circumstances, mainly for public water supplies for counties that "straddle" the Great Lakes basin (Council of Great Lakes Governors 2005). The Compact was approved by the US Senate and House of Representatives, and was signed into law by President George W. Bush in October 2008.

Climate Change

Global temperatures have increased $0.74 \pm 0.18^{o}C$ from 1906-2005, mostly attributable to human activities (IPCC 2007). Although global climate change is often referred to as 'global warming,' it also has likely contributed to rises in sea level; changes in wind patterns and extra-tropical storm tracks; increased temperatures on extreme hot nights, cold nights, and cold days; increased risk of heat waves; increased area affected by drought; and greater frequency of heavy precipitation events (IPCC 2007).Signs that climate change is already occurring in Michigan include increases in average annual temperatures, more frequent severe rainstorms, shorter winters, and decreases in the duration of lake ice cover. By the end of the 21st century, winter and summer temperatures may increase $3\text{-}6^{o}$ C and $4\text{-}7\ ^{o}C$, respectively. The growing season might increase by 8-10 weeks. Annual average precipitation may not change much, but may increase in winter and decrease in summer to the point where soil moisture declines and more droughts occur (Kling et al. 2003). Climate change will affect chemical, biological, and physical aspects of the Great Lakes (Boyer et al. 2006). The Great Lakes are forecast to have a reduced ice cover season, declining lake levels, and reduced groundwater levels and stream baseflows, but higher runoff during extreme precipitation events (IJC 2003). One report predicts that groundwater levels near Lansing, MI will change between -0.6 m to +0.1 m by 2030 (Lofgren et al. 2002).

Substantial uncertainty accompanies almost all the predictions related to global climate change. This is true for the changes in temperature and precipitation, for example, but also in the ecologic implications of these, and other, climatic changes. The uncertainty, though, is not in the general trend, but rather in how large the changes will be, the rate at which they occur, and the net effect of all of the indirect and interactive effects. A wide variety of ecologic processes (Aber et al. 2001) and species-specific responses (Walther et al. 2002; McKenney et al. 2007) have been, or will be, affected.

All predictions of future climate are based on General Circulation Models (GCM), of which there are several, and they vary in their predictions for the 21st century; see Hansen et al. (2001) or Currie (2001) for a brief description of the more commonly used GCMs. All these models are global in scope and thus incorporate and make predictions about only sub-continental scale phenomena. As an example of the difference among models, the predicted increase in average annual temperature by 2100 ranges from 2.6-6.6^{o}C (Hansen et al. 2001). This is one source of uncertainty with regard to the ecologic impacts. Another is that averages may not be the key. That is, the fluctuation in temperature among seasons, the extremes that occur, the timing of certain phenomena, and the duration of a condition could all have more of an impact than the average condition (Morris et al. 2008). Furthermore, for some of the major changes predicted, there will be important regional differences (Walther et al. 2002). For example, precipitation is expected to go up, for at least part of the 21st century; however, some models indicate that at least two regions (the Southeast and the Pacific Northwest) will experience reduced precipitation during that time (Hansen et al. 2001).

Predictions of the ecologic impacts of climate change are achieved by taking the predictions of a GCM and plugging them into one or more other models (see Hansen et al. (2001) and Aber et al. (2001) for the common models used in this way). These, as well as the GCM models, are simplifications of reality and are based on a set of assumptions, creating yet another source of uncertainty in the predictions. Furthermore, we do not have a single model that can even begin to predict the full range of phenomena that are likely to be affected, their interactions, and the 'complete,' net outcome. Thus, all models focus on a few of the changes and ignore the others. For example, we have a limited capacity to predict what biotic disturbances are likely to influence a community if the average temperature increases by 3 or 4^{o}C, and where ice storms are going to be most frequent (Dale et al. 2001). The predictions of models apply to a finite scale, and the majority of ecologic models project for a smaller spatial scale than the GCMs. This makes it difficult to predict what will happen in a specific area. To make these mesh, either the GCM predictions have to be interpolated or the ecologic model extrapolated, creating yet another source of uncertainty.

Lake Michigan Water Level Changes

Wilcox et al. (2007) have documented three major high phases for Lake Michigan in the past 4,700 years (from 2,300 to 3,300, 1,100 to 2,000, and 0 to 800 years ago), and also noted a quasi-periodic rise and fall of about 160 ± 40 years in duration and a shorter fluctuation of 32 ± 6 years superimposed on the 160-year fluctuation. They reported that most of these lake level changes are climate-related. Lake Michigan water levels have fluctuated through approximately 2 m, from 175.58-177.50 m from 1918-2006 (USACE 2006). Record highs were recorded in 1886 and 1986, and lows occurred during the Dust Bowl of the 1930's, a multi-continental severe drought of 1964 (its lowest level ever), and the most recent and strongest El Niño on record of 1997 (NOAA 2008). In early 2008, water levels were near record lows. Sellinger et al. (2008) suggest that the current low lake levels are part of an underlying lake level decline that began around 1973 and continues to the present, but may have been obscured by concurrently increasing precipitation into the 1990s.

Current water level declines are "worrisome" because they appear consistent with several climate change projections (Sellinger et al. 2008). Lake Michigan water levels are projected to drop 0.99-2.48 m with a doubling of CO_2 levels in the atmosphere. Two general circulation model simulations project changes in Lake Michigan water levels of +0.05 m to -0.72 m by 2030 and +0.35 m to -1.38 m by 2090. Of twelve scenarios run, ten project water level declines.

The IJC proposed a study of the St. Clair River in 2005 after a consultant's report suggested that all head drops in Lakes Michigan and Huron since 1970 could be linked to dredging events or operations on the St. Clair River (IJC 2005). Other explanations for the water level declines include hydrologic cycle factors, subsidence and postglacial isostatic rebound in various parts of the Great Lakes system, diversions and consumptive uses, and downstream conveyance capacity (IJC 2005). Changes in rainfall patterns related to land use changes may also be occurring (Lofgren 2006).

Loope and Arbogast (2000) have demonstrated a close relationship between Lake Michigan levels and dune activity. As Pranger (ca. 2005b) explains, increased activity occurs as a result of natural lake level fluctuations. Perched dunes gain material from bluffs during high lake stands, which reoccur approximately every 150 years, and nearshore dunes gain material from beaches during low lake stands that occur in an approximate 30 year cycle. However, some dunes located farther inland in the Platte River embayment may not be linked to these cyclical processes and may be as old as 11,000 years. The likely effect of human-induced lake level decline would be to cause nearshore dunes to migrate more actively and perched dune movement to slow (Pranger ca. 2005b).

Coastal Change Potential

An assessment of the potential for physical coastal change with climate change was conducted for SLBE and two other national lakeshores by the USGS in 2006 (Pendleton et al. 2007). Three geologic variables (geomorphology, historic shoreline change rate, and regional coastal slope) and three physical process variables (significant wave height, annual ice cover, and lake-level change) were used to develop a Change Potential Index (CPI). Nearly 100 km of shoreline were evaluated for SLBE. The most influential variables in the CPI assessment were geomorphology, coastal slope, and significant wave heights. Thirty-seven percent of the mapped shoreline was classified as having very high change potential, including Sleeping Bear Point, the Empire Bluffs, and the shoreline of Platte Bay. Twenty-three percent had high change potential, including Good Harbor Bay, Sleeping Bear Dunes, parts of North Manitou Island, and the northern and western shores of South Manitou Island. Eighteen percent had moderate change potential, including the shoreline between Empire Bluffs and Aral Dunes, and parts of North and South Manitou Islands. Low change potentials were found along 19% of the shoreline, including the north and south shores of North Manitou Island, the eastern shore of South Manitou Island, the area between Pyramid Point and Sleeping Bear Bay, and the area south of Platte River Point (Figure 60; Pendleton et al. 2007).

Other Surface Water Impacts

In the future, surface waters will generally be warmer. DO may decline, and extended periods of thermal stratification may increase the decline’s effects. Lower oxygen levels and warmer temperatures in inland waters may promote phosphorus release and increase mercury release and uptake by biota (Kling et al. 2003). Warming of the Great Lakes will result in greater evaporation of semi-volatile compounds from the water column, which will cause contaminants currently sequestered in sediment reservoirs to leach and re-enter water and air (Boyer et al. 2006). Nonpoint pollution may also increase with higher intensity precipitation events.

Biological productivity of aquatic ecosystems will likely increase with temperature because of longer growing seasons and increased metabolic rates, but existing natural communities may be greatly changed (IJC 2003). However, Lake Michigan’s productivity may decrease because of a

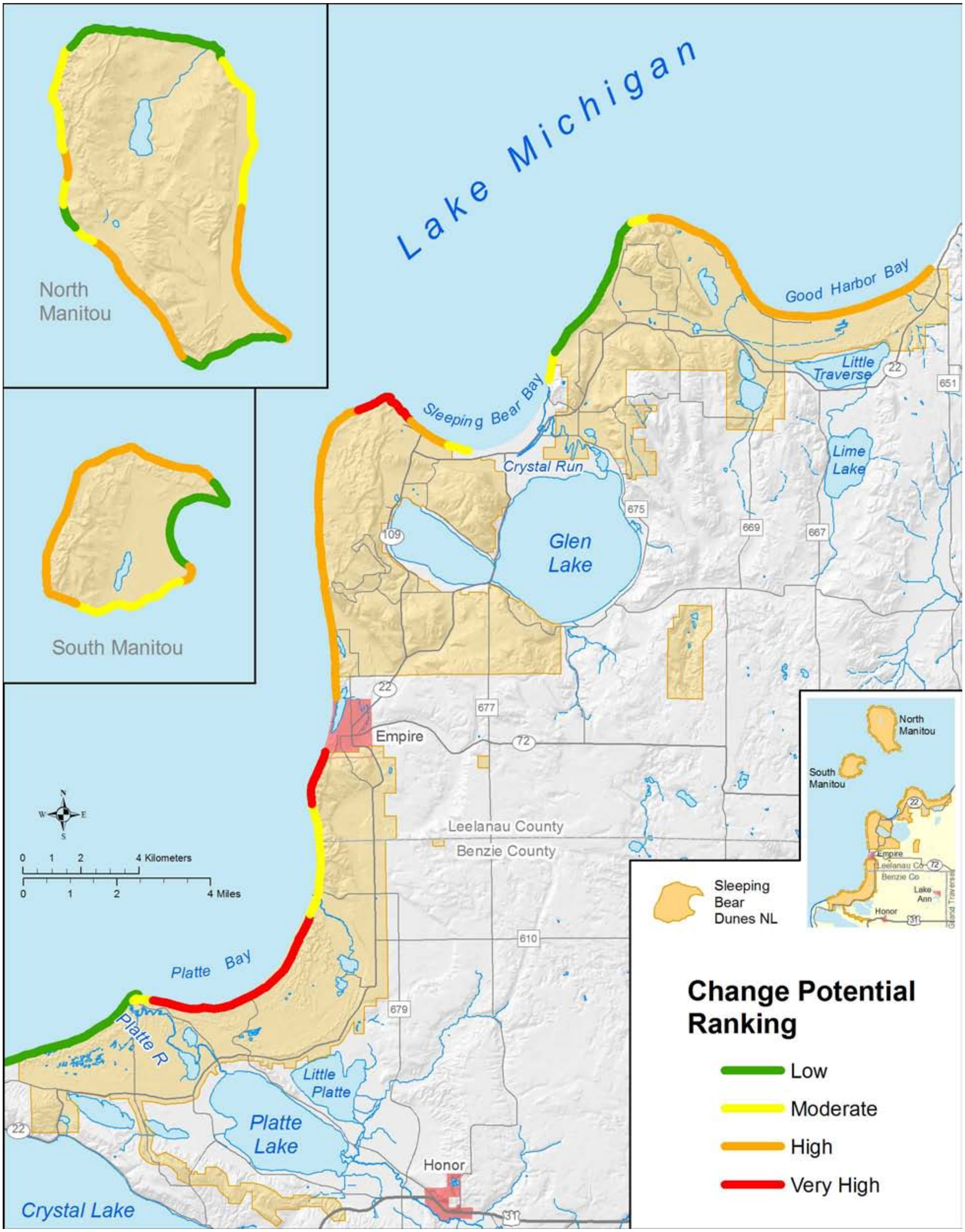

Figure 60. Coastal change potential for shorelines of Sleeping Bear Dunes National Lakeshore (Pendleton 2006).

longer summer stratification period that prevents the recycling of nutrients and redistribution of oxygen (Kling et al. 2003). Populations of coldwater fish may decline. Whitefish reproduction may be harmed by loss of winter ice cover (Kling et al. 2003). Some habitats may be reduced, especially wetlands and their vegetation communities. Invasive species may be more successful (Kling et al. 2003).

Coastal Wetland Impacts

Models for Great Lakes coastal wetlands in the Canadian Great Lakes (Erie, Ontario, and St. Clair) were examined for their responses to climate change and lake level changes as projected by climate models. Results indicated that "the lower water levels projected under most climate change scenarios will have an impact on the distribution and abundance of wetland vegetation, bird, and fish communities; major shifts in all taxonomic groups are likely with long-term water level declines, beginning with vegetation responses" (Mortsch et al. 2006). Wetland communities within lacustrine embayments were the most capable of naturally adapting to lower water levels, while drowned river-mouth wetlands showed the greatest potential for change. Invasive plant species such as purple loosestrife and common reed were less vulnerable to change than native species, and the spread of invasives may be facilitated by cumulative stresses on natural ecosystems. Birds that need prolonged, relatively stable water levels during the breeding season, such as terns, grebes, rails, and bitterns, were considered vulnerable, as were fish that spawn in shallow water in spring and have a preference for vegetated habitat in all life stages (Mortsch et al. 2006).

Terrestrial Impacts

Davis et al. (2000) noted that "the Western Great Lakes parks…" (including SLBE) "…are important reservoirs of biological diversity in a landscape that has been altered by logging, mineral extraction, agriculture, and urbanization." The accumulated pollen record over the Holocene suggests that SLBE's location on Lake Michigan may buffer it from temperature changes, at least temporarily, and allow it to serve as a refuge for plants and animals that cannot survive farther inland. However, that same location may jeopardize plants and animals because it is more subject to precipitation extremes than inland sites (Davis et al. 2000).

Plants and plant communities will be affected in myriad ways that involve a large number of interacting conditions and biotic interactions, as constrained by the local site conditions and genetic variation of each species. These effects will include very basic, cellular level processes; whole plant processes; interactions between plants (e.g., competition), between plants and their mutualists, and between plants and their 'pests;' autogenic disturbances; and community-wide processes and characteristics. In the earlier stages of CO_2 induced warming, the photosynthetic rate and water use efficiency will increase, and thus plant growth will increase (Aber et al. 2001). This will probably not be a universal response; species near the southern end of their range and those closely adapted to mesic site conditions will most likely be stressed by the increased temperatures (Davis et al. 2000). In all likelihood the increase in productivity will be short lived as temperatures continue to rise and drought becomes more common or severe (Dale et al. 2001).

Another well-established response is phenology. An increase in temperature over the past 100 years (primarily 1910-1945 and 1976 to date) has altered the timing of important life history stages of many species (reviewed in Walther et al. 2002; see Post and Stenseth 1999 for examples for plants and ungulates). For example, a broad-scale assessment of initiation of spring growth in North America found that it has occurred 1.2-2.0 days earlier per decade for the past 35-63 years (Walther et al. 2002). Following warm, wet winters, 9 of 13 species bloomed earlier by 13-26 days, and one third bloomed 13-19 days longer (Post and Stenseth 1999); however, woody plants were less sensitive than herbaceous species to climatic variability. Shifts of this magnitude, which will probably continue through the 21st century, could profoundly affect other taxa that key in on a particular stage of the life cycle of plants. Obvious examples include nectar-gathering insects and folivores that key in on new leaves and shoots. These are examples of cascading, or indirect, effects of climate change. Physiologic and phenologic adjustments will continue until climate exceeds the tolerance of the species (capacity to adapt), or subsequently the species may migrate to an area with a more favorable climate (Davis et al. 2005).

At the community scale, it is highly probable that at least a few community types, as we currently know them, will 'disassemble' and reform in different combinations, or into a similar but recognizable community. Others will disappear from the landscape, and species that currently do not commonly associate will do so in the future (Hansen et al. 2001; Williams et al. 2007). This will result in communities that are novel (*sensu* Williams et al. 2007) and thus have no current or prior analog. It is highly unlikely that communities will migrate as a unit because of differences among species (in reality, populations) in genotypic variation, generation time, phenotypic plasticity, subtle differences in physiologic tolerances, impacts of novel insect and fungal pests, and differences in the need for mutualists. Hence, it is quite likely that in a matter of decades there will be groups of species occurring together that have not in the recent (several hundred years) past. The rate at which a species migrates is influenced by its life history (especially its adaptation for dispersal), rate of climate change, and landscape pattern. The degree of fragmentation, characteristics of any corridors present, and the characteristics of the matrix are the most pertinent components of landscape pattern. These characteristics are often more conducive to migration on publicly owned lands because the landscape is less fragmented and the matrix is less likely to be a barrier to dispersal. This is particularly relevant to woodland forbs, many of which are not adapted to long-distance dispersal (Matlack 1994).Management efforts will then be dealing with novel entities or assemblages with unknown levels of temporal stability.

Predicted responses for common tree species (below) highlight the probable magnitude of the impact, as well as what is likely to happen for some other life forms and species. However, it would be dangerous to extrapolate from one or a few species in an assemblage to all of the species; the dendro-chronologic and pollen records clearly show that co-occurring species can respond in very different ways to decade- and century-long climatic change (Villalba et al. 1994; Villalba and Veblen 1998; Black and Abrams 2005). Two key components to the response by a species (or population) are how quickly it can adapt, if at all, and how rapidly it can disperse (Davis et al. 2005; McKenney et al. 2007). It is anticipated that adaptation will vary tremendously among life forms and significantly among species within a life form (Dale et al. 2001; Davis et al. 2005). Herbaceous species should adapt more quickly than trees, and insects more quickly than most plants; this is primarily a function of life cycle length. However, annual plants and short-lived species are more sensitive than longer-lived species to temperature fluctuation (Morris et al. 2008). The factors that influence the capacity to adapt are level of local (population scale) genetic variation, effective population size, mating system, and range size. The second component is migration. Based on the pollen record, we know that species, even within a life form, migrate at very different rates (e.g., Graumlich and Davis 1993) at the scale of millennia. The primary question is whether a species will be able to disperse rapidly enough to match the rates of change in temperature and precipitation regimes (Williams et al. 2007).

McKenney et al. (2007) examined the predicted range response of 130 tree species in the coterminous US. The range response was based on the concept of climate envelope (CE), which simply means that the climatic boundaries of a species today probably indicates the conditions it can endure in the future. If we can predict climate, then we can determine the location and size of the range of a species in the future. Using this approach (note that it ignores many of the possible interactions that may manifest and influence where a species thrives in the future), they determined that 72 species would show a decrease in the size of their range within the coterminous US. Many of the more northerly distributed species will increase dramatically in Canada (McKenney et al. 2007). The extent of the northern range shift varies depending on which GCM model is used and the migration rate of a species. For example, sugar maple could have its range move northward as little as 3.3 degrees of latitude or as much as 8.9 degrees. McKenney et al. (2007) tabulated species based on both the magnitudes of the reduction in size of CE and the range shift. No species from SLBE were in the top 20% of the former category; seven species were in the top 20% of the latter category. In addition to sugar maple, the list included basswood, yellow birch, northern red oak, white ash, white pine, and red maple.

Using a similar conceptual approach, Hansen et al. (2001) predicted the climatic impacts on biomes in the coterminous US. In general, these agree with the predictions for species as noted above; aspen-birch will decrease by 92% and the 'Northeastern Mixed Forest' will shrink by 72%. In contrast, the oak-hickory community type will gain about 34%. Of special relevance to SLBE might be the prediction that the oak-pine type is expected to have the largest gain (>250%). The predictions are mixed on a jack-red-white pine type; some models indicate an increase and others a decrease. This is an example of a prediction that is too coarse to be useful; the 'dry site' pine at SLBE should fare well in the future, but mesic site white pine probably will not. Species found at SLBE that would lose 90% of their range within the US are both species of aspen, sugar maple, northern white cedar, balsam fir, red pine, and white birch (Hansen et al. 2001). Currie (2001) predicted the long-term change in richness (number of species within a community) of trees and ectothermic vertebrates under a scenario of doubling of CO_2. He found that short-term changes are likely to be negative, but vertebrate and tree richness will increase in much of the US, including cooler climates and mountainous areas.

Two finer points that have been made bear mentioning at this point. As noted previously, Lake Michigan has a moderating effect on temperature, and thus the rate and magnitude of temperature increase could be less at SLBE than the predictions for the Great Lakes region as a whole (Davis et al. 2000). However, this pollen-based study of the Holocene climate also suggested that lake effect snowfall is influenced by continental scale temperatures. Thus, there might be a decrease in precipitation in this region which could offset all or part of the moderating effect on temperature. The other point is that winter soil temperature has been going down as air temperatures warmed from 1951 to 2000 (Isard et al. 2007). Although annual and winter air temperatures at a site in Benzie County increased by more than 0.50^{o}C in the period 1976-2000 as compared to 1951-1975, annual and winter soil temperatures showed little or no change over the same time period. Mean winter soil temperatures did decrease in much of lower Michigan in the period 1976-2000 compared to 1951-1975, most likely because of increases in air temperature and decreases in snow cover (Isard et al. 2007). This is another example of the interactions that will manifest in the future, because colder soils would work to delay the onset of plant growth in the spring. In turn, this could mean a shorter growing season, which could offset the increased productivity related to higher CO_2.

At SLBE, there will be biologically significant changes in plant species ranges, species abundance, community composition, and many physiologic and ecosystem properties. It is almost certain that many species associated with the northern hardwood forest type, or near the southern limit of their range, will disappear. Depending on the climate model used, SLBE may be out of the climatic range for white pine and red oak by 2025, and into the range for black walnut by 2090 (Walker 2002). During roughly the same time period an unknown (probably larger) number of novel plant species will expand northward and show up at SLBE. How important taxonomic groups like the arthropods and fungi will respond is unknown, but clearly there will be important ecologic changes as the climatic regime, and the plant composition and abundance, change. Long-term forest health could be compromised by increased concentrations of ground-level ozone (already somewhat problematic in the SLBE area), more frequent droughts and forest fires, and greater risks from insect pests (Kling et al. 2005).

Conclusions

Table 58 summarizes the impact of stressors on aquatic and upland resources in SLBE, while Table 59 summarizes the current condition of SLBE aquatic and upland ecosystems. Specific conclusions by resource type are provided below.

Lake Michigan

The overall status of the Great Lakes ecosystem is mixed, with ecosystem trends varying from improving to worsening (USEPA and Environment Canada 2007). Serious concerns about the Lake's biota include the invasion of dreissenid mussels, round gobies, and other exotic species, and severe losses of the *Diporeia* that are a critical component of the lower levels of the food web. The main pollution issue for Lake Michigan is atmospheric deposition of contaminants, including mercury, PCBs, organochlorine pesticides, and PAHs. The problem with these contaminants is reflected in the consumption advisories for many fish species, especially larger individuals. The status of personal care products and pharmaceuticals in Lake Michigan and especially in the SLBE vicinity is largely unknown.

Lake Michigan is oligotrophic (USEPA 2006c). Phosphorus levels have declined since highs in the 1950s and 1960s and currently meet the International Joint Commission guidelines. However, recent studies suggest that benthic environments are becoming nutrient enriched due to the dreissenid mussel invasion (Hecky et al. 2004; Higgins et al. 2008). Additionally, nitrate loading is on the increase, with about half attributable to atmospheric deposition and the other half to loading from tributaries (Warren and Kreis 2005); this increased nitrogen loading needs assessment for its potential effects on the Lake's trophic status. Nutrient and other water quality sampling for SLBE nearshore waters has not been conducted consistently or recently.

At SLBE, Lake Michigan waters are monitored for fecal coliform and generally meet the USEPA standards for total body contact recreation, with some minor exceptions each year. However, Lake Michigan at SLBE has experienced nuisance blooms of *Cladophora* in recent years. This alga, the dreissenids, and round gobies interact in a complex cycle that has led to outbreaks of Type E botulism, killing thousands of birds, including endangered piping plovers and state-threatened common loons (USGS 2007b).

A fishery survey was conducted for SLBE in 2006 (Fessell 2007), which included some substrate information, and a herptile inventory was completed in 2007 (Casper and Anton 2008), but in general little is known about the other biota or water chemistry of SLBE's bays or coastal wetlands. Lake Michigan's great surface area and depth make it improbable that many local sources would have broad impacts on the lake, but bays could be affected by local wastewater discharges, tributary inputs, and other land use activities. SLBE is located on a major Lake Michigan shipping lane, creating the risk of fuel spills and discharges of human wastes and ballast water containing exotic species. The effects of global climate change on lake levels, storm events, biological communities, and water quality constitute a large threat and need to be assessed over time.

Table 58. Impact of stressors on aquatic and upland resources in Sleeping Bear Dunes National Lakeshore.

Stressor/Resource	Lake Michigan/ and coastal wetlands	Dunes	Inland lakes	Streams	Interior wetlands	Upland resources	Lowland forests
Land-Use Related Stressors							
Agriculture	PP[1]	EP[2]	PP[1]	PP[1]	OK	OK	OK
Golf courses	PP[3]	OK	PP[3]	PP[3]	OK	OK	OK
Atmospheric deposition	EP[4]	EP[4]	EP[4]	EP[4]	EP[4]	PP[4]	PP[4]
Nutrient enrichment	EP[5]	EP[4]	PP[6]	EP[7]	PP[6]	PP[4]	--
Fire exclusion	--	--	--	--	--	EP[8]	OK
Mineral resource development (oil and gas, gravel)	PP[9]	PP[9]	PP[9]	PP[9]	PP[9]	PP[9]	PP[9]
Soil and groundwater contamination	PP[10]	OK	EP[10]	PP[10]	EP[10]	PP[10]	PP[10]
Physical alterations	EP[11]	EP[12]	OK	EP[13]	OK	EP[14]	PP[14]
Habitat fragmentation	--	EP[15]	--	--	OK	EP[15]	EP[15]
Storm water	PP[16]	OK	EP[16]	EP[16]	PP[16]	OK	OK
Wastewater disposal	PP[17]	OK	EP[17]	EP[17, 18]	PP[17]	OK	OK
Cultural landscapes	--	--	--	--	--	EP[19]	--
Recreational and Commercial Use Stressors							
Great Lakes shipping	PP[20]	PP[20]	OK	PP[20]	OK	--	--
Commercial and recreational fishing	PP[21]	OK	PP[21]	PP[21]	--	--	--
Recreational boating	PP[22]	PP[22]	PP[22]	EP[22, 23]	--	--	--
Visitor use	PP[24]	EP[25]	EP[25]	EP[25]	PP[25]	OK	OK
Water use and diversion	PP[26]	PP[26]	OK	EP[27]	PP[26]	--	--
Climate Change	PP[28]	PP[28]	PP[28]	PP[28]	PP[28]	PP[28]	PP[28]
Exotic Species	EP[29]	EP[29]	EP[29]	EP[29]	EP[29]	EP[29]	EP[29]

EP=existing problem; PP=potential problem; OK=not a known problem; shading=insufficient information

Table 58. Impact of stressors on aquatic and upland resources in Sleeping Bear Dunes National Lakeshore (continued).

1. Impact of agricultural fertilizers and pesticides in the upper watershed has not been studied. A small pig farm applies wastes within SLBE boundaries. A small reindeer farm also exists.
2. Although not a current effect of agriculture, former agricultural lands are a source of exotic species for the dunes.
3. Impact of existing golf courses in the upper watershed and along the Lake Michigan shoreline not studied.
4. Atmospheric deposition is the largest source of mercury and organochlorine pesticides to Lake Michigan. These presumably also are deposited inland at the same rates, although specific depositional rates for SLBE were not found. Atmospheric deposition may be contributing to nutrient enrichment on dunes and uplands, favoring non-native invasive plant species and portending future ecosystem changes.
5. Nitrogen levels in Lake Michigan are increasing, approximately half from atmospheric deposition and half from tributary inputs. Nearshore phosphorus levels are increasing while offshore levels are decreasing
6. Some lakes exceeded nutrient reference criteria for their ecoregion (Shell Lake and Lake Manitou for TN, and School Lake for both TN and TP).
7. Elevated nitrogen levels have been observed in Otter Creek.
8. Some of the jack pine, jack-red pine, and pine-oak forests had relatively frequent fire pre-European settlement.
9. Slant drilling for oil and gas is currently banned in the Great Lakes, but the law could be changed in the future. Numerous oil and gas wells currently exist in counties around SLBE. Sand and gravel extraction is occurring on park borders.
10. Numerous soil and groundwater contamination sites, including LUST sites, landfills, and dumps, exist around SLBE, and their impacts on SLBE resources have not been studied. A dump exists in a wetland on Tucker Lake; although it has had some study, park staff are still concerned about its impacts.
11. The Lake Michigan shoreline is susceptible to physical alteration caused by dune instability, water level fluctuations, and climate change.
12. Dunes are inherently unstable physical features, but visitor use increases their instability.
13. Dredging of the Platte River is a major physical and ecologic alteration to the river at its mouth. The dam on the Crystal River at Glen Lake is a major physical alteration whose effects on downstream resources are also largely unstudied.
14. Physical alterations of the upland systems include past logging and conversion of forest land to openland and the continued maintenance of cultural landscapes.
15. The SLBE landscape has been fragmented by roads, clearings, right-of-ways, harvesting, agricultural fields, and municipalities.
16. Some impacts caused by road runoff and culverts have already been noted in inland waters (Day Mill Pond, Crystal River); impacts on Lake Michigan are unstudied.
17. Projected population increases in the watershed will increase either the number of onsite sewage disposal systems or wastewater treatment plants, with unknown effects. Septic system impacts have already been noted on Glen and Little Glen Lakes. Septage is applied on fields within the SLBE watershed.
18. Although the situation is improving, the Platte River State Fish Hatchery is a source of phosphorus to the river.
19. The maintenance of some cultural landscapes (openlands) in the Port Oneida district comes at the expense of the forests that would otherwise naturally occur there. Cultural landscapes are a major potential source of exotic species to other ecosystems.
20. Major Great Lakes shipping lanes pass within 5 km of the SLBE mainland and South Manitou Island and 3 km of North Manitou Island, potentially contributing to spills of fuel or cargo and discharges of human wastes and ballast water, which may contain exotic invasive species.
21. Concerns related to fishing include not only determination of sustainable harvests, but also spread of VHS and other invasives, release of exotic bait species, and disposal of trash and human wastes.
22. Motorized watercraft impacts may include sediment resuspension, water pollution, fish and wildlife disturbance, destruction of aquatic plants, and shoreline erosion.
23. Boating on the Platte River related to fishing requires the frequent dredging of the river mouth, with potential impacts on turbidity, macroinvertebrates, and shoreline processes.
24. Increases in visitor use intensity could have as yet unknown effects on Lake Michigan resources.

Table 58. Impact of stressors on aquatic and upland resources in Sleeping Bear Dunes National Lakeshore (continued).

25. Visitor use impacts have been documented on dunes (trampling, erosion, non-native invasive plant establishment, and formation of social trails), on Loon Lake (overcrowding during the ice fishing season), and in the Platte River (trash, trespassing, improper human waste disposal).
26. The Great Lakes Compact prohibits water diversion outside the basin; it is unknown whether water shortages in other parts of the US will lead to changes in the compact in the future. Many wetland water levels are directly tied to Lake Michigan levels, as is the stability of the dunes.
27. Concerns exist about the management of the Glen Lake dam and flow of the Crystal River.
28. Climate change is a major future stressor for all SLBE ecosystems; current impacts are strongly suspected but as yet undocumented.
29. Exotic species are a major present stressor in most and a major future stressor in all SLBE ecosystems.

Table 59. Condition of ecosystems in Sleeping Bear Dunes National Lakeshore.

Ecosystem – Lake Michigan and Coastal Wetlands

Indicator	Condition	Justification
Water clarity	Good	Secchi depths 6-13.5m at MI47 (p. 41). No recent data for SLBE nearshore waters.
Dissolved oxygen	Good	MI47 well oxygenated at all depths and times of year (p. 43). No recent data for SLBE nearshore waters.
Fecal bacteria	Significant Concern	Fecal bacteria daily geometric mean advisory limits were exceeded in 2006 at CR 651, Lake Michigan near North Bar Lake, and Peterson Road, and in 2007 at Esch Road beach (p. 49).
Nutrients	Caution	Nitrogen levels appear to be rising in Lake Michigan. Nearshore phosphorus levels are increasing while offshore levels are decreasing (p. 45).
Critical pollutants	Significant Concern	Numerous critical pollutants are found in Lake Michigan waters (p. 48).
Aquatic and wetland plant communities	Caution	Plant inventory for SLBE nearshore waters and coastal wetlands were not found.
Invertebrate populations	Caution	Biological inventories for SLBE nearshore waters and coastal wetlands were not found.
Unionid populations	Caution	Biological inventories for SLBE nearshore waters and coastal wetlands were not found.
Amphibian and reptile populations	Caution	An inventory of reptiles and amphibians has recently been completed for the park (p. 63). Some expected species were not present; whether this is due to insufficient inventory effort or ecological factors is not clear. Climate change may alter the assemblage of these animals in the future.
Trophic bioaccumulation	Significant Concern	Lake Michigan fish have fish consumption advisories for polychlorinated biphenyls, chlordane, and dioxins, and fish tissues contain mercury (p. 155).
Exotic species	Significant Concern	At SLBE, known accidentally introduced exotic fish are the alewife, common carp, sea lamprey, and round goby. Zebra mussels and quagga mussels have also been found (p. 180).

Ecosystem – Dunes

Indicator	Condition	Justification
Physical disturbance	Caution	Visitor use impacts such as trampling, erosion, and formation of social trails have been documented on dunes (p. 225). Dunes are also susceptible to larger-scale physical disturbances related to natural cycles of erosion and deposition, and changes in Lake Michigan levels, both natural and human-induced (p. 30, 233)
Exotic species	Significant Concern	Common exotics on and around the dunes are white sweet clover, bladder campion, Jimson-weed, spotted knapweed, bouncing-bet, and baby's breath (p. 201).
Nutrient enrichment	Significant Concern	Atmospheric deposition may be contributing to nutrient enrichment on dunes, portending future ecosystem changes favoring non-native invasive species (p. 169).

Table 59. Condition of ecosystems in Sleeping Bear Dunes National Lakeshore (continued).

Ecosystem – Inland Lakes

Indicator	Condition	Justification
Water clarity	Good	Some SLBE lakes do not meet the ecoregional reference criterion for Secchi depth, but this condition may be caused by natural factors such as sediment resuspension in shallow lakes and marl formation, and detrimental effects have not been attributed to this condition (p. 56).
Dissolved oxygen	Caution	Some SLBE lakes do not meet the ecoregional reference criterion for dissolved oxygen, but this condition may be natural (p. 57); low and declining dissolved oxygen levels in Platte and Loon Lakes may be attributable to cultural eutrophication (p. 117).
Fecal bacteria	Good	Fecal bacteria daily geometric mean advisory limits were exceeded in the past at Little Glen Lake, but management changes have been made to address this problem, likely caused by waterfowl (p. 49).
Nutrients	Caution	Some lakes exceeded nutrient reference criteria for their ecoregion (Shell Lake and Lake Manitou for TN, and School Lake for both TN and TP); the cause and significance of this condition is unclear (p. 67).
Other water quality parameters	Caution	Some SLBE lakes do not meet their ecoregional reference criterion for chlorophyll-a (p. 56). Some older samples (ca. 1973-1980) had elevated levels of metals (cadmium, copper, lead, zinc, aluminum) (p. 153).
Unionid populations	Significant Concern	Nichols reported that they might be threatened by zebra and quagga mussel invasions; zebra mussels have already invaded North Bar Lake, Loon Lake, Otter Lake, Bass Lake (Benzie), and Glen Lake (p.183).
Amphibian and reptile populations	Caution	An inventory of reptiles and amphibians has recently been completed for the park (p. 63). Some expected species were not present; whether this is due to insufficient inventory effort or ecological factors is not clear. Climate change may alter the assemblage of these animals in the future.
Trophic bioaccumulation	Significant Concern	All Michigan inland lakes, reservoirs, and impoundments have fish consumption advisories for mercury. The Glen Lakes have fish consumption advisories for polychlorinated biphenyls and chlordane (p. 155).
Aquatic and wetland plant communities	Significant Concern	Eurasian water-milfoil has been identified in SLBE in North Bar Lake and Loon Lake (p.184).
Exotic species	Significant Concern	Exotic aquatic species already found in SLBE include common carp, rusty crayfish, zebra mussels, Eurasian water-milfoil, purple loosestrife, and curly-leaf pondweed (p. 180).

Table 59. Condition of ecosystems in Sleeping Bear Dunes National Lakeshore (continued).

Ecosystem - Streams

Indicator	Condition	Justification
Water clarity	Good	No reports of concerns with stream water clarity were found in a survey of past studies.
Dissolved oxygen	Good	No reports of concerns with dissolved oxygen levels in streams were found in a survey of past studies.
Fecal bacteria	Significant Concern	The Otter Creek pond had three exceedences of the daily geometric mean advisory limit and two of the 30-day mean advisory limit in 2006, one exceedence of the daily mean in 2007, and two in 2008. Otter Creek also exceeded the daily mean during one of the 2008 events (p. 49). Fecal bacteria levels for the Crystal River and much of the Platte River are unknown, although body contact recreation does occur on these rivers.
Nutrients	Significant Concern	Elevated nitrogen levels have been observed in Otter Creek (p. 137).
Other water quality parameters	Good	Elevated metals concentrations in the Platte River outside SLBE in 1977 and in Shalda Creek in 1990 were followed by reports of values within acceptable limits (p. 154).
Invertebrate populations	Caution	Acceptable populations of invertebrates have been noted in surveys of the Crystal River (p. 99), and Platte River (p. 129), but surveys for Narada, Shalda, and Good Harbor Creeks were not found.
Unionid populations	Significant Concern	Nichols reported that they might be threatened by zebra and quagga mussel invasions; zebra mussels have already invaded the Platte and Crystal Rivers (p.183).
Trophic bioaccumulation	Significant Concern	All Michigan inland lakes, reservoirs, and impoundments have fish consumption advisories for mercury (p. 153); presumably similar concerns exist for streams.
Aquatic and wetland plant communities	Significant Concern	Eurasian water-milfoil has been identified in SLBE in the Platte River (p. 184).
Exotic species	Significant Concern	Exotic aquatic species already found in SLBE include common carp, rusty crayfish, zebra mussels, Eurasian water-milfoil, purple loosestrife, and curly-leaf pondweed (p. 180).

Ecosystem – Interior Wetlands

Indicator	Condition	Justification
Physical status	Unknown	An improved wetland inventory has been identified as a high priority need in SLBE since 2002 (p. 73).
Water chemistry	Unknown	Little is known about the water chemistry of SLBE wetlands, especially those not linked to lakes or streams.
Invertebrate populations	Caution	Little is known about invertebrates of SLBE wetlands, and drought or climate change may make inventorying them more critical.
Amphibian and reptile populations	Caution	A 2007 survey on North and South Manitou Islands found only four species of amphibians, possibly because low precipitation has led to the disappearance of some wetlands (p. 63). Some expected species were not present in a recent inventory of reptiles and amphibians (p. 63); whether this is due to insufficient inventory effort or ecological factors is not clear. Climate change may alter the assemblage of these animals in the future.
Trophic bioaccumulation	Significant Concern	All Michigan inland lakes, reservoirs, and impoundments have fish consumption advisories for mercury (p. 153).
Aquatic and wetland plant communities	Caution	Plant inventories for inland wetlands, although extensive, are dated. Numerous wetlands are experiencing growth of invasive species, especially reeds (p. 184).

Table 59. Condition of ecosystems in Sleeping Bear Dunes National Lakeshore (continued).

Ecosystem – Upland Resources

Indicator	Condition	Justification
Terrestrial pests and pathogens	Caution	Beech bark disease and hemlock woolly adelgid have not yet begun to cause mortality in SLBE, but the impacts will be profound when they arrive.
Understory composition - plants sensitive to white-tailed deer depredation	Significant Concern	White-tailed deer (WTD) herbivory impacts have been studied on North Manitou Island and noted in other locations, and yew populations parkwide have been depleted (p. 196). The level of deer utilization of sugar maple, trillium, sweetroot, mayflower, and baneberry has not been documented.
Understory nitrogen content	Caution	Atmospheric deposition may be contributing to nutrient enrichment on uplands, portending future ecosystem changes (p. 169).
Habitat fragmentation	Significant Concern	The SLBE landscape has been fragmented by roads, clearings, right-of-ways, harvesting, agricultural fields, and municipalities (p. 187).
Exotic plant species	Significant Concern	The greatest numbers of exotic species in SLBE are found, in decreasing order, in grasslands and former agricultural fields, early successional dune assemblages, open to moderately open pine/pine-oak forests on older dunes, forest wetlands, and northern hardwood forests (p. 201).

Ecosystem – Lowland Forests

Indicator	Condition	Justification
Amphibian and reptile populations	Caution	An inventory of reptiles and amphibians has recently been completed for the park (p. 63). Some expected species were not present; whether this is due to insufficient inventory effort or ecological factors is not clear. Climate change may alter the assemblage of these animals in the future.
Terrestrial pests and pathogens	Caution	Emerald ash borer has not yet begun to cause mortality in SLBE, but the impacts will be profound when it arrives.
Understory composition - plants sensitive to white-tailed deer depredation	Significant Concern	White-tailed deer (WTD) herbivory impacts have been studied on North Manitou Island and noted in other locations. WTD herbivory is also a major limitation to the regeneration of white cedar (p. 196).
Aquatic/wetland plant communities	Caution	Plant inventories for inland wetlands, although extensive, are dated.
Habitat fragmentation	Significant Concern	The SLBE landscape has been fragmented by roads, clearings, right-of-ways, harvesting, agricultural fields, and municipalities (p. 187).
Exotic plant species	Significant Concern	Albert (1992) surveyed two wooded dune and swale complexes in the Platte River basin and found two exotic species in their transects (cattails and reeds) (p. 202).

Dunes

SLBE's dunes are a rare and protected habitat in the state of Michigan and are home to endangered birds and plants. They are inherently an unstable landscape feature and go through natural cycles of movement and replenishment. Climate change may speed or otherwise alter these natural cycles; the Sleeping Bear Dunes coastline was considered to have a high change potential in a recent study (Pendleton et al. 2007). Landslides have occurred three times in the last century in a 500 m stretch of coastal dune along Sleeping Bear Point, possibly related to subsurface water flow (Barnhardt et al. 2004).

Visitor use contributes to dune erosion and destabilization of vegetation. Frequent human disturbance, along with the open nature of the dune system, make the dunes susceptible to continued invasion by exotic plants, including white sweet clover, bladder campion, Jimson-weed, baby's breath, leafy spurge, and spotted knapweed. Atmospheric deposition of nutrients may also contribute to changes in the dune flora and favor exotic species.

Inland Lakes, Streams, and Wetlands

SLBE includes 27 named variously sized inland lakes, five named streams (all of Otter and Good Harbor Creeks and parts of the Platte River, Crystal River, and Shalda Creek), and many unnamed lakes, some bogs, several springs, and interdunal wetlands. The USFWS has determined dune and swale formations on the Crystal River to be globally rare. Nine recently sampled SLBE inland lakes were mesotrophic (Elias 2007). Some lakes exceeded nutrient reference criteria for their ecoregion (Shell Lake and Lake Manitou for TN, and School Lake for both TN and TP); others exceeded reference criteria for Secchi depth or DO. Other recent studies showed generally healthy unionid mussel (Nichols et al. 2004), herptile (Casper and Anton 2008), and fish (Fessell 2007) populations.

Numerous short-term studies have generally indicated that all SLBE streams and inland lakes had high water quality and minimal impairments. However, little long-term monitoring data exists, and much of that has not been examined for, or is not suitable for determining, long-term trends. A more explicit description of the rationale used to choose specific SLBE lakes for monitoring would be useful, as would analysis of existing data to divide lakes into type categories. A long-term monitoring strategy that includes the important surface water resources of SLBE is needed for future management decisions.

SLBE surface waters are generally at the downgradient end of many watersheds (Murphy 2004a; see Figure 1), and as development pressures increase, these waters will be vulnerable. Effects of specific contaminants and contaminant sources, such as agricultural chemicals, soil and groundwater contamination sites, and onsite sewage disposal systems (OSDS) have not been evaluated; source data and better delineation of surface water and groundwater subwatersheds would be necessary for such an evaluation.

Climate Change and Forest Resources

The impacts of climate change are difficult to predict precisely – both in terms of the effects and the location; nonetheless, it is clear that ecologically significant changes in plant species ranges, species abundance, community composition, and many physiologic and ecosystem properties will occur within the next 50 years. In general, species at SLBE that are near the southern end of their range, and those that occur exclusively on mesic to wet-mesic sites, will likely be affected the most. It is almost certain that many species that are part of the northern hardwood forest type will disappear, and it is likely that this community type, as we currently know it, will cease to exist at SLBE. However, we do not know what the rate or magnitude of response by understory species in this community will be. Typically, their migration rate is quite slow, but on the other hand, a micro-site with the proper conditions might provide a refugium. Based on model predictions, the pine-oak community type (broadly defined) will expand the most during this period. Concurrently, an unknown (probably larger) number of novel plant species will likely expand northward and show up at SLBE, contributing to novel assemblages. How important taxonomic groups like the arthropods and fungi will respond is unknown, but clearly there will be important ecologic changes as the climatic regime, and the plant composition and abundance, change. Another important unknown is how the disturbances regime(s) will shift.

Northern Hardwood Association

In all likelihood, this type still reflects significant changes due to human activity during the Settlement period. However, there is little doubt that exotic 'pests' represent the most important stressor for this system, when defined as having the greatest impact over a long time frame. Emerald ash borer (EAB), beech bark disease (BBD), and hemlock woolly adelgid (HWA) have not yet begun to cause mortality in SLBE, but the impacts will be profound when they arrive. EAB and BBD are in the immediate vicinity of the park and will begin to affect plant communities containing ash and beech, respectively, very soon. On the other hand, HWA likely will not arrive in the next decade. The changes caused by these agents will be extensive, causing high levels of overstory mortality. Since each is highly specific, the direct effects of each will be limited to one taxon. The length of time from entry to tree mortality varies substantially among the agents, with EAB killing its host rapidly, HWA being intermediate, and BBD taking the longest. BBD will likely have the greatest community-level effects because of the abundance of beech in many SLBE forests. On the other hand, ecosystem processes will likely change much more after HWA infestation than with the other two. Important secondary future threats are white-tailed deer herbivory and exotic earthworms.

Upland Deciduous Association

Some of the aspen, aspen-birch, and aspen-red oak forests will succeed to some version of the northern hardwood association, and thus in the long term, the threats noted for that association will apply. On the other hand, some aspen, oak-aspen, and mixed hardwood forests occur near the shore on older dunes and align more closely, in terms of threats, with the oak-pine type below. The high level of variation in terms of soils and plant composition make it difficult to generalize for this association. On a few sites, it is quite probable that white-tailed deer herbivory, exotic earthworms, and/or exotic plants will constitute the major threats.

Upland Conifer and Pine-Oak Associations

These associations include jack, red, white, and mixed pines, and pine-oak. Three stressors are of roughly equal importance; however, they differ markedly in our ability to counter the effects and in the relevant time frame. For some communities, change resulting from altered disturbance regimes since the pre-European settlement era is the primary stressor. Although this is a past stress, it can likely be reversed. Fire exclusion, an important dimension of altered disturbance regimes, has affected these forest types roughly in inverse proportion to the historic occurrence of fire. Thus, for the white pine-red pine forest and oak/pine with a long fire return interval, fire exclusion has had a minimal impact. Some of the jack pine, jack-red pine, and pine-oak forests likely had relatively frequent fire prior to European settlement; the effects of fire suppression since the 1920s may be pronounced in these areas. Acid deposition and the concurrent nitrogen nutrient enrichment are probably the more problematic second stressors in these systems; these represent both a past and an ongoing threat and are the most difficult to mitigate. Without solid baseline data it is difficult to be sure, but it is likely that soil chemistry, plant vigor, and plant composition are being affected. The third stressor, exotic plants, is mostly one of the future.

Lowland Forest Association

The major alteration of these forests has been the loss of northern white cedar and the conversion of swamps to a mixed deciduous lowland type. This is a legacy of the settlement era, during which much white cedar was cut but did not regenerate. For about the past 70 years, white-tailed deer herbivory has played a major role in preventing successful recruitment and continues to represent the most important ongoing stress. The role of altered hydrology is an important unknown for these lowland forests.

Recommendations

Many useful recommendations for water resource-related monitoring and research, including detailed justifications, are found in Vana-Miller (2002), Murphy (2004a), and Lafrancois and Glase (2005). We have incorporated some of their suggestions into our recommendations.

General

Explore strategies for evaluating the impacts of climate change, including lake level changes, wetland losses, loss of habitat for key species, and others. Develop a plan for mitigating impacts where feasible.

Investigate the possibility of reinstating nutrient monitoring capability to the IADP air monitoring station in SLBE. The two closest NADP stations show quite a bit of variation in deposition rates of some compounds.

Monitoring ozone concentrations at a range of distances from the shore during the warmer months of the year would be advisable.

Lake Michigan

Work with GLKN to establish one or more nearshore sampling sites in Lake Michigan bays, to include water chemistry, invertebrates, unionids, and aquatic plant communities.

Continue monitoring beaches for fecal indicator bacteria. Include monitoring of the spatial extent of shoreline biofouling by *Cladophora* (Lafrancois and Glase 2005). Monitor systematically for new invasive species that are reported for the Lake. Monitor blue-green algae which may be related to dreissenid invasion.

Periodically evaluate the work of lakewide groups studying Lake Michigan (e.g., the Lake Michigan Lakewide Management Planning Process, SOLEC) to determine whether problems identified lakewide have specific potential impacts or need further evaluation at SLBE (e.g. nearshore invasive species, *Cladophora*, botulism, etc.).

Monitor population trends in the watershed and develop and implement strategies to assess the impacts of local land use changes (logging, road building, residential development, golf courses, and agriculture) in proportion to increased development.

Inland Waters

Continue to sample SLBE index lakes to develop a long term record for assessing trends. Sampling should be conducted at the beginning, middle, and end of stratification and include the chemical, physical, and biological variables detailed in Elias and VanderMeulen's (2008) report. Consideration should also be given to limited winter monitoring for DO, nitrate-N, and ammonia-N, especially in shallow lakes or those with elevated nutrient levels, to evaluate potential for winterkill (Murphy 2004a).

Evaluate existing water quality data for its usefulness in examining long-term trends, and standardize future sampling to allow comparisons.

Ensure that the selected index lakes include all SLBE major lake types (e.g., groundwater recharge, surface water, closed basin, flow-through, large and small lakes, bogs, etc.).

Establish a long-term sampling program for the Crystal and Platte Rivers including physical data, water chemistry, bacteriologic quality, and macroinvertebrate biomonitoring. Discharge should be determined monthly for both rivers, or rating curves should be developed so that volunteers could monitor discharge more frequently based on staff gage readings. Use Pranger's (2005a) work as a basis for further evaluation of the ecologic effects of Platte River dredging. (GLKN is currently developing a protocol for monitoring wadeable streams.)

Define more precisely the watersheds and subwatersheds (both surface water and groundwater) for SLBE inland lakes, especially those that exceed their nutrient reference criteria. Map the potential sources, movement, and concentrations of nitrogen and phosphorus species in these watersheds. An initial assessment of agricultural impacts on SLBE water resources could be made by monitoring for nitrogen and phosphorus in groundwater and surface water. Water bodies or groundwater resources with elevated nutrient levels could be further tested for the pesticides known to be used on local crops and transported easily to water resources.

Investigate the effects of groundwater inputs on SLBE stream hydrographs, lake levels, and water chemistry.

Investigate the unique Aral Springs area to determine its biotic composition (Lafrancois and Glase 2005). Several plant species known here exist nowhere else in SLBE.

Continue to evaluate the annual reports from the Platte River Association documenting the discharge of nutrients from the Platte River State Fish Hatchery.

Systematically monitor all surface waters for invasive species yearly. Develop plans for control where feasible. Continue signage and other efforts to educate users (boaters, anglers) about appropriate prevention strategies.

Evaluate erosion from the county roads that pass through the park (Ozaki 2001).

Wetlands

Document, ground-truth, photograph, and map all the wetlands in SLBE, including coastal wetlands and small undocumented ponds.

Map non-native invasive plants, evaluate their threat levels, and prioritize their control.

Follow the progress of efforts underway to better define how wetland quality should be assessed (e.g. the Minnesota Comprehensive Wetland Assessment, Monitoring, and Mapping Strategy (http://files.dnr.state.mn.us/eco/wetlands/wetland_monitoring.pdf) and the USEPA National Wetlands Condition Assessment (http://www.epa.gov/owow/wetlands/survey/) to design a future wetland monitoring strategy.

Uplands

Select representative samples (spatial coverage, etc) of the northern hardwood community type, using the sites sampled by Hazlett (1986, pg. 19-20) as much as possible. Set up permanent sampling locations of 0.5 to 2.0 m^2 quadrats. Compile a complete list of all understory species. This strategy will allow monitoring for the arrival and abundance of exotics, track overall white-tailed deer browsing pressure, and quantify and track the abundance of browse sensitive species.

Discuss the deer herd management issue with the MDNR to check the possibility of reducing the target density in the SLBE vicinity (unlikely but perhaps worth a try).

Cooperate with any federal (mainly USDA-Forest Service) and university ongoing efforts to monitor for hemlock woolly adelgid presence in the LP.

Use nitrate and base cation concentrations of select streams and rivers to evaluate the nutrient depositional status of uplands.

Implement Alternative #2 of the Fire Management Plan for the park (NPS 2004a); that is, begin use of prescribed fire in the Mainland Fire Management Unit in the pine and oak-pine forest types. Collect pre-burn data on a suitable range of taxonomic groups, and monitor the impacts at appropriate times of the year and over a suitable time frame.

Collect baseline data on the understory of a representative sample of a combination of the pine and pine-oak community types. There were two pine conifer communities sampled by Hazlett (1986) that might be suitable. Establish long-term tracking of herbaceous layer composition, total nitrogen content for the layer as a whole, and the nitrogen concentration in a representative sample of species and life forms. Such monitoring would provide indications of nitrogen saturation, monitor for exotic plants, and establish and track level of white-tailed deer browse pressure in these community types. Set up specific deer herd browsing impact studies, possibly using exclosures to document changes.

Monitor the following locations for presence and spread of terrestrial exotic species:

- Old fields and the roads, trails etc., leading away from them. Include the Empire Bluff Trail, Matelski Field (sampled by Hazlett [1986]), and a representative sample of other locations based on their size, location, presence of problem species, and other factors.
- Major trails. Establish transects from the trail into adjacent habitats. Perform intensive sampling around the trailhead and the first 0.25 km, and extensive sampling along the remainder of the trail.
- Campgrounds, large parking lots, etc.. Inventory a set of concentric circles around these areas (truncated as necessary due to unsusceptible habitat) on a regular basis.

Allocate additional resources to control and monitor exotic plant species.

Literature Cited

Aber, J., W. McDowell, K. Nadelhoffer, A. Magill, G. Berntson, M. Kamakea, S. McNulty, W. Currie, L. Rustad, and I. Fernandez. 1998. Nitrogen saturation in temperate forest ecosystems. BioSci. **48**:921-33.

Aber, J, R.P. Neilson, S. McNulty, J.M. Lenihan, D. Bachelet, and R.J. Drapek. 2001. Forest processes and global environmental change: predicting the effects of individual and multiple stressors. BioSci. **51(9)**:735-50.

Aber, J.D., C.L. Goodale, S.V. Ollinger, M. Smith, A.H. Magill, M.E. Martin, R.A. Hallett, and J.L. Stoddard. 2003. Is nitrogen deposition altering the nitrogen status of northeastern forests. BioSci. **53(4)**:375-88.

Abrams, M.D. 1984. Uneven-aged jack pine in Michigan. J. For. **82**:306-07.

Abrams, M.D. 1992. Fire and the development of oak forests. BioSci. **42(5)**:346-53.

Abrams, M.D. and M.S. Scott. 1989. Disturbance-mediated accelerated succession in two Michigan forest types. For. Sci. **35**:42-49.

Abrams, M.D., D.G. Sprugel, and D.I. Dickmann. 1985. Multiple successional pathways on recently disturbed Jack pine sites in Michigan. For. Ecol. Mngt. **10**:31-48.

Adkison, G.P. and M.T. Jackson. 1996. Changes in ground-layer vegetation near trails in Midwestern U.S. forests. Nat. Areas J. **16**:14-23.

Agius, A.C., D.M. McCullough, and D.A. Cappaert. 2005. Host range and preference of the emerald ash borer in North America: preliminary results. Pages 28-29 *in* V. Mastro and R. Reardon, compilers. Emerald ash borer research and technology development meeting. FHTET-2004-15. USDA-Forest Service, Morgantown, WV.

Albert, D. 1992. A survey of lakes, streams, and wetlands of the Sleeping Bear Dunes National Lakeshore. Michigan Natural Features Inventory, Michigan Department of Natural Resources, Lansing, MI.

Albert, D. 1995. Regional landscape ecosystems of Michigan, Minnesota, and Wisconsin: a working map and classification. Gen. Tech. Rep. NC-178 (Version 03JUN98). USDA-Forest Service North Central Forest Experiment Station. St. Paul, MN. (http://www.ncrs.fs.fed.us/pubs/gtr/other/gtr-nc178/rlandscp.htm#contents). Accessed July 31, 2007.

Albert, D.A. 2003. Between Land and Lake: Michigan's Great Lakes Coastal Wetlands. Extension Bulletin E-2902. 96 p. Michigan Natural Features Inventory, Michigan State University Extension, East Lansing, MI. (http://web4.msue.msu.edu/mnfi/pub/pdfs/BetweenLandAndLake.pdf). Accessed September 10, 2007.

Albert, D.A. 2007. Natural community abstract for sand and gravel beach. 7 p. Michigan Natural Features Inventory, Lansing, MI. (http://web4.msue.msu.edu/mnfi/abstracts/ecology/Sand_and_gravel_beach.pdf). Accessed August 22, 2008.

Albright, J., M. Martin, and B. Jackson. 2002. Preliminary hydrologic and hydraulic characterization of instream flows of the Crystal River, Sleeping Bear Dunes National Lakeshore, Leelanau County, Michigan. Unpublished report, National Park Service, Water Resources Division, Fort Collins, CO.

Allen, D.C. 1988. Entomological consequences of even- and uneven-aged management in northern hardwood forests. Pages 57-68 *in* C.W. Martin et al. (eds.). New perspectives on silvicultural management of northern hardwoods. GTR-NE-124. USDA Forest Service, Newtown Square, PA.

Alverson, W.S., D.M. Waller, and S.L. Solheim. 1988. Forests too deer: edge effects in northern Wisconsin. Cons. Biol. **2(4)**:348-58.

Anton, T.G. 2007. Review of amphibian monitoring program at Sleeping Bear Dunes National Lakeshore. GLKN/2007/05. National Park Service, Great Lakes Inventory and Monitoring Network, Ashland, WI. (http://science.nature.nps.gov/im/units/GLKN/SLBE%20Herp%20Monitoring%20Review.pdf). Accessed April 28, 2008.

Apple, B.A. and H.W. Reeves. 2007. Summary of hydrogeologic conditions by county for the state of Michigan. Open-File Report 2007-1236. USGS, Reston, VA. (http://pubs.water.usgs.gov/ofr2007-1236/). Accessed December 27, 2007.

Asplund, T.R. 2000. The effects of motorized watercraft on aquatic ecosystems. PUBL-SS-948-00. Wisconsin Department of Natural Resources, Bureau of Integrated Science Services and University of Wisconsin-Madison, Water Chemistry Program, Madison, WI. (http://www.dnr.state.wi.us/org/water/fhp/papers/lakes.pdf). Accessed July 23, 2007.

Attiwill, P.M. 1994. The disturbance of forest ecosystems: the ecological basis for conservative management. For. Ecol. Mngt. **63**:247-300.

Augustine, D.J. and L.E. Frelich. 1998. Effects of white-tailed deer populations on an understory forb in fragmented deciduous forests. Cons. Biol. **12**:995-1004.

Augustine, D.J. and P.A. Jordan. 1998. Predictors of white-tailed deer grazing intensity in fragmented deciduous forests. J. Wildlf. Mngt. **62**:1076-85.

Badra, P. and R. Goforth. 2003. Freshwater mussel surveys of Great Lakes tributary rivers in Michigan. 44pp. Prepared for Michigan DEQ Coastal Zone Management Unit. Michigan Natural Features Inventory, Lansing, MI.

Baker, P. and D. Hornbach. 1996. Can a species be "fouled" into extinction? Zebra mussels vs native bivalves in the upper Mississippi River. J. Shellfish Res. **15**(**2**):524.

Baldwin, N.A., R.W. Saalfeld, M.R. Dochoda, H.J. Buettner, and R.L. Eshenroder. 2002. Commercial fish production in the Great Lakes 1867-2000. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/databases/commercial/commerc.php). Accessed December 17, 2007.

Barbiero, R.P. and M.L. Tuchman. 2001. Results from the U.S. EPA's biological open water surveillance program of the Laurentian Great Lakes: I. Introduction and phytoplankton results. J. Great Lakes Res. **27**(**2**): 134-154.

Barbiero, R.P. and M.L. Tuchman. 2002. Results from the Great Lakes National Program Office's biological open water surveillance program of the Laurentian Great Lakes for 1999. EPA-905-R00-006. USEPA, Chicago, IL. (http://www.epa.gov/glnpo/monitoring/biology/Laurentian99/GL-Lau99.pdf). Accessed September 25, 2007.

Barbiero, R.P. and M.L. Tuchman. 2005. Phytoplankton and zooplankton. *In* M.E. Holey and T.N. Trudeau (eds.). The state of Lake Michigan in 2000. Special Publication 05-01. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/pubs/SpecialPubs/Sp05_1.pdf). Accessed November 6, 2007.

Barbiero, R.P., M.L. Tuchman, G.J. Warren, and D.C. Rockwell. 2002. Evidence of recovery from phosphorus enrichment in Lake Michigan. Can. J. Fish. Aquat. Sci. **59**: 1639-1647.

Barbiero, R.P., L.L. Schacht, R.E. Little, and M.L. Tuchman. 2005. Crustacean zooplankton communities in Lake Michigan. *In* T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society, Burlington, Ontario.

Barnes, B.V., D.R. Zak, S.R. Denton, and S.H. Spurr. 1998. Forest ecology. 4th edition. John Wiley and Sons, New York.

Barnhardt, W.A., B.E. Jaffe, R.E. Kayen, and G.R. Cochrane. 2004. Influence of near-surface stratigraphy on coastal landslides at Sleeping Bear Dunes National Lakeshore. Journal of Coastal Research **20**(**2**): 510-522.

Barton, A.M. 1999. Pines versus oaks: effects of fire on the composition of Madrean forests in Arizona. For. Ecol. Mngt. **120**:143-56.

Beals, E.W., G. Cottam, and R.J. Vogl. 1960. Influence of deer on vegetation of the Apostle Islands, Wisconsin. J. Wildlf. Mngt. **24**:68-80.

Beeton, A.M., C.E. Sellinger, and D.F. Reid. 1999. An introduction to the Laurentian Great Lakes ecosystem. In W.W. Taylor and C.P. Ferreri (eds). Great Lakes fisheries policy and management: a binational perspective. Michigan State University Press, East Lansing, MI.

Beletsky, D., J.H. Saylor, and D.J. Schwab. 1999. Mean circulation in the Great Lakes. J. Great Lakes Res. **25**(**1**): 78-93. (http://www.glerl.noaa.gov/pubs/fulltext/1999/19990004.pdf). Accessed July 7, 2007.

Benn, T. 2004. "A boatwatcher's guide to the Manitou Passage". Glen Arbor Sun. (http://www.glenarborsun.com/archives/2004/07/a_boatwatchers.html). Accessed July 10, 2007.

Benzie Conservation District. 2006. Benzie Conservation District resource assessment. Beulah, MI.

Benzie County Board of Commissioners. 1989. Environmental health regulations for Benzie County Health Department: authority, jurisdiction, purpose and general definition. Benzonia, MI. (http://www.bldhd.org/publications/benziecode.pdf). Accessed October 16, 2007.

Benzie County Planning Commission. 2000. Benzie County 2020 Comprehensive Plan. Beulah, MI. (http://www.benzieco.net/dept_planning.htm#master_plan). Accessed September 4, 2007.

Berg, D.J. 2004. The spiny water flea, *Bythotrephes longimanus*: an unwelcome species to the Great Lakes. 2 pp. OHSU-FS-049. Ohio Sea Grant College Program, Columbus, OH. (http://ohioseagrant.osu.edu/_documents/publications/FS/FS-049%202004%20Spiny%20Water%20Flea,%20Bythotrephes%20cederstroemi.pdf). Accessed December 11, 2007.

Bidleman, T.F., F. Wong, C.V. Audette, P. Blanchard, and H. Alegria. 2006. DDT in Great Lakes air: long-range transport or home-grown? Abstracts, International Association for Great Lakes Research, 49th Annual Conference: Great Lakes in a changing environment. University of Windsor, Windsor, Ontario.

Black, B.A. and M.D. Abrams. 2005. Disturbance history and climate response in an old-growth hemlock-white pine forest, central Pennsylvania. Journal of the Torrey Botanical Society. **132(1)**:103-114.

BLDHD (Benzie-Leelanau District Health Department). 2002. Environmental health division: land disposal and waste water management. Benzonia, MI. (Online). (http://www.bldhd.org/ehealth/landdisp.htm). Accessed October 16, 2007.

Blossey, B., V. Nuzzo, H. Ninz, and E. Gerber. 2001. Developing biological control of *Alliaria petiolata* and *grande* (garlic mustard). Nat. Areas J. **21**:357-67.

Bobiec, A., H. van der Burgt, K. Meijer, C. Zuyderduyn, J. Haga, and B. Vlaanderen. 2000. Rich deciduous forests in Bialowiez as a dynamic mosaic of developmental phases: premises for nature conservation and restoration management. For. Ecol. Mngt. **130**:159-75.

Bohlen, P.J., S. Scheu, C.M. Hale, M.A. McLean, S. Migge, P.M. Groffman, and D. Parkinson. 2004. Non-native invasive earthworms as agents of change in northern temperate forests. Frontiers in Ecology and Environment **2**:427-435.

Borgmann, K.L., D.M. Waller, and T.P. Rooney. 1999. Does balsam fir (*Abies balsamea*) facilitate the recruitment of eastern hemlock (*Tsuga canadensis*)? Am. Midl. Nat. **141**:391-97.

Bortier, K., R. Ceulemans, and L. Temmerman. 1999. Effects of tropospheric ozone on woody plants. Page 153 *in* S. Agrawal and M. Agrawal (eds.).Environmental pollution and plant responses. Lewis Publishers, London.

Bossenbroek, J.M. 2006. The importance of stream connections for the dispersal of aquatic invasive species. Abstracts, International Association for Great Lakes Research, 49th Annual Conference: Great Lakes in a changing environment. University of Windsor, Windsor, Ontario.

Boulinier, T., J.D. Nichols, J.E. Hines, J.R. Sauer, C.H. Flather, and K.H. Pollock. 2001. Forest fragmentation and bird community dynamics: inference at regional scales. Ecology **82**:1159-69.

Bowen, K.D. and J.C. Gillingham. 2004. Distribution of reptiles and amphibians on the islands of eastern Lake Michigan: summary and analysis. Michigan Academician **36**: 213-223.

Bowen, K.D., S.D. McMahon, and E.A. Beever. 2007. Geographic distribution: *Elaphe vulpina* (western foxsnake). Herpetological Review **38**(**4**): 486.

Bowen, K.D. and E.A. Beever. 2008. Amphibian monitoring on the Manitou Islands, Sleeping Bear Dunes National Lakeshore. GLKN/2008/01. National Park Service, Great Lakes Inventory and Monitoring Network, Ashland, WI. (http://science.nature.nps.gov/im/units/GLKN/monitor/amphibians/docs/Bowen_Beever_SLBE_2008.pdf). Accessed April 14, 2008.

Boyer, P., A. Jones, and D. Swackhamer (eds.). 2006. Expert consultation on emerging issues of the Great Lakes in the 21st century: papers submitted to the expert consultation on emerging issues of the Great Lakes in the 21st Century. Hosted by the International Joint Commission's Great Lakes Science Advisory Board at Wingspread, Racine, Wisconsin, February 5-7, 2003. (http://www.ijc.org/php/publications/pdf/ID1598.pdf). Accessed February 25, 2008.

Boyle, T. and N. Hoefs. 1993a. Water resources inventory of Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Boyle, T. and N. Hoefs. 1993b. Manual for monitoring lakes and streams of Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Braun, E.L. 1950. Deciduous forests of eastern North America. Blakiston. Philadelphia, PA. 596 pp.

Brazner, J.C., N.P. Danz, G.J. Niemi, R.R. Regal, A.S. Trebitz, R.W. Howe, J.M. Hanowski, L.B. Johnson, J.J.H. Ciborowski, C.A. Johnson, E.D. Reavie, V.J. Brady, and G.V. Sgro. 2007. Evaluation of geographic, geomorphic and human influences on Great Lakes wetland indicators: a multi-assemblage approach. Ecological Indicators **7**: 610-635.

Brooks, M.L., C.M. D'Antonio, D.M. Richardson, J.B. Grace, J.E. Keeley, J.M. DiTomaso, R.J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fires regimes. BioSci. **54**(**7**):677-85.

Brose, P., T. Schuler, D. Van Lear, and J. Berst. 2001. Bringing fire back: the changing regimes of Appalachian mixed-oak forests. J. For. **99**(**11**):30-35.

Brothers, T.S. and A. Spingarn. 1992. Forest fragmentation and alien plant invasion of central Indiana old-growth forests. Cons. Biol. **6**(**1**):91-99.

Brown, C. and J. Funk. 1940. Fisheries survey of Big Platte Lake and Round Lake with some observations on the lower Platte River, Benzie County, Michigan. Institute for Fisheries Research Report No. 631. Michigan Dept. of Conservation, Lansing, MI.

Buckler, W.R. 1979. Dune type inventory and barrier dune classification study of Michigan's Lake Michigan shore. Geological Survey Division Investigation 23, Michigan Department of Natural Resources, Lansing, MI. (http://www.deq.state.mi.us/documents/deq-gsd-sanddune-RI23.pdf). Accessed October 22, 2007.

Bunnell, D.B., C.P. Madenjian, J.D. Holuszko, T.J. Desorcie, and J.V. Adams. 2007. Status and trends of prey fish populations in Lake Michigan, 2006. Great Lakes Science Center, Ann Arbor, MI. (http://www.glsc.usgs.gov/_files/reports/2006LakeMichiganPreyfish.pdf). Accessed November 6, 2007.

Cain, S.A. 1935. Studies on virgin hardwood forest, III. Warren's Woods, a beech-maple climax forest in Berrien Country, Michigan. Ecology **16**: 500-513.

California Environmental Protection Agency Air Resources Board. 1999. Fact sheet: New regulations for gasoline marine engines. Sacramento, CA. (http://www.arb.ca.gov/msprog/marine/facts.pdf). Accessed July 23, 2007.

Callaway, R.M and E.T. Aschehoug. 2000. Invasive plants versus their new and old neighbors: a mechanism for exotic invasion. Science **290**:521-24.

Calver, J. 1946. The glacial and post-glacial history of the Platte and Crystal lake depressions, Benzie County, MI. Pub. No. 45, pt. II. Michigan Geological Survey, MDEQ, Lansing, MI.

Canale, R.P., R. Harrison, P. Moskus, T. Naperala, W. Swiecki, and G. Whelan. 2004. Case study: reduction of total phosphorus loads to Big Platte Lake, MI through point source control and watershed management. Presented at the Water Environment Foundation Watershed Conference 2004, July 11-14, 2004, Dearborn, MI. (http://www.platte-lake.org/Canale_WEF_Manuscript.pdf). Accessed November 26, 2007.

Canale, R.P., G. Whelan, and W.J. Swiecki. 2006. Annual report for the year 2005-consent agreement regarding the operation of the Platte River Hatchery. Platte Lake Improvement Association, Honor, MI. (http://www.platte-lake.org/AnnualReportText2005.pdf). Accessed November 26, 2007.

Canham, C.D., M.J. Papaik, and E.F. Latty. 2001. Interspecific variation in susceptibility to windthrow as a function of tree size and storm severity for northern temperate tree species. Can. J. For. Res. **31**:1-10.

Capelli, G.M. 1982. Displacement of northern Wisconsin crayfish by *Orconectes rusticus*. Limnol. Oceanogr. **27**:741-745.

Carlson, E. 2007. "Golf course foreclosure sale set." The Leelanau Enterprise, July 2, 2007. (http://www.leelanaunews.com/blog/2007/07/02/golf-course-foreclosure-sale-set/). Accessed November 19, 2007.

Carlson, R.E. 1977. A trophic state index for lakes. Limnology and Oceanography **22**:361-369.

Carlson, R.E. and J. Simpson. 1996. A coordinator's guide to volunteer lake monitoring methods. 96 pp. North American Lake Management Society. 96 pp. Kent State University, Kent, OH. (http://dipin.kent.edu/tsi.htm). Accessed February 26, 2008.

Case, F.W. Jr. 1987. Orchids of the western Great Lakes region, rev. ed. Bull. Cranbrook Inst. Sci. **48**.

Casper, G.S. and T.G. Anton. 2008. An amphibian and reptile inventory of Sleeping Bear Dunes National Lakeshore. Natural Resource Technical Report NPS/GLKN/NRTR—2008/147. National Park Service, Fort Collins, CO.

Castello, J.D., D.J. Leopold, and P.J. Smallidge. 1995. Pathogens, patterns and processes in forest ecosystems. BioSci. **45**(**1**):16-24.

Charlebois, P.M., M.J. Raffenberg, and J.M. Dettmers. 2001. First occurrence of *Cercopagis pengoi* in Lake Michigan. J. Great Lakes Res. **27**(**2**): 258-261.

Cho, D.S. and R.E.J. Boerner. 1991. Canopy disturbance patterns and regeneration of *Quercus* species in two Ohio old-growth forests. Vegetation **93**:9-18.

Clapp, D.F., P.J. Schneeberger, R.P. O'Neal, T.J. Lychwick, B. Belonger, and S.M. Shroyer. 2005. Inshore fish community. In M.E. Holey and T.N. Trudeau (eds.). The state of Lake Michigan in 2000. Special Publication 05-01. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/pubs/SpecialPubs/Sp05_1.pdf). Accessed November 6, 2007.

Clark, B.M. and T. Dutzik. 2002. Dirty drilling: the threat of oil and gas drilling in Michigan's Great Lakes. Public Interest Research Group in Michigan (PIRGIM) Education Fund. Ann Arbor, MI. (http://www.pirgim.org/reports/dirtydrilling.pdf). Accessed December 31, 2007.

Clements, W. and O. Cox. 2006. An integrated assessment of polycyclic aromatic hydrocarbons (PAHs) and benthic macroinvertebrates of Isle Royale National Park, Michigan, USA. Final report submitted to the National Park Service, Isle Royale National Park, Houghton, MI.

Clinton, B.D., L.R. Boring, and W.T. Swank. 1993. Canopy gap characteristics and drought influences in oak forests of the Coweeta basin. Ecology **74**:1551-58.

Clinton, B.D., L.R. Boring, and W.T. Swank. 1994. Regeneration patterns in canopy gaps of mixed-oak forests of the Southern Appalachians: influences of topographic position and evergreen understory. Am. Midl. Nat. **132**:308-19

Code of Federal Regulations. 1899. Refuse act of 1899. 33 USC 407. (http://www4.law.cornell.edu/uscode/html/uscode33/usc_sec_33_00000407----000-.html). Accessed July 10, 2007.

Code of Federal Regulations. 1987. Federal water pollution control act (Clean Water act) (as amended). 33 USC 1251-1376, P.L. 845, 62 Stat. 1155 (Fish and Wildlife Service). (http://www.thecre.com/fedlaw/legal14water/fwatrpo.htm). Accessed July 10, 2007.

Cole, D.N. 2004. Impacts of hiking and camping on soils and vegetation: a review. Pages 41-60 *in* R. Buckley (ed.) Environmental impacts of ecotourism. CAB International: Wallingford UK. (http://leopold.wilderness.net/research/fprojects/docs12/Ecotourism.pdf). Accessed January 29, 2008.

Cole, D.N. and J. Dalle-Molle. 1982. Managing campfire impacts in the backcountry. Gen. Tech. Rep. INT-135. USDA-Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT. 16 pp.

Comer, P.J., D.A. Albert, H.A. Wells, B.L. Hart, J.B. Rabb, D.L. Price, D.M. Kashian, R.A. Corner, and D.W. Schuen. 1995. Michigan's native landscape, as interpreted from the General Land Office Surveys 1816–1856. Michigan Natural Features Inventory, Lansing MI. 78 p. + digital map.

Comer, R.A. and D.A. Albert. 1999. Landtype associations of Northern Michigan Section VII. Michigan Natural Features Inventory, Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/). Accessed April 30, 2007.

Cook, D.G. and M.G. Johnson. 1974. Benthic macroinvertebrates of the St. Lawrence Great Lakes. J. Fish. Res. Bd. Canada **31**: 763-782.

Copeland, C. 2005. Cruise ship pollution: background, laws and regulations, and current issues. Report RL32450. Congressional Research Service, Library of Congress. (http://www.ncseonline.org/NLE/CRSreports/05feb/RL32450.pdf). Accessed July 7, 2007.

Corace, R.G. III, P.C. Goebel, and T.C. Wyse. 2003. A multi-scale assessment and evaluation of historic openlands at Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI. (http://science.nature.nps.gov/im/units/GLKN/SLBE%20Openland%20Avian%20Study.pdf). Accessed September 28, 2008.

Corbett, J.J. and P.S. Fischbeck. 2000. Emissions from waterborne commerce vessels in United States continental and inland waterways. Env. Sci Tech. **34**(**15**): 3254-3260.

Corbett, J.J. and H.W. Koehler. 2003. Updated emissions from ocean shipping. J. Geophys. Res. **108** (D20), 4650. (http://www.ocean.udel.edu/cms/jcorbett/CorbettKoehlerJGR2003.pdf). Accessed July 17, 2007.

Cornett, M.D., P.J. Bauman, and D.D. Breyfogle. 2006. Can we control leafy spurge? Adaptive management and the recovery of native vegetation. Ecol. Restor. **24**(**3**):145-50.

Cote, S.D., T.P. Rooney, J.-P. Tremblay, D. Dussault, and D.M. Waller. 2004. Ecological impacts of deer overabundance. Ann. Rev. Ecol. Evol. Syst. **35**:113-47.

Coulter, S. 1904. An ecological comparison of some typical swamp areas. Miss. Bot. Gard. Ann. Rept. **15**:38-71.

Council of Great Lakes Governors. 2005. Great Lakes-St. Lawrence River Basin water resources compact. Chicago, IL. (http://www.cglg.org/projects/water/CompactImplementation.asp#Great%20Lakes--St.%20Lawrence%20River%20Basin%20Waters%20Resources%20Compact--Resource%20Kit). Accessed March 3, 2008.

Cowardin, L., V. Carter, F. Golet, and E. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. FWS/OBS 79/31. U.S. Fish and Wildlife Service, Washington, D.C.

Cowles, H.C. 1899. The ecological relations of the vegetation on the sand dunes of Lake Michigan. Bot. Gaz. **27**:95-117,167-202, 281-308, 361-91.

Crall, A.W., L.A. Meyerson, T.J. Stohlgren, C.S. Jarnevich, G.J. Newman, and J. Graham. 2006. Show me the numbers: what data currently exist for non-native species in the USA? Front. Ecol. Environ. **4**(**8**):414-18.

Crow, T.R., D.S. Buckley, E.A. Nauertz ,and J.C. Zasada. 2002. Effects of management on the composition and structure of northern hardwood forests in Upper Michigan. For. Sci. **48**:129-45.

Currie, D.J. 2001. Projected effects of climate changes on patterns of vertebrate and tree species richness in the conterminous United States. Ecosystems **4**:216-25.

Currie, W.S., J.D. Aber, and C.T. Driscoll. 1999. Leaching of nutrient cations from the forest floor: effects of nitrogen saturation in two long-term manipulations. Can. J. For. Res. **29**:609-20.

Curry, K. 1977. Species structure of midge communities in Crystal River drainage basin, Leelanau County, Michigan 1972. M.S. thesis, Central Michigan University. Mt. Pleasant, MI.

Curtis, J.T. 1959. The vegetation of Wisconsin. Univ. Wisc. Press, Madison, WI.

Cutter, B.E. and R.P. Guyette. 1994. Fire frequency on an oak-hickory ridgetop in the Missouri Ozarks. Am. Midl. Nat. **132**:393-98.

Cwynar, L.C. 1977. The recent fire history of Barron Township, Algonquin Park. Can. J. Bot. **55**:1524-38.

Czarapata, E.J. 2005. Invasive plants of the Upper Midwest – an illustrated guide to their identification and control. Univ. Wisc. Press, Madison, WI.

Czypinski, G.D., A.K. Bowen, M.A. Goehle, and B. Brownson. 2007. Surveillance for ruffe in the Great Lakes, 2006. 19 pp. U.S. Fish and Wildlife Service, Ashland, WI. (http://www.fws.gov/midwest/ashland/ruffe/surv/2006/pdf/RuffeSurveillance2006.pdf). Accessed November 27, 2007.

Dahir S.E. and C.G. Lorimer. 1996. Variation in canopy gap formation among developmental stages of northern hardwood stands. Canadian J. Forest Research **26**:1875-1892.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks, and B.M. Wotton. 2001. Climate change and forest disturbances. BioSci **51**(**9**):723-34.

Danz, N.P., G.J. Niemi, R.R. Regal, T. Hollenhorst, L.B. Johnson, J.M. Hanowski, R.P. Axler, J.J.H. Ciborowski, T. Hrabik, V.J. Brady, J.R. Kelly, J.A. Morrice, J.C. Brazner, R.W. Howe, C.A. Johnston, and G.E. Host. 2007. Integrated measures of anthropogenic stress in the U.S. Great Lakes basin. Environ. Management **39**:631-647.

Davies, M.A. 2004. What's burning in your campfire: garbage in, toxics out. 8 pp. Tech Tip 0423-2327-MTDC. USDA-Forest Service Missoula Technology and Development Center. Missoula, MT.

Davis, M., C. Douglas, R. Calcote, K.L. Cole, M.G. Winkler, and R. Flakne. 2000. Holocene climate in the western Great Lakes national parks and lakeshores: implications for future climate change. Conservation Biology **14**(**4**): 968-983.

Davis, M.B., R.G. Shaw, and J.R. Etterson. 2005. Evolutionary responses to changing climate. Ecology **86**:1704-14.

Dawson, K.A., R.L. Eshenroder, M.E. Holey, and C. Ward. 1997. Quantification of historic lake trout (*Salvelinus namaycush*) spawning aggregations in Lake Michigan. Can. J. Fish. Aquat. Sci. **54**: 2290-2302.

Debinski, D.M and R.D. Holt. 2000. A survey and overview of habitat fragmentation experiments. Cons. Biol. **14**(**2**):342-55.

de Blij, H.J. and P.O. Muller. 1993. Physical Geography of the Global Environment. John Wiley & Sons, Inc. New York.

Dermott, R. and D. Kerec. 1997. Changes to the deepwater benthos of eastern Lake Erie since the invasion of *Dreissena*: 1979-1993. Can. J. Fish. Aquat. Sci. **54**:922-930.

Delcourt, H.R. and P.A. Delcourt. 2000. Eastern deciduous forests. Pages 357-396 *in* M.G. Barbour and W.D. Billings (eds). North American Terrestrial Vegetation, 2nd edition. Cambridge Univ. Press.

Dickens, S.J., F. Gerhardt, and S.K. Collinge. 2005. Recreational portage trails as corridors facilitating non-native plant invasions of the Boundary Waters Canoe Area Wilderness (U.S.A.). Cons. Biol. **19**:1653-57.

Dimock, E.J. II, R.R. Silen, and V.E. Allen. 1976. Genetic resistance in Douglas-fir to damage by snowshoe hare and black-tailed deer. For. Sci. **22**(**2**):106-21.

DiTomaso, J.M. 2000. Invasive weeds in rangelands: species, impacts and management. Weed Sci. **48**(**2**):255-65.

Dittman, J.A., C.T. Driscoll, P.M. Groffman, and T.J. Fahey. 2007. Dynamics of nitrogen and dissolved organic carbon at the Hubbard Brook Experimental Forest. Ecology **88**:1153-66.

Dodds, W.K. and D.A. Gudder. 1992. The ecology of *Cladophora*. J. Phycol **28**(**4**): 415-427.

Dorr, J.A. Jr. and D.F. Eschman. 1970. Geology of Michigan. University of Michigan Press, Ann Arbor, MI.

Drexler, C. 1974. Geologic report on Sleeping Bear Dunes National Lakeshore. In Natural History Report for Sleeping Bear Dunes National Lakeshore by U. of Michigan. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Driscoll, C.T., G.B. Lawrence, A.J. Bulger, T.J. Butler, C.S. Cronan, C. Eagar, K.F. Lambert, G.E. Likens, J.L. Stoddard, and K.C.Weathers. 2001. Acid rain revisited: advances in scientific understanding since the passage of the 1970 and 1990 Clean Air Act Amendments. Science Links™ Publication. Vol. 1, no.1. Hubbard Brook Research Foundation, North Woodstock, NH. (http://www.hbrook.sr.unh.edu/hbfound/report.pdf) Accessed March 29, 2007.

Duffy, D.C. and A.J. Meier. 1992. Do Appalachian herbaceous understories ever recover from clearcutting? Cons. Biol. **6**(**2**):196-201.

Duval, M.D. and D.F. Grigal. 1999. The effects of timber harvesting on coarse woody debris in red pine forests across the Great Lakes states, USA. Can. J.Forest Res. **29**: 1926–1934.

Edmonds, R.L., J.K. Agee, and R.L. Gara. 2000. Forests health and protection. McGraw-Hill, New York.

Edsall, T.A. 2001. Burrowing mayflies (*Hexagenia*) as indicators of ecosystem health. Aquatic Ecosystem Health and Management **4**:283-292.

Edsall, T.A. and W.E. Phillips. 2004. Burrowing mayflies (*Hexagenia*) as indicators of aquatic ecosystem health at Sleeping Bear Dunes National Lakeshore. Park Science **23**(**1**). (http://www.nature.nps.gov/ParkScience/index.cfm?ArticleID=179). Accessed September 29, 2008.

Ehrenfeld, J.G. 2003. Effects of exotic plant invasions on soil nutrient cycling processes. Ecosystems **6**:503-23.

Elias, J. 2007. Water quality sampling at Pictured Rocks and Sleeping Bear Dunes National Lakeshores, 2005. GLKN/2007/06. NPS, Great Lakes Inventory and Monitoring Network, Ashland, WI. (http://science.nature.nps.gov/im/units/GLKN/SLBE%20Water%20Quality.pdf). Accessed March 3, 2008.

Elias, J. and D. VanderMeulen. 2008. Monitoring Water Quality of Inland Lakes, 2007. Annual Summary Report. GLKN/2008/05. NPS, Great Lakes Inventory and Monitoring Network, Ashland, WI.

Ellison, A.M and 19 others. 2005. Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. Front. Ecol. Envir. **3**:479-86.

Environmental Resources Management. 1985. Platte River Corridor Study. Final Report to the National Park Service, Midwest Region, Contract No. CX6000-3-0059, Environmental Resources Management-North Central, Frankfort, MI.

Enviroscience. 1995. Phase 1 Environmental Site Assessment Tucker Lake dump, Glen Arbor township, Michigan. NPS, Sleeping Bear Dunes National Lakeshore. Empire, MI.

Enviroscience. 1996. Phase 2 Environmental Site Assessment Tucker Lake dump, Glen Arbor township, Michigan. NPS, Sleeping Bear Dunes National Lakeshore. Empire, MI.

Eschtruth, A., N. Cleavitt, J.J. Battles, and T. Fahey. 2005. Vegetation dynamics in declining hemlock stands in the Delaware Water Gap National Recreation Area: 9 years of forest response to hemlock woolly adelgid infestation. 4th Biennial North American Forest Ecology Workshop, Michigan Technological University, Houghton, MI.

Eshenroder, R.L., M.E. Holey, T.K. Gorenflo, and R.D. Clark, Jr. 1995. Fish-community objectives for Lake Michigan. Special Publication 95-3. 56 p. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/pubs/SpecialPubs/Sp95_3.pdf). Accessed December 17, 2007.

ESRI (Environmental Systems Research Institute). 2002. ESRI Data and Maps (Canada Provinces, U.S. States, U.S. Lakes). Redlands, CA.

ESRI (Environmental Systems Research Institute). 2006. ArcGIS 9.2. Redlands, CA.

Everham, E.M. III and N.V.L. Brokaw. 1996. Forest damage and recovery from catastrophic wind. Bot. Rev. **62**(**2**):113-85.

Farrand, W.R. and D.L. Bell. 1982. Quaternary geology of southern Michigan. Department of Geological Sciences, University of Michigan, Ann Arbor, MI.

Fenn, D.B., G.J. Gogue, and R.E. Burge. 1976. Effects of campfire on soil properties. Ecological Services Bulletin 5. NPS. Washington, D.C. 16 pp.

Fessell, B. 2007. Inventory and evaluation of inland fisheries at Sleeping Bear Dunes National Lakeshore. Report GLKN/2007/03. National Park Service, Great Lakes Inventory and Monitoring Network, Ashland, WI. (http://science.nature.nps.gov/im/units/GLKN/reports/SLBE_Fishreport_final_20080529.pdf). Accessed August 4, 2008.

Finzi, A.C., N. van Breemen, and C.C. Canham. 1998. Canopy tree-soil interactions within temperate forests: species effects on soil carbon and nitrogen. Ecological Applications **8**: 440-446.

Fleischer, G., C.M. Madenjian, R.F. Elliott, and M.L. Toneys. 2005. Planktivores. In M.E. Holey and T.N. Trudeau (eds.). The state of Lake Michigan in 2000. Special Publication 05-01. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/pubs/SpecialPubs/Sp05_1.pdf). Accessed November 6, 2007.

Flower, H. and B. Walker. 1999a. A biological survey of the Crystal River, Leelanau County, Michigan, September 30, 1998. Staff Report MI/DEQ/SWQ-99/068. Michigan Department of Environmental Quality, Surface Water Quality Division, Lansing, MI.

Flower, H. and B. Walker. 1999b. Crystal River Biosurvey, September 1998, Leelanau County. Interoffice Communication dated May 27, 1999 to Mike Stifler, Michigan DEQ, Cadillac District Office, Surface Water Quality Division.

Fogarty, L.R. 2007. Bacteria and emerging chemical contaminants in the St. Clair River/Lake St. Clair Basin, Michigan: Open-File Report 2007-1083, 10 p. U.S. Geological Survey, Reston, VA. (http://pubs.usgs.gov/of/2007/1083/pdf/OFR2007-1083.pdf). Accessed April 8, 2008.

Forrester, J.A., G.G. McGee, and M.J. Mitchell. 2003. Effects of beech bark disease on aboveground biomass and species composition in a mature northern hardwood forest, 1985 to 2000. Journal of the Torrey Botanical Society **130**: 70–78.

Foster, D.R. 1988. Species and stand response to catastrophic wind in central New England, U.S.A. J. Ecol. **76**:135-51.

Frawley, B.J. 2008. Michigan deer harvest survey report, 2007 seasons. Wildlife Rep. No. 3485. MDNR, Lansing, MI. (http://www.michigan.gov/documents/dnr/3485_236922_7.pdf). Accessed January 26, 2009.

Freeman, C. 2004. An annotated list of the Odonata of Sleeping Bear Dunes National Lakeshore 1998-2004. Report ? (no publication data – volunteer for the Michigan Odonata Survey) 12pp.

Frelich, L.E. 1992. The relationship of natural disturbances to white pine stand development. Pages 27-37 *in* Publication NR-BU-6044-S, R.A. Stine and M.J. Baughman (eds.), White Pine Symposium Proceedings. Dept. For. Res. and Minn. Extension Service, Duluth, MN.

Frelich, L.E. 1995. Old forest in the Lakes States today and before European settlement. Nat. Areas J. **15**(**2**):157-67.

Frelich, L.E. and C.G. Lorimer. 1985. Current and predicted long-term effects of deer browsing in hemlock forests in Michigan, USA. Biol. Cons. **34**:99-120.

Frelich, L.E. and C.G. Lorimer. 1991. Natural disturbance regimes in hemlock-hardwood forests of the Upper Great Lakes region. Ecol. Monogr. **61**:145-64.

Friedland, A.J. and E.K. Miller. 1999. Major-element cycling in a high-elevation Adirondack forest: patterns and changes, 1986-1996. Ecol. Appl. **9**:958-67.

Frissell, S.S. Jr. 1973. The importance of fire as a natural ecological factor in Itasca State Park, Minnesota. Quaternary Research **3**:397-407.

Gannon, J.E. and R.S. Stemberger. 1978. Zooplankton (especially crustaceans and rotifers) as indicators of water quality. Trans. Amer. Micros. Soc. **97**(**1**): 16-35.

Gannon, J. and J. Stockwell. 1978. Limnological investigations of Florence Lake, South Manitou Island, Michigan. Tech. Rept. No. 5, 48 pp. University of Michigan Biological Station, Pellston, MI. (http://hdl.handle.net/2027.42/49263). Accessed August 22, 2008.

Gelbard, J.L. and A.J. Belnap. 2003. Roads as conduits for exotic plant invasions in a semiarid landscape. Cons. Biol. **17**(**2**):420-32.

Getchell, R.G. and P.R. Bowser. 2006. Ecology of type E botulism within dreissenid mussel beds. Aquatic Invaders **17**(**2**): 1-8.

Gilliam, F.S. and M.R. Roberts (eds). 2003. The herbaceous layer of forests of eastern North America. Oxford Univ. Press.

Gleason, H.A. and A. Cronquist. 1963. Manual of vascular plants of the northeastern United States. Van Nostrand Co. Princeton.

Glen Lake Association. 2009. Invasive species (online). Glen Arbor, MI. (http://glenlakeassociation.org/services/zebra-mussel-invasive-species/). Accessed January 5, 2009.

Glen Lake Water Level Committee. 2007. Water Level Committee report, August 11, 2007 (powerpoint presentation). Glen Lake Association, Glen Arbor, MI. (http://www.mlswa.org/gla-916/images/CommRpts/WaterLevel/WLC2007.pdf). Accessed June 23, 2008.

GLIFWC (Great Lakes Indian Fish and Wildlife Commission). 2007. GLIFWC-maps.org (online). Odanah, WI. (http://www.glifwc-maps.org/default.htm). Accessed November 27, 2007.

Godman, R.M. and K. Lancaster. 1990. Tsuga canadensis (L.) Carr. Pages 604-612 in R.M. Burns and B.H. Honkala, (eds). Silvics of North America. Volume 1, Conifers. U.S. Department of Agriculture Handbook 654. USDA-Forest Service, Washington, DC.

Goebel, P.C, T.C. Wyse, and R.G. Corace III. 2005. Determining reference ecosystem conditions for disturbed landscapes within the context of contemporary resource management issues. J. For. (**10**):351-56.

Goslee, S.C., W.A. Niering, D.L. Urban, and N. Christensen. 2005. Influence of environment, history and vegetative interactions on stand dynamics in a Connecticut forest. J. Torr. Bot. Soc. **132**:471-82.

Graham, R.T., S.McCaffrey, and T.B. Jain. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rept. RMRS GTR-120. USDA-Forest Service, Fort Collins, CO. (http://www.fs.fed.us/rm/pubs/rmrs_gtr120.html). Accessed January 26, 2009.

Grand Traverse Band Ottawa and Chippewa Indians. 2008. GTB News, July 2008. Peshawbestown, MI. (http://www.gtbindians.org/images/pdf_files/July08Part3.pdf). Accessed February 3, 2009.

Grannemann, N., R. Hunt, J. Nicholas, T. Reilly, and T. Winter. 2000. The importance of ground water in the Great Lakes Region. Water Resources Investigations Report 00-4008. U.S. Geological Survey, Lansing, MI. (http://water.usgs.gov/ogw/pubs/WRI004008/WRIR_00-4008.pdf). Accessed November 25, 2008.

Grant, J. 1979. Water quality and phosphorus loading analysis of Platte Lake 1970-1978. Pub. No. 4833-9792. MDNR, Water Quality Division, Lansing, MI.

Graumlich, L.J. and M.B. Davis. 1993. Holocene variation in spatial scales of vegetation patterns in the Upper Great Lakes. Ecology **74**:826-39.

Great Lakes Commission. 2001. Northern Michigan sub-area contingency plan February 2001. Ann Arbor, MI. (http://www.great-lakes.net/partners/epa/northmi/). Accessed July 10, 2007.

Grigorovich, I., R. Colautti, E. Mills, K. Holeck, A. Ballert, and H. MacIsaac. 2003. Ballast-mediated animal introductions in the Laurentian Great Lakes: retrospective and prospective analyses. Can. J. Fish. Aquat. Sci. **60**: 740-756.

Griffin, J.M., G.M. Lovett, M.A. Arthur, and K.C. Weathers. 2003. The distribution and severity of beech bark disease in the Catskill Mountains, NY. Can. J. For. Res. **33**: 1754 -60.

Gucciardo, S., B. Route, and J. Elias. 2004. Conceptual models for long-term ecological monitoring in the Great Lakes Network. Technical Report GLKN/2004/04. 101pp. National Park Service, Great Lakes Inventory and Monitoring Network, Ashland, WI. (http://science.nature.nps.gov/im/units/glkn/Conceptual%20Ecosystem%20Models.pdf). Accessed November 12, 2007.

Gundale, M.J. 2002. Influence of exotic earthworms on the soil organic horizon and the rare fern *Botrychium mormo*. Cons. Biol. **16**:1555-61.

Gunderson, J. 2006. Rusty crayfish factsheet. Minnnesota Sea Grant, University of Minnesota, Minneapolis, MN. (http://www.seagrant.umn.edu/exotics/rusty.html) Accessed December 10, 2007.

Gunderson, J. and R. Kinnunen (eds). 2004. AIS-HAACP aquatic invasive species-hazard analysis and critical control point training curriculum. University of Minnesota, Duluth, MN. (http://www.deq.state.mi.us/documents/deq-ogl-AIS-HACCP_manual.pdf). Accessed January 15, 2008.

Gunderson, J.L., M.R. Klepinger, C.R. Bronte, and J.E. Marsden. 1998. Overview of the International Symposium on Eurasian ruffe (*Gymnocephalus cernuus*): biology, impacts, and control. J. Great Lakes Res. **24**(**2**): 165-169. (http://www.sgnis.org/publicat/papers/jglr24_2.pdf). Accessed December 11, 2007.

GWPC (Ground Water Protection Council). 2007. Ground water report to the nation: a call to action. Oklahoma City, OK. (http://www.gwpc.org/CallToAction/CallToAction.aspx). Accessed October 16, 2007.

Habeck, J.R. 1960. Winter deer activity in the white cedar swamps of northern Wisconsin. Ecology **41**(**2**):327-33.

Hale, C.M, L.E. Frelich, and P.B. Reich. 2005. Exotic European earthworm invasion dynamics in northern hardwood forests of Minnesota, USA. Ecol. Appl. **15**(**3**):848-60.

Hale, C.M., L.E. Frelich, and P.B. Reich. 2006. Changes in hardwood forest understory plant communities in response to European earthworm invasions. Ecology **87**:1637-49.

Halpern, C.B. and J.F. Franklin. 1990. Physiognomic development of *Pseudotsuga* forests in relation to initial structure and disturbance intensity. J. Veg. Sci. **1**:475-82.

Halvorsen, K.E., H.S. Gorman, and K. Bradof. 2004. Strengths and weaknesses of Great Lakes onsite sewage system regulatory programs. Michigan Technological University. Houghton, MI. (http://www.ss.mtu.edu/documents/septicre.pdf). Accessed October 16, 2007.

Handy, A.H. and J.R. Stark. 1984. Water resources of Sleeping Bear Dunes National Lakeshore, Michigan. Water-Resources Investigations Report 83-4253. U.S. Geological Survey. Lansing, MI. (http://pubs.er.usgs.gov/usgspubs/wri/wri834253). Accessed January 7, 2008.

Hane, E.N. 2003. Indirect effects of beech bark disease on sugar maple seedling survival. Can. J. For. Res. **33**:807-813.

Hansen, A.J., R.P. Neilson, V.H. Dale, C.H. Flather, L.R. Iverson, D.J. Currie, S. Shafer, R. Cook, and P.J. Bartlein. 2001. Global change in forests: responses of species, communities and biomes. BioSci **51**(**9**):765-79.

Hardt, R.A. and W.T. Swank. 1997. A comparison of structural and compositional characteristics of southern Appalachian young second-growth, maturing second-growth and old-growth stands. Nat. Areas J. **17**:42-52.

Harlow, J.W., D.J. Leopold and F.M. White. 2001. Textbook of dendrology, 9th edition. McGraw-Hill, New York.

Harman, J.R. and A.F. Arbogast. 2004. Environmental ethics and coastal dunes in western lower Michigan: developing a rationale for ecosystem preservation. Annals of the Association of American Geographers **94**(**1**):23-36.

Harris, V. 2004. Cladophora confounds coastal communities-public perceptions and management dilemmas. *In* Bootsma, H.A., E.T. Jensen, E.B. Young, and J.A. Berges. Cladophora research and management in the Great Lakes: proceedings of a workshop held at the Great Lakes WATER Institute, University of Wisconsin-Milwaukee, December 8, 2004. Milwaukee, WI. (http://www.glwi.uwm.edu/research/aquaticecology/cladophora/Cladophora_Proceedings.pdf). Accessed January 8, 2008.

Haswell, S.O. and A.R. Alanen. 1994. A garden apart: an agricultural and settlement history of Michigan's Sleeping Bear Dunes National Lakeshore region. NPS, Omaha, NE.

Hazlett, B.T. 1986. The terrestrial vegetation and flora of the mainland portion of Sleeping Bear Dunes National Lakeshore, Benzie and Leelanau counties, Michigan. Tech. Rept. No. 13. University of Michigan Biological Station, Douglas Lake, MI. (http://hdl.handle.net/2027.42/49255). Accessed July 7, 2008.

Hazlett, B.T. 1988. The aquatic vegetation and flora of Sleeping Bear Dunes National Lakeshore, Benzie and Leelanau counties, Michigan. Tech. Rept. No. 15. University of Michigan Biological Station, Douglas Lake, MI. (http://hdl.handle.net/2027.42/49253). Accessed July 7, 2008.

Hazlett, B.T. 1991. The flora of Sleeping Bear Dunes National Lakeshore, Benzie and Leelanau Counties, Michigan. Michigan Botanist **30**: 139-200.

Hazlett, B.T. and R.J. Vande Kopple. 1983. The terrestrial vegetation and flora of North and South Manitou Islands, Sleeping Bear Dunes National Lakeshore. Technical Report 11, 143 pp. University of Michigan Biological Station. (http://hdl.handle.net/2027.42/49257). Accessed August 4, 2008.

Hecky, R., R. Smith, D. Barton, S. Guildford, W. Taylor, M. Charlton, and T. Howell. 2004. The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences **61**:1285-1293.

Hecnar, S.J. 2004. Great Lakes wetlands as amphibian habitats: a review. Aquatic Ecoysystem Health and Management **7**(**2**): 289-303.

Hedin, L.O., L. Granat, G.E. Likens, T.A. Buishand, J.N. Galloway, T.J. Butler, and H. Rodhe. 1994. Steep declines in atmospheric base cations in regions of Europe and North America. Nature **367**: 351-354.

Heiman, M. and M.M. Woller. 2003. Glen Lake/Crystal River watershed management plan. Glen Lake Association, Glen Arbor, MI. (http://www.mlswa.org/gla-916/WaterQualityRpt.htm#GLCRWMP). Accessed August 14, 2007.

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quart. Res. **3**:329-82.

Heinselman, M.L. 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. Pages 7-57 *in* Mooney, H.A. et al. (eds.). Fire regimes and ecosystem properties. General Technical Report WO26. USDA-Forest Service, Washington, D.C.

Henderson, N. and J.N. Long. 1984. A comparison of stand structure and fire history in two black oak woodlands in northwestern Indiana. Bot. Gaz. **145**(**2**):222-28.

Hendrix, P.F and P.J. Bohlen. 2002. Exotic earthworm invasions in North America: ecological and policy implications. BioSci **52**:801-11.

Heneghan, L., F. Fatemi, L. Umek, K. Grady, K. Fagen, and M. Workman. 2006. The invasive shrub European buckthorn (*Rhamnus cathartica* L.) alters soil properties in Midwestern U.S. woodlands. Applied Soil Ecol. **32**:142-48.

Henne, P.D., F.S. Hu, and D.T. Cleland. 2007. Lake-effect snow as the dominant control of mesic forest distribution in Michigan, USA. J. Ecology **95**:517-29.

Herdendorf, C.E., S.M. Hartley, and M.D. Barnes. 1981. Fish and wildlife resources of the Great Lakes coastal wetlands within the United States, Volume 5: Lake Michigan, Part 1. FWS/OBS-81/02-V5. US Fish and Wildlife Service, Division of Ecological Services. Twin Cities, MN.

Herdendorf, E. 1987. The ecology of the coastal marshes of western Lake Erie: a community profile. US Fish and Wildlife Service. Washington, D.C.

Heuschele, A. 1999. Invertebrate fauna of Aral Springs. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Heuschele, A. 2000. Sponges of Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Higgins, S., S. Malkin, E. Howell, S. Guildford, L. Campbell, V. Hiriart-Baer, and R. Hecky. 2008. An ecological review of *Cladophora glomerata* (Chlorophyta) in the Laurentian Great Lakes. Journal of Phycology **44**:839-854.

Hildebrand, S. 1971. The effects of coho spawning on the benthic invertebrates of the Platte River, Benzie County, Michigan. Trans. Amer. Fish. Soc. **100**:61-68.

Hix, D.M. and B.V. Barnes. 1984. Effects of clear-cutting on the vegetation and soil of an eastern hemlock dominated ecosystem, western Upper Michigan. Can. J. For. Res. **14**:914-23.

Hobbs, R.J. and L.F. Huenneke. 1992. Disturbance, diversity and invasion: implications for conservation. Cons. Biol. **6**(**3**):324-37.

Holey, M.E. and T.N. Trudeau (eds.). 2005. The state of Lake Michigan in 2000. Spec. Pub. 05-01. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/pubs/SpecialPubs/Sp05_1.pdf). Accessed December 17, 2007.

Holtschlag, D.J. and J.R. Nicholas. 1998. Indirect ground-water discharge to the Great Lakes. Open-File Report 98-579. USGS, Lansing, MI. (http://mi.water.usgs.gov/pdf/glpf.pdf). Accessed August 4, 2008.

Horsely, S.B., S.L. Stout, and D.S. DeCalesta. 2003. White-tailed deer impact on the vegetation dynamics of a northern hardwood forest. Ecol. Applic. **13**:98-118.

Houston, D.R. 1986. Insects and diseases of northern hardwood ecosystems. Pages 109-138 *in* G.D. Mroz and D.D. Reed (compilers). The northern hardwood resource: management and potential. Michigan Technological University. Houghton, MI.

Houston, D.R. 2005. Beech bark disease: 1934 to 2004: what's new since Ehrlich? Pages 2-15 *in* C.A. Evans, J.A. Lucas, and M.J. Twery. Beech Bark Disease: Proceedings of the Beech Bark Disease Symposium. Gen. Tech. Rep. NE-331. USDA-Forest Service, Newtown Square, PA. (http://treesearch.fs.fed.us/pubs/20356). Accessed September 28, 2008.

Hunter, M.D. and J.C. Schultz. 1995. Fertilization mitigates chemical induction and herbivore responses within damaged oak trees. Ecology **76**:1226-32.

Hurley, P.M and D. Flaspohler. 2005. An assessment of long-term biodiversity recovery from intense and sustained deer browse on North Manitou Island, Sleeping Bear Dunes National Lakeshore. Mich. Soc. Amer. For. Conf., June 9-10, 2005. St. Ignace, MI.

IADN (United States-Canada IADN Scientific Steering Committee). 2002. Technical summary of progress of the Integrated Atmospheric Deposition Network (IADN) 1997-2002. USEPA, Washington, D.C. (http://www.epa.gov/glnpo/monitoring/air/iadn/IADN_Tech_Rpt_Final_verC.pdf). Accessed March 26, 2007.

IJC (International Joint Commission). 1980. Phosphorus management for the Great Lakes. Final report of the Phosphorus Management Strategies Task Force to the International Joint Commission's Great Lakes Water Quality Board and Great Lakes Science Advisory Board, Windsor, Ontario. 129 p.

IJC (International Joint Commission). 2003. Climate change and water quality in the Great Lakes basin. Report of the Great Lakes Water Quality Board to the International Joint Commission, August, 2003. Washington, D.C. (http://www.ijc.org/php/publications/html/climate/index.html). Accessed February 25, 2008.

IJC (International Joint Commission) Upper Lakes Plan of Study Revision Team. 2005. Upper Lakes plan of study for the review of the regulation of outflows from Lake Superior. Washington, D.C. (http://www.ijc.org/conseil_board/upper_greatlakes/upper_pub.php?language=english). Accessed February 26, 2008.

International Maritime Organization. 1978. International convention for the prevention of pollution from ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78). London, United Kingdom. (http://www.imo.org/Conventions/contents.asp?doc_id=678&topic_id=258). Accessed June 2006.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007-the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK. (http://www.ipcc.ch/ipccreports/ar4-wg1.htm). Accessed February 25, 2008.

Isard, S.A., R.J. Schaetzl, and J.A. Andresen. 2007. Soils cool as climate warms in the Great Lakes region: 1951-2000. Annals of the Association of American Geographers **97**(**3**): 467-476.

Janssen, J. and J. Quinn. 1985. Biota of the naturally rocky area of Lake Michigan with emphasis on potential fish prey. *In* F.M. D'Itri (ed.). Artificial reefs in the Great Lakes. Lewis Publishers, Chelsea, MD.

Jarnigan, S.T. 1998. Direct and indirect estimates of death rates and predator-mediated dispersal of *Bythotrephes cederstroemi*. Dissertation. Michigan Technological University. Houghton, MI.

Jenkins, J.C., J.D. Aber, and C.D. Canham. 1999. Hemlock woolly adelgid impacts on community structure and N cycling rates in eastern hemlock forests. Can. J. For. Res. **29**:630-45.

Johnson, D.W., D.D. Richter, H. van Miegroet, and D.W. Coles. 1983. Contributions of acid deposition and natural processes to cation leaching from forest soils: a review. J. Air Poll. Control Assoc. **33**:1036-41.

Johnson, D.W., B.A. Hungate, P. Dijkstra, G. Hymus, C.R. Hinkle, P. Stiling, and B.G. Drake. 2003. The effects of elevated CO2 on nutrient distribution in a fire-adapted scrub oak forest. Ecol. Appl. **13**:1388-99.

Johnston, C.A. and R.J. Naiman. 1990. Browse Selection by Beaver: Effects on Riparian Forest Composition. Canadian Journal of Forest Research **20**:1036–1043.

Jonas, J.L., D.F. Clapp, J.R. Bence, and M.E. Holey. 2005. Salmonine community. In M.E. Holey and T.N. Trudeau (eds.). The state of Lake Michigan in 2000. Special Publication 05-01. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/pubs/SpecialPubs/Sp05_1.pdf). Accessed November 6, 2007.

Jude, D., E. Stoermer, T. Johengen, and A. Perakis. 2002. Non-indigenous species in the Great Lakes: ecology, interactions, impacts, and future research directions. White Paper prepared for the Office of the Vice President for Research, University of Michigan, Ann Arbor, MI. (http://www.miseagrant.umich.edu/symposium/papers/AQUATI.pdf). Accessed December 10, 2007.

Jude, D., D. Albert, D.G. Uzarski, and J. Brazner. 2005a. Lake Michigan's coastal wetlands: distribution, biological components with emphasis on fish, and threats. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Jude, D., J. Janssen, and E. Stoermer. 2005b. The uncoupling of trophic food webs by invasive species in Lake Michigan. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Karamanski, T.J. 2000. A nationalized lakeshore: the creation and administration of Sleeping Bear Dunes National Lakeshore. NPS, Washington, D.C. (http://www.cr.nps.gov/history/online_books/slbe/index.htm). Accessed May 10, 2007.

Karnosky, D.F., K. Percy, B. Xiang, B. Callan, A. Noormets, B. Mankovska, A. Hopkin, J. Sober, W. Jones, R. Dickson, and J. Isebrands. 2002. Interacting elevated CO_2 and tropospheric O_3 predisposes aspen (*Populus tremuloides*) to rust infection (*Melamspora medusae* f. sp. t*remuloidae*). Global Change Biol. **8**:329-38.

Katovich, S., D. McDougall, and Q. Chavez. 1998. Impact of forest stressors on the tree species of the Nicolet National Forest – past, present and future. NA-TP-02-98. USDA-Forest Service NE Area State and Private Forestry, Newtown Square, PA.

Keane, R.E., K.C. Ryan, T.T. Veblen, C.D. Allen, J. Logan, and B. Hawkes. 2002. Cascading effects of fire exclusion in Rocky Mountain ecosystems: a literature review. GTR-RMRS-91. USDA-Forest Service, Fort Collins, CO. (http://www.fs.fed.us/rm/pubs/rmrs_gtr091.html). Accessed January 26, 2009.

Kearney**,** A., D.G. McCullough, and M. Walters. 2005. Impacts of beech bark disease on understory composition in Michigan. Pages 58-59 *in* C.A. Evans, J.A. Lucas, and M.J. Twery. Beech Bark Disease: Proceedings of the Beech Bark Disease Symposium. Gen. Tech. Rep. NE-331. USDA-Forest Service, Newtown Square, PA. (http://treesearch.fs.fed.us/pubs/20356). Accessed September 28, 2008.

Keillor, J.P. 1998. Coastal processes manual: how to estimate the conditions of risk to coastal property from extreme lake levels, storms, and erosion in the Great Lakes basin. WISCU-H-98-003. UW Sea Grant Institute. Madison, WI. (http://aqua.wisc.edu/Publications/PDFs/CoastalProcessesManual.pdf) Accessed December 22, 2008.

Keilty, T. 1992. Clean Lakes Program, Glen Lake, Leelanau County, Michigan: Phase 1 Diagnostic/Feasibility Study, Final report (preliminary draft), funded by the US Environmental Protection Agency (Region V) and the Michigan DNR.

Kelly, T. and B. Price. 1979. Fishes of the Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Kemezis, A. 1983. Visitor use survey, Platte River corridor. Final Report to Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Kenaga, D. 1980. Heavy metals in the sediments of the Platte River, Brundage Creek and Platte Lake, Benzie County, Michigan, October 30, 1979. Water Quality Division, MDNR, Lansing, MI.

Kenaga, D. and E. Evans. 1982. The effect of the Platte River anadromous fish hatchery on fish, benthic macroinvertebrates and nutrients in Platte Lake. Water Quality Division, MDNR, Lansing, MI.

Keough, J.R., T.A. Thompson, G.R. Guntenspergen, and D.A. Wilcox. 1999. Hydrogeomorphic factors and ecosystem response in coastal wetlands of the Great Lakes. Wetlands **19**: 821-834.

Kern, C.C., B.J. Palik, and T.F. Strong. 2006. Ground-layer plant community responses to even-age and uneven-age silvicultural treatments in Wisconsin northern hardwood forests. For. Ecol. Mngt. **230**:162-170.

Kinnunen, R. 2003. Great Lakes commercial fisheries. Michigan Sea Grant Extension, Marquette, MI. (http://www.miseagrant.umich.edu/downloads/fisheries/GLCommercialFinal.pdf). Accessed September 28, 2008.

Kling, G.W., D. Zak, and M. Wilson. 2003. State summary: Michigan. Findings from Confronting climate change in the Great Lakes region: impacts on Michigan communities and ecosystems. A report of the Union of Concerned Scientists, Cambridge, MA, and the Ecological Society of America, Washington, D.C. (http://www.ucsusa.org/greatlakes/glchallengereport.html). Accessed February 25, 2008.

Kling, G.W., D.J. Wuebbles, K. Hayhoe, R.L. Lindroth, J.J. Magnuson, M. Wander, M. Wilson, and D. Zak. 2005. Updated executive summary: confronting climate change in the Great Lakes region: impacts on our communities and ecosystems. A report of the Union of Concerned Scientists, Cambridge, MA, and the Ecological Society of America, Washington, D.C. (http://www.ucsusa.org/greatlakes/glchallengereport.html). Accessed February 25, 2008.

Kost, M.A., D.A. Albert, J.G. Cohen, B.S. Slaughter, R.K. Schillo, C.R. Weber, and K.A. Chapman. 2007. Natural communities of Michigan: classification and description. Report Number 2007-21. Michigan Natural Features Inventory. Lansing, MI. (http://web4.msue.msu.edu/mnfi/reports/2007-21_Natural_Communites_of_Michigan_Classification_and_Description.pdf). Accessed January 13, 2009.

Kratzer, C. and P. Brezonik. 1981. A Carlson type trophic state index for nitrogen in Florida lakes. Water Res. Bull. **17**:713-715.

Krug, E.C. and C.R. Frink. 1983. Acid rain on acid soil: a new perspective. Science **221**:520-25.

Lafrancois, B. Moraska and J. Glase. 2005. Aquatic studies in National Parks of the upper Great Lakes states: past efforts and future directions. Water Resources Division Technical Report, NPS/NRWRD/NRTR-2005/334. National Park Service, Denver, CO. (http://www1.nature.nps.gov/im/units/glkn/aquatic synthesis with links.zip). Accessed September 28, 2008.

Lake Carriers' Association. 2006. Map of U.S. and Canadian Great Lakes ports. Cleveland, OH.

Larson, G.J., T.E. Wallbom, J.S. Linker, and N.J. Waterson. 2000. Surficial Geology of Sleeping Bear Dunes National Lakeshore, Northwestern Lower Peninsula Michigan. Michigan State University (prepared in cooperation with USGS and the Michigan Geological Survey), EDMAPs 97-HQ-AG-01730, 98-HQ-AG-2099, and 99-HQ-AG-0113, 1:24,000 scale.

Last, L., R. Whitman, and P. Gerovac. 1995. Limnological variation of selected lakes of Sleeping Bear Dunes National Lakeshore, Michigan. Presented at the 1995 Michigan Academy of Science, Arts and Letters annual meeting. USGS, Lake Michigan Ecological Station. Porter, IN.

Last, L. and R. Whitman. 1996. Maintaining a water quality monitoring program at Sleeping Bear Dunes. Park Science **16** (3):19-21.

Latty, E.F. 2005. Stand-level patterns and ecosystem consequences of beech bark disease. Pages 36-42 *in* C.A. Evans, J.A. Lucas, and M.J. Twery. Beech Bark Disease: Proceedings of the Beech Bark Disease Symposium. Gen. Tech. Rep. NE-331. USDA-Forest Service, Newtown Square, PA. (http://treesearch.fs.fed.us/pubs/20356). Accessed September 28, 2008.

Lavis, D.S. 2005. A review of sea lamprey (*Petromyzon marinus*) control in Lake Michigan, 1960-2001. In T. Edsall and M. Munawar (eds.) State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Lavoie, C. and A. Saint-Louis. 2008. Can a small park preserve its flora? A historical study of Bic National Park, Quebec. Botany **86**:26-35.

Leahy, M.J. and K.S. Pregitzer. 2003. A comparison of presettlement and present-day forests in northeastern lower Michigan. Am. Midl. Nat. **149**:71-89.

Ledder, T. 2003. Water resources information and assessment report for the Great Lakes Inventory and Monitoring Network. GLKN/2003/05. National Park Service, Great Lakes Inventory and Monitoring Network, Ashland, WI.

Ledder, T. 2005. Water quality standards information for the Great Lakes Inventory and Monitoring Network. GLKN/2005/12. National Park Service, Great Lakes Inventory and Monitoring Network, Ashland, WI. 54806. (http://www1.nature.nps.gov/im/units/glkn/WQ%20Standards%20Report%202005.pdf). Accessed February 4, 2008.

Lee, D., C. Gilbert, C. Hocutt, R. Jenkins, D. McAllister, and J. Stauffer, Jr. 1980 et seq. Atlas of North American freshwater fishes. N.C. State Mus. Nat. History. Raleigh, NC.

Lee, Y., D.A. Hyde, and J. Legge. 2000. Special animal abstract for *Acris crepitans blanchardi* (Blanchard's cricket frog). Michigan Natural Features Inventory. Lansing, MI. 4 pp. (http://web4.msue.msu.edu/mnfi/abstracts/zoology/Acris_crepitans_blanchardi.pdf). Accessed April 8, 2008.

Leelanau County Board of Supervisors. 2005. The Leelanau general plan: policy guidelines for managing growth on the Leelanau Peninsula. Suttons Bay, MI. (http://www.leelanau.cc/government656254.asp#INLINK001). Accessed April 10, 2007.

Lehman, J.T. and C.E. Caceres. 1993. Food-web responses to species invasion by a predatory invertebrate: *Bythotrephes* in Lake Michigan. Limnol. and Oceanogr. **38**(**4**):879-891.

Lehrer, J.A., M. Bacou, B. Blankespoor, D. McCubbin, J. Sacks, C.R. Taylor, and D.A. Weinstein. 2007. Technical report on ozone exposure, risk and impact assessments for vegetation. Final Report, Contract No. 68-D-03-002, USEPA, Research Triangle Park, NC.

LeLievre, R. (ed.) 2006. Know your ships: guide to boats and boatwatching Great Lakes and St. Lawrence Seaway. Marine Publishing Company. Sault St. Marie, MI.

Lellinger, D.B. 1985. A field manual of the ferns and fern-allies of the United States and Canada. Smithsonian Institution Press. Washington, D.C.

Lewey, S., M. Pourzanjani, and P. Wybrow. 2001. Marine Environmental Issues in Maritime Education and Training. Pages 165-170 *in* Proceedings, International Association of Maritime Universities 2nd Annual Conference, Kobe, Japan. (http://www.plwmarine.co.uk/publications/kobe.htm). Accessed July 7, 2007.

Likens, G.E., C.T.Driscoll, and D.C. Buso. 1996. Long-term effects of acid rain: response and recovery of a forest ecosystem. Science **272**:244-46.

Lind, C.T. and R.J. Cottam. 1969. The submerged aquatics of University Bay: a study in eutrophication. Amer. Midl. Nat. **81**:353-369.

Linton, M. 1987. Analysis of habitat for invertebrates in the stream systems of Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

LMTC (Lake Michigan Technical Committee). 2000. Lake Michigan lakewide management plan. USEPA, Washington, D.C. (http://epa.gov/greatlakes/lakemich/index.html). Accessed September 11, 2007.

LMTC (Lake Michigan Technical Committee). 2006. Lake Michigan lakewide management plan (LaMP) 2006. USEPA, Washington, D.C. (http://www.epa.gov/glnpo/lakemich/2006/). Accessed March 26, 2007.

Lodge, D.M. and J.G. Lorman. 1987. Reductions in submerged macrophyte biomass and species richness by the crayfish *Orconectes rusticus*. Can. J. Fish. Aquat. Sci. **44**:591-597.

Lofgren, B.M., F.H. Quinn, A.H. Clites, R.A. Assel, A.J. Eberhardt, and C.L. Luukkonen. 2002. Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. J. Great Lakes Res. **28**(**4**): 537-554. (http://www.glerl.noaa.gov/pubs/fulltext/2002/20020020.pdf). Accessed February 25, 2008.

Lofgren, B.M. 2006. Land surface roughness effects on lake effect precipitation. J. Great Lakes Res. **32**:839–851. (http://www.glerl.noaa.gov/pubs/fulltext/2006/20060045.pdf). Accessed February 26, 2008.

Long, Z.T., W.P. Carson, and C.J. Peterson. 1998. Can disturbance create refugia from herbivores: an example with hemlock regeneration on treefall mounds. J. Torr. Bot. Soc. **125**(**2**):165-68.

Loope, W.L. and A.F. Arbogast. 2000. Dominance of an ~150-year cycle of sand-supply change in late Holocene Dune-building along the eastern shore of Lake Michigan. Quaternary Research **54**:414-422.

Loope, W.L. and J.B. Anderton. 1998. Human vs. lightning ignition of presettlement surface fires in coastal pine forests of the Upper Great Lakes. Am. Midl. Nat. **140**:206–218

Lovett, G.M., C.D. Canham, M.A. Arthur, K.C. Weathers, and R.D. Fitzhugh. 2006. Forest ecosystem responses to exotic pests and pathogens in eastern North America. BioSci. **56**(**5**):395-402.

Lovis, W.A. 1984. Sleeping Bear Dunes National Lakeshore: Archaeological Survey. NPS, Denver, CO.

Ludwig H., Jr. and J. Leitch. 1996. Interbasin transfer of aquatic biota via anglers' bait buckets. Fisheries **21**(**7**): 14-18.

Lundstrom, S. 2001. Appendix E: Park geological setting. In Ozaki, V. (ed). 2001. Geoindicators scoping report for Sleeping Bear National Lakeshore, May 29-30, 2001, Empire, MI. (http://www2.nature.nps.gov/geology/monitoring/ib4/reports/slbe_geoindicators_report.pdf). Accessed July 30, 2007.

MacKenzie, J.J. and M.T. El-Ashry. 1988. Ill winds: airborne pollution's toll on trees and crops. World Res. Instit. Publication.

Madenjian, C.P. 2005. Role of a lake-wide prey fish survey in understanding ecosystem dynamics and managing fisheries of Lake Michigan. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Madenjian, C.P., G.L. Fahnenstiel, T.H. Johengen, T.F. Nalepa, H.A. Vanderploeg, G.W. Fleischer, P.J. Schneeberger, D.M. Benjamin, E.B. Smith, J.R. Bence, E.S. Rutherford, D.S. Lavis, D.M. Robertson, D.J. Jude, and M.P. Ebener. 2002. Dynamics of the Lake Michigan food web, 1970-2002. Can. J. Fish Aquat. Sci **59**: 736-753. (http://www.glerl.noaa.gov/pubs/fulltext/2002/20020015.pdf). Accessed November 5, 2007.

Makarewicz, J.C. 2005. The pelagic phytoplankton community of Lake Michigan. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Malcolm, J.R. and L.F. Pitelka. 2000. Ecosystems and global climate change: a review of potential impacts on U.S. terrestrial ecosystems and biodiversity. Prepared for the Pew Center on Global Climate Change, Arlington, VA. (http://www.pewclimate.org/docUploads/env_ecosystems.pdf). Accessed February 25, 2008.

Maniero, T. and D. Pohlman. 2003. Air quality monitoring considerations for the Great Lakes Network parks. GLKN/2003/06. 54p. National Park Service, Great Lakes Inventory and Monitoring Network, Ashland, WI. (http://www1.nature.nps.gov/im/units/glkn/Great%20Lakes%20Air%20Quality%20Monitoring%20Considerations.pdf). Accessed September 4, 2007.

Manion, P.D. 1981. Tree disease concepts. Prentice-Hall, Inc. Englewood Cliffs, NJ.

Marion, J.L. and D.N. Cole. 1996. Spatial and temporal variation in soil and vegetation impacts on campsites. Ecological Applications **6**: 520-530.

Martin, H.M. 1955. Map of the surface formation of the southern peninsula of Michigan. Geol. Surv. Div. Publ. 49. Michigan Department of Conservation, Lansing, MI.

Matlack, G.R. 1994. Vegetation dynamics of the forest edge – trends in space and successional time. J. Ecol. **82**:113-23.

Mattson, W.J. and N.D. Addy. 1975. Phytophagous insects as regulators of forest primary production. Science **190**:512-22.

McCullough, D.G., R.L. Heyd, and J.G. O'Brien. 2001. Biology and management of beech bark disease. Ext. Bull. E-2746. Michigan State University, East Lansing, MI.

McCullough, D.G. and S.A. Katovich. 2004. Pest Alert – Emerald ash borer. NA-PR-02-04. USDA-Forest Service NE Area State & Private Forestry, Newtown Square, PA. (http://na.fs.fed.us/pubs/detail.cfm?id=4316). Accessed January 26, 2009.

MCGI (Michigan Center for Geographic Information). n.d. Lake Michigan Great Lakes bathymetry. State of Michigan. Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/?rel=thext&action=thmname&cid=13&cat=Great+Lakes+Bathymetry). Accessed April 30, 2007.

MCGI (Michigan Center for Geographic Information). 2006. Michigan Geographic Framework: ver 6b. State of Michigan. Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/). Accessed January 18, 2007.

McKenney, D.W., J.H. Pedlar, K. Lawrence, K. Campbell, and M.F. Hutchinson. 2007. Potential impacts of climate change on the distribution of North American trees. BioSci **57**(**11**):939-48.

McLaughlin, S.B. 1985. Effects of air pollution on forests. J.Air Poll. Control Assoc. **35**(**3**): 512-534.

McMacken, M. 2003. "Foam steams residents: Lather can be traced back to fish hatchery." Traverse City Record-Eagle, September 7, 2003. Traverse City, MI.

McMahon, S. 2007. Water quality and aquatic ecology program 2007, Sleeping Bear Dunes National Lakeshore. 12 pp. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

McNulty, S.A. and R.D. Masters. 2005. Changes to the Adirondack Forest: Implications of Beech Bark Disease on Forest Structure and Seed Production. Pages 52-57 *in* C.A. Evans, J.A. Lucas, and M.J. Twery. Beech Bark Disease: Proceedings of the Beech Bark Disease Symposium. Gen. Tech. Rep. NE-331. USDA-Forest Service, Newtown Square, PA. (http://treesearch.fs.fed.us/pubs/20356). Accessed September 28, 2008.

MDCH (Michigan Department of Community Health). 2007. 2007 Michigan family fish consumption guide. Lansing, MI. (http://www.michigan.gov/documents/FishAdvisory03_67354_7.pdf). Accessed January 22, 2008.

MDEQ (Michigan Department of Environmental Quality). 1996a. Critical Dune Area-Benzie County-BENZIE_CDA.shp. Lansing, MI.

MDEQ (Michigan Department of Environmental Quality). 1996b. Critical Dune Area-Leelanau County-LEELANAU_CDA.shp. Lansing, MI.

MDEQ (Michigan Department of Environmental Quality). 1998a. Michigan's major watersheds (map). Lansing, MI. (http://www.michigan.gov/deqhydrology). Accessed November 12, 2007.

MDEQ (Michigan Department of Environmental Quality). 1998b. Watershed Boundary Data. Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/). Accessed January 18, 2007.

MDEQ (Michigan Department of Environmental Quality), Office of the Great Lakes. 2002. Michigan's aquatic nuisance species state management plan update: prevention and control in Michigan waters. Lansing, MI. (http://www.deq.state.mi.us/documents/deq-ogl-ANSPlan2002.pdf). Accessed December 2005.

MDEQ (Michigan Department of Environmental Quality). 2003. Arcadia Bluffs litigation settled (online). Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3308_3323-74212--,00.html). Accessed February 11, 2008.

MDEQ (Michigan Department of Environmental Quality). Water Bureau. 2004a. Water withdrawals for self-supplied industrial manufacturing in Michigan. Lansing, MI. (http://www.deq.state.mi.us/documents/deq-wd-wurp-Industrial04.pdf). Accessed September 28, 2008.

MDEQ (Michigan Department of Environmental Quality). 2004b. Water withdrawals for golf course irrigation in Michigan 2004. Lansing, MI. (http://www.deq.state.mi.us/documents/deq-wd-wurp-golf04.pdf). Accessed September 18, 2007.

MDEQ (Michigan Department of Environmental Quality). 2005a. Authorization to discharge under the National Pollutant Discharge Elimination System-MDNR Platte River Hatchery. Permit No. MI0035769. Lansing, MI.

MDEQ (Michigan Department of Environmental Quality). Water Bureau. 2005b. Water quality maps for Michigan by county (online). Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3313_3675_3690-76500--,00.html). Accessed February 4, 2008.

MDEQ (Michigan Department of Environmental Quality). 2006a. Final Wetland Inventory, Benzie County. Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3313_3687-11178--,00.html). Accessed August 16, 2007.

MDEQ (Michigan Department of Environmental Quality). 2006b. Final Wetland Inventory, Leelanau County. Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3313_3687-11178--,00.html). Accessed August 16, 2007.

MDEQ (Michigan Department of Environmental Quality, Air Quality Division). 2006c. Michigan's 2005 annual air quality report. Lansing, MI. (http://www.deq.state.mi.us/documents/deq-aqd-air-reports-05AQReport.pdf). Accessed March 26, 2007.

MDEQ (Michigan Department of Environmental Quality). 2006d. Permit No. MIG140000-Ballast water control general permit-port operations and ballast water discharge. Lansing, MI. (http://www.deq.state.mi.us/documents/deq-water-npdes-generalpermit-MIG140000.pdf). Accessed July 17, 2007.

MDEQ (Michigan Department of Environmental Quality). 2006e. Water quality and pollution control in Michigan: 2006 Sections 303(d), 305(b), and 314 integrated report. Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3307_7255-12711--,00.html). Accessed September 10, 2007.

MDEQ (Michigan Department of Environmental Quality Water Bureau). 2006f. Water withdrawals for major water uses in Michigan. Lansing, MI. (http://www.deq.state.mi.us/documents/deq-wd-wurp-report04.pdf). Accessed October 29, 2007.

MDEQ (Michigan Department of Environmental Quality). 2007a. About beach monitoring in Michigan. (web page). Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3313_3686_3730-11005--,00.html). Accessed November 26, 2007.

MDEQ (Michigan Department of Environmental Quality). 2007b. Part 201 site list (online). Lansing, MI. (http://www.deq.state.mi.us/part201ss/). Accessed December 3, 2007.

MDEQ (Michigan Department of Environmental Quality). 2007c. Storage tank information database (online). Lansing, MI. (http://www.deq.state.mi.us/sid-web/Default.aspx). Accessed December 3, 2007.

MDEQ (Michigan Department of Environmental Quality). 2007d. Water withdrawal reports, data and graphics. Water Bureau, Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3313_3684_45331-72931--,00.html). Accessed October 29, 2007.

MDEQ (Michigan Department of Environmental Quality). 2007e. Wellogic-Statewide Wells. Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/). Accessed April 30, 2007.

MDEQ (Michigan Department of Environmental Quality). 2007f. Michigan online oil and gas information system. Lansing, MI. (http://ww2.deq.state.mi.us/mir/). Accessed December 31, 2007.

MDEQ (Michigan Department of Environmental Quality). 2007g. Municipal program (online). Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3313_3682_3716-24995--,00.html). Accessed January 8, 2008.

MDEQ (Michigan Department of Environmental Quality). 2007h. Community water supply reports (online). Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3313_3675_3691---,00.html). Accessed December 27, 2007.

MDEQ (Michigan Department of Environmental Quality). 2007i. Sand, gravel, peat, marl, and nonmetallic minerals (web page). Lansing, MI. (http://www.michigan.gov/deq/0,1607,7-135-3311_4111_18442-44960--,00.html). Accessed February 11, 2008.

MDEQ (Michigan Department of Environmental Quality). 2007j. A biological survey of the Platte River system, Benzie County, July 14-15, 2003. Staff Report MI/DEQ/WB-07/111. 12 pp. Lansing, MI.

MDEQ (Michigan Department of Environmental Quality). 2008a. Michigan water chemistry monitoring, Great Lakes tributaries, 1998-2005 report. MI/DEQ/WB-08/014. Lansing, MI. (http://www.michigan.gov/documents/deq/wb-swas-9805tribreport_222804_7.pdf). Accessed February 11, 2008.

MDEQ (Michigan Department of Environmental Quality) Water Bureau. 2008b. Water quality and pollution control in Michigan: 2008 sections 303(d), 305(b), and 314 integrated report. Lansing, MI. (http://www.michigan.gov/documents/deq/wb-swas-ir-final-2008report_230026_7.pdf). Accessed September 22, 2008.

MDNR (Michigan Department of Natural Resources). 1999. Land use/land cover 1978. Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/). Accessed March 15, 2007.

MDNR (Michigan Department of Natural Resources) Forest, Mineral, and Fire Management Division. 2001. Michigan (Lower Peninsula) GAP land stewardship coverage. Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/) Accessed January 23, 2007.

MDNR (Michigan Department of Natural Resources) Forest, Mineral, and Fire Management Division. 2003. IFMAP/GAP Lower Peninsula land cover. Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/). Accessed March 15, 2007.

MDNR (Michigan Department of Natural Resources). 2006. Michigan fishing guide. Michigan DNR. Lansing, MI. (http://www.michigan.gov/dnr/0,1607,7-153-10364-137191--,00.html). Accessed September 24, 2007.

MDNR (Michigan Department of Natural Resources). 2007a. Platte River State Fish Hatchery (web page) Lansing, MI. (http://www.michigan.gov/dnr/1,1607,7-153-10364_10949_11241-22491--,00.html). Accessed November 26, 2007.

MDNR (Michigan Department of Natural Resources). 2007b. Data by lake and port: charter fishing data-Leland. (online) Lansing, MI. (http://www.michigan.gov/documents/dnr/TargetedHarvestLelandSite116CB2006_190158_7.pdf). Accessed December 17, 2007.

MDNR (Michigan Department of Natural Resources). 2007c. Rusty crayfish (*Orconectes rusticus*) (online). Lansing, MI. (http://www.michigan.gov/dnr/0,1607,7-153-10370_12145_12203-33021--,00.html). Accessed December 10, 2007.

MDNR (Michigan Department of Natural Resources). 2007d. Designated trout streams for the state of Michigan (FO 210.07). Lansing, MI. (http://www.michigan.gov/documents/dnr/FO-210-07_182400_7.pdf). Accessed February 4, 2008.

MDNR (Michigan Department of Natural Resources). 2008a. 2007 consent decree (web page). Lansing, MI. (http://www.michigan.gov/dnr/0,1607,7-153-10364_47864---,00.html). Accessed February 11, 2008.

MDNR (Michigan Department of Natural Resources) Forest, Mineral, and Fire Management Division. 2008b. 2008 Michigan forest health highlights. Lansing, MI. (http://www.michigan.gov/documents/dnr/2008ForestHealthHighlights_262764_7.pdf). Accessed February 9, 2009.

MEC and MLCVEF (Michigan Environmental Council and Michigan League of Conservation Voters Education Fund). 2007. 2007-2008 Michigan Environmental Briefing Book. Lansing, MI. (http://www.mecprotects.org/07briefingbook.pdf). Accessed October 16, 2007.

MEDC (Michigan Economic Development Corporation). 2007a. Benzie County-Economy. (online). Lansing, MI. (http://www.michigan.org/medc/miinfo/places/BenzieCounty/?section=economy). Accessed September 17, 2007.

MEDC (Michigan Economic Development Corporation). 2007b. Leelanau County-Economy. (online). Lansing, MI. (http://www.michigan.org/medc/miinfo/places/LeelanauCounty/?section=economy). Accessed September 17, 2007.

Metcalfe, C.D., X. Miao, B.G. Koenig, and J. Struger. 2003. Distribution of acidic and neutral drugs in surface waters near sewage treatment plants in the Lower Great Lakes, Canada. Environmental Toxicology and Chemistry **22**(**12**): 2881-2889.

Metzger, F. and J. Schultz. 1981. Spring ground layer vegetation 50 years after harvesting in northern hardwood forests. Am. Midl. Nat. **105**:44-50.

Metzger, F. and J. Schultz. 1984. Understory response to 50 years of management of a northern hardwood forest in Upper Michigan. Am. Midl. Nat. **112**:209-23.

Michigan Groundwater Inventory and Mapping Project. 2005a. Water table grid. East Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/). Accessed April 30, 2007.

Michigan Groundwater Inventory and Mapping Project. 2005b. Water table contours. East Lansing, MI. (http://www.mcgi.state.mi.us/mgdl/). Accessed April 30, 2007.

Michigan Sea Grant. 2006. Guidelines for Clean Boats, Clean Waters, Michigan's aquatic invasive species volunteer program, 2006 edition. (online). East Lansing, MI. (http://www.miseagrant.umich.edu/downloads/ais/CBCW-handbook.pdf). Accessed January 15, 2008.

Michigan Sea Grant. 2007a. Type-E botulism confirmed in waterfowl deaths. (online) East Lansing, MI. (http://miseagrant.umich.edu/news/2007/16-avian-botulism.html). Accessed December 11, 2007.

Michigan Sea Grant. 2007b. Upwellings online edition, April 2007. East Lansing, MI. (http://www.miseagrant.umich.edu/upwellings/issues/pdf/April07-upwellings.pdf). Accessed January 7, 2008.

Michigan State Climatologist's Office. n.d. Climate of Maple City. East Lansing, MI. (http://climate.geo.msu.edu/stations/5097/). Accessed May 15, 2007.

Michigan Underwater Preserve Council. 2004. Manitou Passage underwater preserve (online). St. Ignace, MI. (http://www.michiganpreserves.org/manitou.htm). Accessed July 8, 2007.

Millar, C.I. and W.B. Woolfenden. 1999. The role of climate changes in interpreting historical variability. Ecol. Appl. **9**:1207-16.

Miller, S.G., S.P. Bratton and J. Hadidian. 1992. Impacts of white-tailed deer on endangered and threatened vascular plants. Nat. Areas. J. **12**(**2**):67-73.

Miller, S.M., C.W. Sweet, J.V. DePinto, and K.C. Hornbuckle. 2000. Atrazine and nutrients in precipitation: results from the Lake Michigan mass balance study. Environ. Sci. Technol **34**(**1**): 55-61.

Minnesota Sea Grant. 2006. A field guide to aquatic exotic plants and animals. Duluth, MN. (http://www.seagrant.umn.edu/exotics/fieldguide.html). Accessed December 11, 2007.

Minnesota Sea Grant. 2007. Zebra mussels threaten inland waters: an overview. Duluth, MN. (http://www.seagrant.umn.edu/exotics/zmoverview.html). Accessed December 10, 2007.

Mladenoff, D.J. and F. Stearns. 1993. Eastern hemlock regeneration and deer browsing in the northern Great Lakes region: a re-examination and model simulation. Cons. Biol **7**:889-900.

MNFI (Michigan Natural Features Inventory). 2000. Lake sturgeon. Michigan Natural Features Inventory. Lansing, MI. (http://web4.msue.msu.edu/mnfi/abstracts/aquatics/acipenser_fulvescens.pdf). Accessed November 6, 2007.

MNFI (Michigan Natural Features Inventory). 2004. Open dunes: community abstract. Michigan Natural Features Inventory. Lansing, MI. (http://web4.msue.msu.edu/mnfi/abstracts/ecology/Open_dunes.pdf). Accessed September 18, 2007.

MNFI (Michigan Natural Features Inventory). 2006. Michigan's natural communities: draft features and descriptions. Michigan Natural Features Inventory. Lansing, MI. (http://web4.msue.msu.edu/mnfi/data/MNFI_Natural_Communities.pdf). Accessed September 19, 2007.

MNFI (Michigan Natural Features Inventory). 2007. Rare Species Explorer (Web Application). *Castanea dentata* (American Chestnut). Michigan Natural Features Inventory, Lansing, MI. (http://web4.msue.msu.edu/mnfi/explorer). Accessed Feb 9, 2009.

MNFI (Michigan Natural Features Inventory). 2008. Michigan's special animals. Michigan Natural Features Inventory. Lansing, MI. (http://web4.msue.msu.edu/mnfi/data/special_animals_list_categorized.pdf). Accessed December 22, 2008.

Momot, W.T. 1992. Further range extensions of the crayfish *Orconectes rusticus* in the Lake Superior basin of northwestern Ontario. Can. Field-Nat. **106**(**3**):397-399.

Montgomery, M.F., A.F. Lagalante, and K.S. Shields. 2005. Resistance of hemlock to *Adelges tsugae*: promising new developments. In B. Onken and R. Reardon (compilers). Third symposium on hemlock woolly adelgid in the eastern United States, Asheville, North Carolina, February 1-3, 2005. Northeastern Center for Forest Health Research, USDA-Forest Service, Newtown Square, PA. (http://na.fs.fed.us/fhp/hwa/pub/2005_proceedings/montgomery.pdf). Accessed October 6, 2008.

Morris, W.F., C.A. Pfister, S. Tuljapurkar, C.V. Haridas, C.L. Boggs, M.S. Boyce, E.M. Bruna, D.R. Church, T. Coulson, D.F. Doak, S. Forsyth, J. Gaillard, C.C. Horvitz, S. Kalisz, B.E. Kendall, T.M. Knight, C.T. Lee, and E.S. Menges. 2008. Longevity can buffer plant and animal populations against changing climatic variability. Ecology **89**:19-25.

Mortsch, L., J. Ingram, A. Hebb, and S. Doka (eds.). 2006. Great Lakes coastal wetland communities: vulnerability to climate change and response to adaptation strategies. Final report submitted to the Climate Change Impacts and Adaptation Program, Natural Resources Canada. Environment Canada and the Department of Fisheries and Oceans, Toronto, Ontario. 251 pp. + appendices. (http://www.fes.uwaterloo.ca/research/aird/wetlands/index_files/page0012.htm). Accessed March 17, 2008.

MSU (Michigan State University). n.d. MSU Agricultural Weather Office (online). East Lansing, MI. (http://www.agweather.geo.msu.edu/). Accessed September 4, 2007.

MSU (Michigan State University) Remote Sensing and Geographic Information Science Research and Outreach Services. 2009. Emerald ash borer viewer (online). East Lansing, MI. (http://eabviewer92.rsgis.msu.edu/). Accessed February 9, 2009.

MTESP (Michigan Turfgrass Environmental Stewardship Program). 1999. Michigan turfgrass environmental stewardship program overview. (online). Michigan Turfgrass Foundation, Lansing, MI. (http://mtesp.org/uploads/modules/Section2ProgramOverview-August06.pdf). Accessed September 18, 2007.

Muirhead, J.R., B. Leung, C. Overdijk, D. Kelly, K. Nandakumar, K. Merchant ,and H. MacIsaac. 2006. Modeling local and long-distance dispersal of invasive emerald ash borer *Agrilus planipennis* (Coleoptera) in North America. Divers. and Distrib. **12**(**1**):71-79.

Munawar, M., I.F. Munawar, M. Fitzpatrick, and D. Lynn. 2005. A preliminary assessment of the planktonic food web in Lake Michigan. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Murphy, P.C. 2003. Water quality and aquatic ecology at Sleeping Bear Dunes National Lakeshore: 2003 year end review. NPS, Sleeping Bear Dunes National Lakeshore. Empire, MI.

Murphy, P.C. 2004a. Water quality and aquatic ecology at Sleeping Bear Dunes National Lakeshore: 2004 year end review. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Murphy, P. 2004b. Water Quality (map). NPS (National Park Service). Sleeping Bear Dunes National Lakeshore. Accessed from NPS DataStore (http://science.nature.nps.gov/nrdata/index.cfm) January 18, 2007.

NADP (National Atmospheric Deposition Program). 2007a. NADP/NTN monitoring location MI53 annual data. Online. Champaign, IL. (http://nadp.sws.uiuc.edu/sites/siteinfo.asp?id=MI53&net=NTN). Accessed June 22, 2007.

NADP (National Atmospheric Deposition Program). 2007b. NADP/NTN monitoring location MI29 annual data. Online. Champaign, IL. (http://nadp.sws.uiuc.edu/sites/siteinfo.asp?net=NTN&id=MI29) Accessed June 22, 2007.

Nalepa, T.F., D.W. Schloesser, S.A. Pothoven, D.W. Hondorp, D.L. Fanslow, M.L. Tuchman, and G.W. Fleischer. 2001. Note: first finding of the amphipod *Echinogammarus ischnus* and the mussel *Dreissena bugensis* in Lake Michigan. J. Great Lakes Res. **27**(**3**):384-391. (http://www.sgnis.org/publicat/papers/naleschl.pdf). Accessed December 10, 2007.

Nalepa, T.F., D.L. Fanslow, G.A. Lang, and S.A. Ruberg. 2005. Recent trends in benthic macroinvertebrate communities in Lake Michigan. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Nalepa, T.F., D.L. Fanslow, A.J. Foley III, G.A. Lang, B.J. Eadie, and M.A. Quigley. 2006. Continued disappearance of the benthic amphipod *Diporeia* spp. in Lake Michigan: is there evidence for food limitation? Can. J. Fish. Aquat. Sci. **63**: 872–890. (http://www.glerl.noaa.gov/pubs/fulltext/2006/20060003.pdf). Accessed September 25, 2007.

NAPAP (National Acid Precipitation Assessment Program). 2005. National Acid Precipitation Assessment Program Report to Congress: an integrated assessment. Washington, D.C. (http://www.esrl.noaa.gov/csd/AQRS/reports/napapreport05.pdf). Accessed July 15, 2008.

NCDC (National Climatic Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce). 2004. Climatography of the United States No. 20, 1971-2000. Asheville, NC. (http://cdo.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl). Accessed May 15, 2007.

Neff, B.P., A.R. Piggott, and R.A. Sheets. 2005. Estimation of shallow ground-water recharge in the Great Lakes basin. Scientific Investigations Report 2005-5284. USGS, Reston, VA. (http://pubs.usgs.gov/sir/2005/5284/). Accessed August 14, 2007.

Nevers, M.B. and R.L. Whitman. 2004. Characterization and comparison of phytoplankton in selected lakes of five Great Lakes area National Parks. Aquat. Ecosyst. Health Manage. **7**(**4**):515-528.

NGDC and GLERL (National Geophysical Data Center and Great Lakes Environmental Research Laboratory). 2006. Lake Michigan bathymetry. Ann Arbor, MI. (http://gis.glin.net/ogc/services.php#lake_michigan_bathymetry). Accessed May 2, 2007.

Nichols, G.E. 1935. The hemlock-white pine-northern hardwood region of eastern North America. Ecology **16**(**3**):403-14.

Nichols, S.J. 1993. Appendix A: Life history and ecological requirements of the Zebra Mussel-North American Experience through 1992. Pages 24-27 *in* Reid, D. F. et al. Zebra-Mussel-Specific Containment Protocols. Contribution No. 890. NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI.

Nichols, S., E. Crawford, J. Amberg, G. Kennedy, G. Black, and J. Allen. 2001. Status of freshwater unionid populations at Pictured Rocks National Lakeshore, 1999-2000. Final report to National Park Service, Pictured Rocks National Lakeshore, U.S. Geological Survey, Great Lakes Science Center, Ann Arbor, MI.

Nichols, S.J., J. Allen, G. Black, G. Kennedy, and J.M. Craig. 2004. Status of freshwater unionid populations at Sleeping Bear Dunes National Lakeshore, 2000-2003. 102pp. USGS, Ann Arbor, MI.

Niese, J.N. and T.F. Strong. 1992. Economic and tree diversity trade-offs in managed northern hardwoods. Can. J. For. Res. **22**:1807-13.

NOAA (National Oceanic and Atmospheric Administration) National Center for Research on Aquatic Invasive Species. 2006a. Great Lakes AIS list (online). Ann Arbor, MI. (http://www.glerl.noaa.gov/res/Programs/ncrais/projects.html). Accessed November 27, 2007.

NOAA (National Oceanic and Atmospheric Administration) Great Lakes Environmental Research Laboratory. 2006b. The impact of *Diporeia* spp. decline on the Great Lakes fish community. 2 pp. Ann Arbor, MI. (http://www.glerl.noaa.gov/pubs/brochures/dipoflyer/dipo.pdf). Accessed December 27, 2008.

NOAA (National Oceanic and Atmospheric Administration). Office of Coast Survey. 2007a. United States Coast Pilot 6, 37th edition. Washington, D.C. (http://nauticalcharts.noaa.gov/nsd/coastpilot6.htm). Accessed July 8, 2007.

NOAA (National Oceanic and Atmospheric Administration). Office of Coast Survey. 2007b. 14901 Lake Michigan (electronic navigation chart). Washington, D.C. (http://chartmaker.ncd.noaa.gov). Accessed March 22, 2007.

NOAA (National Oceanic and Atmospheric Administration). Office of Coast Survey. 2007c. 14902 North End of Lake Michigan including Green Bay (electronic navigation chart). Washington, D.C. (http://chartmaker.ncd.noaa.gov). Accessed March 22, 2007.

NOAA (National Oceanic and Atmospheric Administration). 2007d. Great Lakes commercial fishery landings database. (online). Silver Spring, MD. (http://www.st.nmfs.noaa.gov/st1/commercial/landings/gl_query.html). Accessed December 11, 2007.

NOAA (National Oceanic and Atmospheric Administration). 2008. Water levels of the Great Lakes (2 pp). Ann Arbor, MI. (http://www.glerl.noaa.gov/pubs/brochures/lakelevels/lakelevels.pdf). Accessed February 25, 2008.

NPS (National Park Service). 1997a. Sleeping Bear Dunes NL Roads (slbeardl). NPS Midwest Field Area. Accessed from NPS DataStore (http://science.nature.nps.gov/nrdata/index.cfm) January 18, 2007.

NPS (National Park Service). 1997b. Baseline water quality data inventory and analysis: Sleeping Bear Dunes National Lakeshore. Technical Report NPS/NRWRD/NRTR-97/106. NPS, Water Resources Division. Fort Collins, CO. (http://nrdata.nps.gov/SLBE/nrdata/water/baseline_wq/docs/SLBEWQAA.pdf). Accessed October 2, 2007.

NPS (National Park Service). 1999a. Boundary Map. Sleeping Bear Dunes National Lakeshore. Accessed from NPS DataStore (http://science.nature.nps.gov/nrdata/index.cfm) January 18, 2007.

NPS (National Park Service). 1999b. Land status map ("Tract Map"). Sleeping Bear Dunes National Lakeshore. Accessed from NPS DataStore (http://science.nature.nps.gov/nrdata/index.cfm) January 18, 2007.

NPS (National Park Service). 1999c. Vegetation Map. Sleeping Bear Dunes National Lakeshore. Accessed from NPS DataStore (http://science.nature.nps.gov/nrdata/index.cfm) January 18, 2007.

NPS (National Park Service). 2001a. Preliminary draft-General Management Plan for Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

NPS (National Park Service). 2001b. Historic Buildings and Structures. Sleeping Bear Dunes National Lakeshore. Accessed from NPS DataStore (http://science.nature.nps.gov/nrdata/index.cfm) January 18, 2007.

NPS (National Park Service). 2002. Pictured Rocks National Lakeshore personal watercraft use environmental assessment. NPS, Pictured Rocks National Lakeshore, Munising, MI.

NPS (National Park Service). 2004a. Sleeping Bear Dunes National Lakeshore Fire Management Plan Environmental Assessment. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

NPS (National Park Service). 2004b. The Homestead wastewater disposal environmental assessment. Sleeping Bear Dunes National Lakeshore, Empire, MI.

NPS (National Park Service). 2004c. Research prospectus: Biomonitoring prospects for diatoms and paleolimnology in the Western Great Lakes National Parks. Memo to Bill Route, Great Lakes Network Coordinator, and Joan Elias, Great Lakes Network Aquatic Ecologist, from Mark Edlund, Associate Scientist, St. Croix Watershed Research Station, Daniel Engstrom, Director, St. Croix Watershed Research Station, and Brenda Moraska Lafrancois, Aquatic Ecologist, National Park Service. (http://www.nps.gov/slbe/naturescience/upload/Biomonitoring%20proposal.pdf). Accessed December 15, 2008.

NPS (National Park Service). 2005a. Beach Water Monitoring at Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI. 5 pp.

NPS (National Park Service). 2005b. Finding of no significant impact: the Homestead wastewater disposal. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

NPS (National Park Service). 2006a. Map of cultural resources. NPS. (http://www.nps.gov/slbe/historyculture/culturalresourcesmap.htm). Accessed May 18, 2007.

NPS (National Park Service). 2006b. Compendium listing of special regulations for Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI. (http://www.nps.gov/slbe/parkmgmt/upload/2006%20Superintendent's%20Compendium.pdf). Accessed July 23, 2007.

NPS (National Park Service). 2006c. Sleeping Bear Dunes National Lakeshore-nonnative species (U.S. National Park Service). (web page). NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI. (http://www.nps.gov/slbe/naturescience/nonnativespecies.htm). Accessed November 27, 2007.

NPS (National Park Service). 2006d. River use counts 2006. 3pp. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

NPS (National Park Service). 2006e. Special mandates, Sleeping Bear Dunes National Lakeshore, July 2006. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI. (http://www.nps.gov/slbe/parkmgmt/upload/sp_mandates_072606.pdf). Accessed February 11, 2008.

NPS (National Park Service). 2007. Public use statistics office (online). Washington, D.C. (http://www2.nature.nps.gov/stats/). Accessed May 17, 2007.

NPS (National Park Service). 2008a. Statistical abstract. NPS, Washington, D.C. (http://www2.nature.nps.gov/stats/abst2006.pdf). Accessed November 17, 2008.

NPS (National Park Service). 2008b. Sleeping Bear Dunes National Lakeshore, Draft General Management Plan/Wilderness Study/Environmental Impact Statement-April 2008. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI. (http://parkplanning.nps.gov/document.cfm?parkId=165&projectId=14651&documentID=22818). Accessed April 28, 2008.

NPSpecies. 2007. The National Park Service Biodiversity Database. Secure online version. (https://science1.nature.nps.gov/npspecies/web/main/start) (park list). Accessed June 8, 2007.

NRCS (Natural Resources Conservation Service). n.d. Climate Information (online). East Lansing, MI. (http://www.mi.nrcs.usda.gov/technical/engineering/climate.html). Accessed August 14, 2007.

NRCS (Natural Resources Conservation Service). 2006a. Digital general soil map of United States. United States Department of Agriculture. Fort Worth, TX. (http://SoilDataMart.nrcs.usda.gov). Accessed September 14, 2007.

NRCS (Natural Resources Conservation Service) Pest Management Team. 2006b. United States Department of Agriculture. Pesticide Properties Database. Amherst, MA. (http://www.wsi.nrcs.usda.gov/products/W2Q/pest/winpst.html#pst%20ppd). Accessed August 29, 2007.

NRCS (Natural Resources Conservation Service) Soil Survey Staff. 2007a. Web Soil Survey (online). United States Department of Agriculture. Fort Worth, TX. (http://websoilsurvey.nrcs.usda.gov/). Accessed October 15, 2007.

NRCS (Natural Resources Conservation Service) 2007b. Soil survey geographic database. United States Department of Agriculture. Fort Worth, TX. (http://SoilDataMart.nrcs.usda.gov). Accessed January 17, 2007.

NRCS (Natural Resources Conservation Service). 2008. The PLANTS Database National Plant Data Center, Baton Rouge, LA. (http://plants.usda.gov). Accessed July 28, 2008.

Nuzzo, V.A. 1991. Experimental control of garlic mustard (*Alliaria petiolata*) in northern Illinois using fire, herbicide and cutting. Nat. Areas J. **11**(**3**):158-67.

NWHC (National Wildlife Health Center). 2007. USGS National Wildlife Health Center quarterly wildlife mortality report, April 2007 to June 2007. (online). Madison, WI. (http://www.nwhc.usgs.gov/publications/quarterly_reports/2007_qtr_2.jsp). Accessed December 11, 2007.

NWMCOG (Northwest Michigan Council of Governments). 2004. Benchmarks Northwest quality of life indicators and community assessment tool: growth and change report. Traverse City, MI. (http://www.nwm.org/downloads/growth_and_change.pdf). Accessed April 10, 2007.

NWMCOG (Northwest Michigan Council of Governments). 2006. 2007 economic forecast for the 5-county region of Antrim, Benzie, Grand Traverse, Kalkaska, and Leelanau Counties. Prepared for the Traverse City Area Chamber of Commerce. Traverse City, MI. (http://www.tcchamber.org/economic/forecast.php). Accessed April 10, 2007.

NWMOWTF (Northwest Michigan Onsite Wastewater Task Force). 2006. Water to waste. Traverse City, MI. (http://www.michigan-onsitewastewater.org/watertowaste/page4.jpg). Accessed October 16, 2007.

NWMOWTF (Northwest Michigan Onsite Wastewater Task Force). 2007. 2007 SWQIF project plan for Benzonia and Lake townships, MI. (online). Traverse City, MI. (http://www.michiganonsite.org/contents.html). Accessed October 16, 2007.

Ocean Conservancy. 2001. Good mate recreational boating and marina manual. The Ocean Conservancy, Washington, D.C.

O’Gorman, R., O. Gorman, and D. Bunnell. 2007. Great Lakes prey fish populations: a cross-basin view of status and trends in 2006. USGS Great Lakes Science Center, Ann Arbor, MI. (http://www.glsc.usgs.gov/_files/reports/2006xbasin_preyfish.pdf). Accessed November 5, 2007.

Ohman, L.F. and D.F. Grigal. 1990. Spatial and temporal patterns of sulfur and nitrogen in wood of trees across the north central United States. Can. J. For. Res. **20**:508-13.

O’Keefe, D. 2008. Red flags analysis and the future of Lake Michigan salmon. West Michigan Angler’s News **2**(**2**). Michigan Sea Grant. Grand Haven, MI. (http://miseagrant.umich.edu/sw/images/SWNewsletterMay08.pdf). Accessed August 4, 2008.

Olcott, P.G. 1992. Ground water atlas of the United States: Iowa, Michigan, Minnesota, Wisconsin. Hydrologic Investigations Atlas HA 730-J. USGS, Reston, VA. (http://capp.water.usgs.gov/gwa/ch_j/index.html). Accessed January 29, 2008.

Olson, C. 2007. “Empire sewer plan is rejected.” The Leelanau Enterprise, August 1, 2007. (http://www.leelanaunews.com/blog/2007/08/01/empire-sewer-plan-is-rejected/). Accessed December 3, 2007.

Olson, J.S. 1958. Rates of succession and soil changes on southern Lake Michigan sand dunes. Bot. Gazette **119**(**3**):125-49.

Orwig, D.A. and D.R. Foster. 2000. Stand, landscape and ecosystem analyses of hemlock woolly adelgid outbreaks in southern New England: an overview. Pages 123-125 *in* K.A. McManus, K.S. Shields, and D.R. Souto (eds.) Proceedings: symposium on sustainable management of hemlock ecosystems in eastern North America. Gen. Tech. Rep. NE-267. USDA-Forest Service Northeastern Research Station, Newtown Square, PA. (http://www.treesearch.fs.fed.us/pubs/4141). Accessed September 30, 2008.

Orwig, D.A., D.R. Foster, and D.L. Mausel. 2002. Landscape patterns of hemlock decline in New England due to the introduced hemlock woolly adelgid. Journal of Biogeography **29**: 1475-1487.

Orwig, D.A., R.C. Cobb, A.W. D’Amato, M.L. Kizlinski, and D.R. Foster. 2008. Multi-year ecosystem response to hemlock woolly adelgid infestation in southern New England forests. Can. J. For. Res. **38**:834-43.

Ozaki, V. (ed.) 2001. Geoindicators scoping report for Sleeping Bear Dunes National Lakeshore: strategic planning goal IB4. May 29-30, 2001, Empire, MI. (http://www2.nature.nps.gov/geology/monitoring/ib4/reports/slbe_geoindicators_report.pdf). Accessed December 27, 2007.

Page, D.D. and M.J. Mitchell. 2008. The influence of basswood (*Tilia americana*) and soil chemistry on soil nitrate concentration in a northern hardwood forest. Can. J. For. Res. **38**:667-76.

Palik, D.J. and P.G. Murphy. 1990. Disturbance versus edge effects in sugar maple/beech forest fragments. For. Ecol. Mngt. **32**:187-202.

Parker, T.H, B.M. Stansberry, D.D. Becker, and P.S. Gipson. 2005. Edge and area effects on the occurrence of migrant forest songbirds. Cons. Biol. **19**:1157-67.

Parsons, M.J., S.S.Yohn, D.T. Long, L.C. Patino, and K.A. Stone. ca. 2004. Inland lakes sediment trends: mercury sediment analysis results for 27 Michigan lakes. MI/DEQ/WB/-06/090. 43 pp. Aqueous and Environmental Geochemical Laboratories, Michigan State University, East Lansing, MI. (http://www.deq.state.mi.us/documents/deq-wb-swas-sedimenttrend9904finalreport.pdf). Accessed September 22, 2008.

Pavlovic, N., K.M. Quinlan, and T. Ford. 2005. Developing rare and exotic plant geographic information system databases for Indiana Dunes and Sleeping Bear Dunes National Lakeshores. GLKN/2005/17. Great Lakes Inventory and Monitoring Network, Ashland, WI. (http://science.nature.nps.gov/im/units/glkn/INDU%20and%20SLBE%20rare%20and%20exotic%20plants%20(publicwithExotics).pdf). Accessed November 27, 2007.

Peet, R. and O.L. Loucks, 1977. A gradient analysis of southern Wisconsin forests. Ecology **58**:485-499.

Peloquin, R.L. and R.D. Hiebert. 1999. The effects of black locust (*Robinia pseudoacacia* L.) on species diversity and composition of black oak savanna/woodland communities. Nat. Areas J. **19**:121-31.

Pendleton, E. 2006. Slbe_shore- Coastal change potential (CPI) assessment of Sleeping Bear Dunes National Lakeshore. USGS, Woods Hole, MA. (http://woodshole.er.usgs.gov/project-pages/nps-cvi/parks/slbe.htm). Accessed December 29, 2006.

Pendleton, E.A., E.R. Thieler, and S.J. Williams. 2007. Coastal change-potential assessment of Sleeping Bear Dunes, Indiana Dunes, and Apostle Islands National Lakeshores to lake-level changes: U.S. Geological Survey Open-File Report 2005-1249, Web Only. (http://pubs.usgs.gov/of/2005/1249/images/pdf/report.pdf). Accessed February 26, 2008.

Perry, D.A. 1994. Forest ecosystems. John Hopkins Univ. Press, Baltimore. 649 pp.

Peterson, R.T. and M. McKenny. 1968. A field guide to wildflowers. Houghton Mifflin. Boston, MA.

Pickett, S.T.A. and P.S. White, (eds). 1985. The ecology of natural disturbance and patch dynamics. Elsevier Science & Technology.

Poff, N. 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. Freshwater Biology **36**:71-91.

Poland, T.M and D.G. McCullough. 2006. Emerald ash borer: invasion of the urban forest and the threat to North America's ash resource. J. For. **104**(**4**):118-122.

Post, E. and N. C. Stenseth. 1999. Climatic variability, plant phenology and northern ungulates. Ecology **80**:1332-39.

Pothoven, S.A., I.A. Grigorovich, G.L. Fahnenstiel, and M.D. Balcer. 2007. Note: Introduction of the Ponto-Caspian Bloody-red mysid *Hemimysis anomala* into the Lake Michigan basin. J. Great Lakes. Res. **33**:285-292. (http://www.glerl.noaa.gov/pubs/fulltext/2007/20070007.pdf). Accessed January 15, 2008.

Pranger, H. ca. 2005a. Evaluation & recommendations for Platte River mouth dredging, Sleeping Bear Dunes National Lakeshore, Michigan. NPS Natural Resource Program Center, Geologic Resources Division.

Pranger, H. ca. 2005b. Evaluation of the sensitivity of dunes to foot traffic, Sleeping Bear Dunes National Lakeshore, Michigan. NPS Natural Resource Program Center, Geologic Resources Division.

Public Law 108–229: An act to provide for expansion of Sleeping Bear Dunes National Lakeshore.(118 Stat. 645; Date 5/28/04). Text from the Library of Congress (http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=108_cong_public_laws&docid=f:publ229.108.pdf) . Accessed January 16, 2009.

Quinby, P.A. 1991. Self-replacement in old-growth white pine forests of Temagami, Ontario. For. Ecol. Manage. **41**:95-109.

Quinlan, H., M. Dryer, G. Czypinski, J. Pyatskowit, and J. Krajniak. 2007. Strategic approach to problem identification and monitoring of aquatic invasive species within Great Lakes Inventory and Monitoring Network park units. U.S. Fish and Wildlife Service, Ashland Fishery Resources Office, Ashland, Wisconsin, for National Park Service, Great Lakes Inventory and Monitoring Network, Ashland, Wisconsin. GLKN/2007/08. (http://science.nature.nps.gov/im/units/GLKN/reports/USFWS_AIS_Final_Report_20070927.pdf). Accessed November 18, 2008.

Quinn, F.H. 1977. Annual and seasonal flow variations through the Straits of Mackinac. Water Resources Res. **13**(**1**): 137-144.

Rainey, S.M, K.J. Nadelhoffer, W.L. Silver, and M.R. Downs. 1999. Effects of chronic nitrogen additions on understory species in a red pine plantation. Ecol. Appl. **9**:949-57.

Rayburn, T., A. Whelan, M. Jaster, and R. Wingrove. 2004. Net environmental benefit analysis for Isle Royale National Park. Final report. Proceedings from the Workshop held January 6-8, 2004 in Duluth, Minnesota. Great Lakes Commission, Ann Arbor, MI. (http://www.glc.org/irps/irps/docs/NEBA-final.pdf). Accessed July 17, 2007.

Reavie, E.D., R.P. Axler, G.V. Sgro, N.P. Danz, J.C. Kingston, A.R. Kireta, T.N. Brown, T.P. Hollenhorst, and M.J. Ferguson. 2006. Diatom-based weighted-averaging transfer functions for Great Lakes coastal water quality: relationships to watershed characteristics. J. Great Lakes Res. **32**: 321-347.

Rebertus, A.J., S.R. Shifley, R.H. Richards, and L.M. Roovers. 1997. Ice storm damage to an old-growth oak-hickory forest in Missouri. Amer. Midl. Nat. **137**:48-61.

Reid, S.E. and J.L. Marion. 2005. A comparison of campfire impacts and policies in seven protected areas. Env. Management **36**(**1**): 48-58.

Remaley, T. 2005. Fact sheet: Eurasian watermilfoil (online). Plant Conservation Alliance, Washington, D.C. (http://www.nps.gov/plants/alien/fact/pdf/mysp1.pdf). Accessed August 7, 2006.

Richardson, C.J. 2000. Freshwater wetlands. In M.G. Barbour and W.D. Billings (eds.) North American terrestrial vegetation. 2nd edition. Cambridge Univ. Press.

Richmond, G.M. and D.S. Fullerton (eds.), with W.R. Farrand, D.M. Mickelson, W.R. Cowan, and J.E. Goebel. 2001. Quaternary geologic map of the Lake Superior 4 degrees x 6 degrees quadrangle, United States and Canada (1984 I 1420(NL-16)). USGS, Reston, VA. (http://pubs.usgs.gov/imap/i-1420/nl-16/). Accessed July 30, 2007.

Roberts, M.R. 2004. Response of the herbaceous layer to natural disturbance in North American forests. Can. J. Bot. **82**:1273-83.

Rodeheffer, I.A. and J. Day. 1950. A fisheries survey report of Glen Lake, Leelanau County, Michigan (Fisheries Research Report: 1251). MDNR, Fisheries Division. Lansing, MI. (http://dev.umdl.umich.edu/cgi/t/text/text-idx?c=fishery;cc=fishery;rgn=main;view=text;idno=AAG2862.1251.001). Accessed August 4, 2008.

Rogers, J. 1966. South Manitou Island – a field trip source book and guide. Northwestern Michigan College. Traverse City, MI. 31 pp.

Rogers, L.L., J.J Mooty, and D. Dawson. 1981. Foods of white-tailed deer in the Upper Great Lakes regions – a review. Gen. Tech. Rep. NC-65. USDA-Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Rogers, R.S. 1978. Forests dominated by hemlock (*Tsuga canadensis*): distribution as related to site and postsettlement history. Can. J. Bot. **56**:843-54.

Rogers, R.S. 1982. Early spring herb communities in mesophytic forests of the Great Lakes region. Ecology **63**:1050-1063.

Rooney, T.P. 1997. Escaping herbivory: refuge effects on the morphology and shoot demography of the clonal forest herb *Maianthemum canadense.* J. Torrey Bot. Soc. **124**:280-285.

Rooney, T.P., R.J. McCormick, S. Solheim, and D.M. Waller. 2000. Regional variation in recruitment of hemlock seedlings and saplings in the Upper Great Lakes, USA. Ecol. Appl. **10**:1119-1132.

Rooney, T.P. S.L. Solheim, and D.M. Waller. 2002. Factors affecting the regeneration of northern white cedar in lowland forests of the Upper Great Lakes region, USA. For. Ecol. Mngt. **163**:119-130.

Rooney, T.P., S.M. Wiegmann, D.A. Rogers, and D.M. Waller. 2004. Biotic impoverishment and homogenization in unfragmented forest understory communities. Cons. Biol. **18**:787-98.

Route, B. and J. Elias (editors). 2006. Phase III Report: Long-term Ecological Monitoring Plan for the Great Lakes Network. GLKN/2006/02. NPS, Great Lakes Inventory and Monitoring Network, Ashland, WI. (http://www1.nature.nps.gov/im/units/glkn/index.htm). Accessed November 12, 2007.

Route, B. and J. Elias. 2007. Supplemental Document 7: Protocol Development Summaries for the Great Lakes Network. In B.Route and J. Elias. Long-term Ecological Monitoring Plan: Great Lakes Inventory & Monitoring Network. National Park Service, Fort Collins, CO. (http://www.nature.nps.gov/im/units/glkn/Vital%20Signs%20Monitoring.htm). Accessed October 8, 2007.

Ruben, J.A., D.T. Bolger, D.R. Peart, and M.P. Ayres. 1999. Understory herb assemblages 25 and 60 years after clearcutting of a northern hardwood forest, USA. Biol. Cons. **90**:203-15.

Rudolph, B.A. 2005. Population biology, abundance and management history of Michigan white-tailed deer. Mich. Soc. Amer. For. Conf., June 9-10, 2005, St. Ignace MI.

Runkle, J.R. 1982. Patterns of disturbance in some old-growth mesic forests of eastern North America. Ecology **63**:1533-45.

Russell, F.L., D.B. Zippin and N.L. Fowler. 2001. Effects of white-tailed deer (*Odocoileus virginianus*) on plants, plant populations and communities: a review. Am. Midl. Nat. **146**:1-26.

Saad, D.A. 1994. Nitrate in ground water in the western Lake Michigan drainage basin, Wisconsin and Michigan. Fact Sheet FS-070-94. USGS, Madison, WI. (http://wi.water.usgs.gov/pubs/FS-070-94/FS_070-94.pdf). Accessed January 29, 2008.

Saunders, D.A., R.J. Hobbs, and C.R. Margules. 1991. Biological consequences of ecosystem fragmentation: a review. Cons. Biol. **5**(**1**):18-32.

Sauer, J. R., J. E. Hines, and J. Fallon. 2001. The North American breeding bird survey, results and analysis 1966–2000, version 2001.2. U.S. Geological Survey, Patuxent Wildlife Research Center, Laurel, MD.

Sayles, B. 1988. A biological survey of the Crystal River, Leelanau County, MI, July 20, 1987. MI/DNR/SWQ-88/018. MDNR Surface Water Quality Division, Lansing, MI.

Scheller, R.M and D.J. Mladenoff. 2002. Understory species patterns and diversity in old-growth and managed northern hardwood forests. Ecol. Appl. **12**:1329-1343.

Schloesser, D. and T. Nalepa. 1994. Dramatic decline of unionid bivales (Bivalvia: Unionidae) in offshore waters of western Lake Erie after infestation by the zebra mussel (*Dreissena polymorpha*). Can. J. Fish. Aq. Sci. **51**:134-139.

Schloesser, D., T. Nalepa, and G. Mackie. 1996. Zebra mussel infestation of unionid bivalves (Unionidae) in North America. Am. Zool. **36**(**3**): 300-310.

Schneeberger, P.J., R.F. Elliott, J.L. Jonas, and S. Hart. 2005. Benthivores. *In* M.E. Holey and T.N. Trudeau (eds.). The state of Lake Michigan in 2000. Special Publication 05-01. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/pubs/SpecialPubs/Sp05_1.pdf). Accessed November 6, 2007.

Schwab, D.J., T.E. Croley II, and W.M. Schertzer. 2005. Physical limnology and hydrological characteristics of Lake Michigan. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Seaber, P.R., F.P. Kapinos, and G.L. Knapp. 1987. Hydrologic unit maps. Water Supply Paper 2294. USGS, Reston, VA. (http://pubs.usgs.gov/wsp/wsp2294/). Accessed May 10, 2007.

Sellinger, C.E., C.A. Stow, E.C. Lamon, and S.S. Qian. 2008. Recent water level declines in the Lake Michigan-Huron system. Environ. Sci. Technol. **42**:367-373. (http://pubs.acs.org/cgi-bin/article.cgi/esthag/2008/42/i02/pdf/es070664+.pdf). Accessed February 25, 2008.

Shaw, B., 1994. Nitrogen contamination sources: a look at relative contributions. Page 23 *in* Nitrate in Wisconsin's groundwater: strategies and challenges: Conference proceedings. Central WI Groundwater Center, UW-Stevens Point, Stevens Point, WI.

Shaw, B., C. Mechenich, and L. Klessig. 1996. Understanding lake data. Publication G3582. University of Wisconsin-Extension, Madison, WI. (http://dnr.wi.gov/org/water/fhp/lakes/under/). Accessed October 9, 2007.

Sheffy, T. 1984. Interpreting acid rain research findings in Wisconsin: what does it all mean? Wisconsin Natural Resource **8**(**6**):29-32.

Sherfy, M. and J. Thompson. 2001. Potential risk of aquatic invasive species introductions due to international trade in live bait. Pages 12-14 *in* North American Commission for Environmental Cooperation, Preventing the Introduction and Spread of Aquatic Invasive Species in North America, Workshop Proceedings, 28-30 March 2001. Montreal, Quebec. (http://www.cec.org/files/pdf/BIODIVERSITY/aquatic-invasives_en.pdf). Accessed January 5, 2009.

Shields, K.S. and C. A. Cheah. 2004. 2002-2003 winter mortality of hemlock woolly adelgid in the northeastern Unites States. Page 72 *in* K.W. Gottschalk (ed.). Proceedings, XV U.S. Department of Agriculture interagency research forum on gypsy moth and other invasive species 2004. January 13-16; Annapolis, MD. Gen. Tech. Rep. NE-332. USDA-Forest Service Northeastern Research Station, Newtown Square, PA. (http://www.treesearch.fs.fed.us/pubs/20726). Accessed October 2, 2008.

Shifley, S.R., B.L. Brookshire, D.R. Larsen, and L.A. Herbeck. 1997. Snags and down wood in Missouri old-growth and mature second-growth forests. N. J. Appl. For. **14**(**4**):165-72.

Siegert, N.W., D.G. McCullough, A.M. Liebhold, and F. W. Telewski. 2005. Reconstructing the temporal and spatial dynamics of emerald ash borer in black ash: a case study of an outlier site in Roscommon County, Michigan. EAB Res. and Tech. Develop. Michigan State University, East Lansing, MI. (http://www.ipm.msu.edu/landreport/2004/EAB%20reconstructing.pdf). Accessed January 26, 2009.

Simon, T.P., R.L. Dufour, P.M. Stewart, and M.L. Moffett. 2005. Distribution, classification, and selection rationale of coastal wetlands in Lake Michigan. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

SLSMC (St. Lawrence Seaway Management Corporation). 2006. Seaway continues to attract new cargoes as innovative program gains momentum. (online). Washington, D.C. (http://www.greatlakes-seaway.com/en/news/pr20061013.html). Accessed January 14, 2008.

Smith, A., D. Herms, and R. Long. 2005. Does community structure influence forest susceptibility and response to emerald ash borer? Contributed Oral Session 130, Ecological Society of America Annual Meeting, Montreal, Canada.

Smith, B.R. and J.J. Tibbles. 1980. Sea lamprey (*Petromyzon marinus*) in Lakes Huron, Michigan and Superior: history of invasion and control, 1936-78. Can. J. Fish. Aquat. Sci. **37**: 1780-1801.

Smith, S. 1970. Species interactions of the alewife in the Great Lakes. Trans. Amer. Fish. Soc. **99**: 754-765.

Smith, W.H. 1985. Forest quality and air quality. J. For. **83**(**2**):82-92.

Snyder, F.L., M.B. Hilgendorf, and D.W. Garton. 1997. Zebra mussels in North America: the invasion and its implications. OHSU-FS-045. 4 pp. Ohio Sea Grant College Program, Columbus, OH. (http://www.sg.ohio-state.edu/_documents/publications/FS/FS-045%20Zebra%20mussels%20in%20North%20America.pdf). Accessed December 10, 2007.

Sousa, W.P. 1984. The role of disturbance in natural communities. Ann. Rev. Ecol. Syst. **15**:353-391.

Souto, D.R. and K.S. Shields. 2000. Overview of hemlock health. Pages 76-80 *in* K.A. McManus, K.S. Shields, and D.R. Souto (eds.) Proceedings: symposium on sustainable management of hemlock ecosystems in eastern North America. Gen. Tech. Rep. NE-267. USDA-Forest Service Northeastern Research Station, Newtown Square, PA. (http://www.treesearch.fs.fed.us/pubs/14657). Accessed September 30, 2008.

St. Hilaire, L.R. and D.J. Leopold. 1995. Conifer seedling distribution in relation to micro-site conditions in a central New York forested minerotrophic peatland. Can. J. For. Res. **25**:261-269.

Stackpoole, S. 1997. Purple loosestrife in Michigan: biology, ecology, and management. Bulletin E-2632. MICHU-SG-97-501. 6pp. Michigan Sea Grant, East Lansing, MI. (http://miseagrant.umich.edu/downloads/ais/fs-97-501_purple_loosestrife.pdf). Accessed December 11, 2007.

Stadler, B., T. Muller, and D. Orwig. 2006. The ecology of energy and nutrient fluxes in hemlock forests invaded by hemlock woolly adelgid. Ecology **87**:1792-1804.

Stankovich, W. 2004. The interaction of two nuisance species in Lake Michigan: *Cladophora glomerata* and *Dreissena polymorpha*. In Bootsma, H.A., E.T. Jensen, E.B. Young, and J.A. Berges. 2005. Cladophora research and management in the Great Lakes: proceedings of a workshop held at the Great Lakes WATER Institute, University of Wisconsin-Milwaukee, December 8, 2004. UW-Milwaukee Great Lakes WATER Institute Special Report No. 2005-01. Milwaukee, WI. (http://www.glwi.uwm.edu/research/aquaticecology/cladophora/page_report.php). Accessed December 10, 2007.

State of Michigan. 1989. State Office of Administrative Hearings and Rules. Manitou Passage Great Lakes state bottomland preserve. Michigan Administrative Code Supplement 7, R299.6007 eff. January 4, 1989. (http://www.state.mi.us/orr/emi/admincode.asp?AdminCode=Single&Admin_Num=29906001&Dpt=&RngHigh=29999999). Accessed September 17, 2007.

State of Michigan. 1994. Natural Resources and Environmental Protection Act 451 of 1994. Part 353. Sand dunes protection and management. (http://www.legislature.mi.gov/(S(5ic14c45rtrcihv3mqg453me))/mileg.aspx?page=getobject&objectname=mcl-451-1994-iii-1-land-habitats-353). Accessed October 22, 2007.

State of Michigan. 1996a. Natural Resources and Environmental Protection Act 451 of 1994. Part 201 Environmental remediation. (http://www.legislature.mi.gov/(S(kwotuza5fkb3pd55omsdfryf))/mileg.aspx?page=GetMCLDocument&objectname=mcl-451-1994-ii-7-201). Accessed December 3, 2007.

State of Michigan. 1996b. Natural Resources and Environmental Protection Act 451 of 1994. Part 213 Leaking underground storage tanks. (http://www.legislature.mi.gov/(S(juxh1h555needgjbwx0u3uju))/mileg.aspx?page=GetMCLDocument&objectname=mcl-451-1994-ii-8-213). Accessed December 3, 2007.

State of Michigan. 2006. State Office of Administrative Hearings and Rules. R323.1098 Antidegradation. Eff. Jan. 13, 2006. (http://www.state.mi.us/orr/emi/admincode.asp?AdminCode=Single&Admin_Num=32301041&Dpt=EQ&RngHigh=). Accessed November 13, 2007.

Stearns, F. 1986. Ecological view of the second hardwood forest and implications for the future. Pages 51-66 *in* G.D. Mroz and D.D. Reed (compilers). The northern hardwood resource: management and potential. Michigan Technological University, Houghton, MI.

Stearns, F. 1992., Ecological characteristics of white pine. Pages 10-18 *in* Publication NR-BU-6044-S, R.A. Stine and M.J. Baughman (eds.), White Pine Symposium Proceedings. Dept. For. Res. and Minn. Extension Service, Duluth, MN.

Steggall, J.W. and J.H. Judd. 1983. Recent and historical changes in the aquatic macrophyte community of First Sister Lake, Washtenaw County, Michigan. Michigan Acadamician **15**:209-220.

Steuer, J., W. Selbig, N. Hornewer, and J. Prey. 1997. Sources of contamination in an urban basin in Marquette, Michigan and an analysis of concentrations, loads, and data quality. Water-Resources Investigations Report 97-4242. USGS, Reston, VA. (http://pubs.er.usgs.gov/pubs/wri/wri974242). Accessed December 31, 2007.

Stevenson, J. 1992. Report on Glen Lake plankton assemblages. Final Report to Sleeping Bear Dunes National Lakeshore. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Stinson, K.A., S.A. Campbell, J.R. Powell, B.W. Wolfe, R.M. Callaway, G.C. Thelen, S.G. Hallett, D. Prati, and J.N. Klironomos. 2006. Invasive plant suppresses the growth of native tree seedlings by disrupting belowground mutualisms. PLoS Biol. **4**(**5**):1-8.

Stockwell, J. and J. Gannon. 1975. Water quality studies in the Sleeping Bear Dunes National Lakeshore region: the lower Platte River System, Michigan. U. of Michigan Biological Station, Pellston, MI. (http://hdl.handle.net/2027.42/49265). Accessed July 8, 2008.

Stoermer, E.F. 2005. Lake Michigan paleolimnology. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Stromayer, K.A. and R.J. Warren. 1997. Are overabundant deer herds in the eastern U.S. creating alternate stable states in forest plant communities? Wildlf. Soc. Bull. **25**(**2**):227-34.

Stuckey, R.L. 1971. Changes of vascular aquatic flowering plants during 70 years in Put-In-Bay Harbor, Lake Erie, Ohio. Ohio J. Sci. **71**:321-342.

Sullivan, Janet. 1995. *Molothrus ater*. In: Fire Effects Information System, [Online]. USDA-Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. (http://www.fs.fed.us/database/feis/) Accessed January 7, 2009.

Sun, D. and D. Walsh. 1998. Review of studies on environmental impacts of recreation and tourism in Australia. J. Environmental Management **53**(**4**): 323-338.

Swann, C. 2001. The influence of septic systems at the watershed level. Watershed Protection Techniques **3**(**4**): 821-834. (http://www.cwp.org/WPI_WV/Wednesday/O/Influence%20of%20Septics.pdf) Accessed October 16, 2007.

Swift, E. 1948. Wisconsin's deer damage to forest reproduction survey – final report. Publ. No. 347. Wisconsin Conservation. Dept., Madison WI.

Taube, C. 1974. A descriptive and historical account of the Platte River, its surrounding area, and its salmonid fishes. Research Rept. No. 1809. Fisheries Division, MDNR, Ann Arbor, MI.

Taylor, R.A.J., L.S. Bauer, D.L. Miller, and R.A. Haack. 2005. Emerald ash borer flight potential. Pages 15-16 *in* V. Mastro and R. Reardon, compilers. Emerald ash borer research and technology development meeting. FHTET-2004-15. USDA-Forest Service, Morgantown, WV

Temple, P.J. and P.R. Miller. 1998. Seasonal influences of ozone uptake and foliar injury to ponderosa and Jeffrey pines at a southern California site. Pages 221-228 *in* A. Bytnerowicz, M.J. Arbaugh, and S.L. Schilling (tech. coords). Proceedings of the international symposium on air pollution and climate change effects on forest ecosystems. Gen. Tech. Rep. PSW-GTR-166. USDA-Forest Service Pacific Southwest Research Station, Albany, CA. (http://www.treesearch.fs.fed.us/pubs/26980). Accessed October 2, 2008.

Thompson, P. 1967. Vegetation and common plants of Sleeping Bear. Cranbrook Inst. Sci. Bull. **52**.

Tilman, D., P. Reich, H. Phillips, M. Menton, A. Patel, E. Vos, D. Peterson and J. Knops. 2000. Fire suppression and ecosystem carbon storage. Ecol. **81**:2680-85.

Transport Canada, U.S. Army Corps of Engineers, U.S. Department of Transportation, The St. Lawrence Seaway Management Corporation, Saint Lawrence Seaway Development Corporation, Environment Canada, and U.S. Fish and Wildlife Service. 2007. Great Lakes St. Lawrence Seaway Study, Final Report, Fall 2007. Detroit, MI. (http://www.glsls-study.com/Supporting%20documents/GLSLS%20finalreport%20Fall%202007.pdf). Accessed January 14, 2008.

Tubbs, C.H. 1977. Natural regeneration of northern hardwoods in the northern Great Lakes region. Res. Pap. NC-150. USDA-Forest Service North Central Research Station, St. Paul, MN. (http://www.ncrs.fs.fed.us/pubs/rp/rp_nc150.pdf). Accessed January 26, 2009.

Tubbs, C.H. 1978. Northern hardwood ecology. Pages 329-333 *in* Proc. Joint Soc. Amer. Foresters and Can. Inst. Forestry Conv., St. Louis, MO.

Twery, M.J. and W.A. Patterson III. 1984. Variations in beech bark disease and its effects on species composition and structure of northern hardwood stands in central New England. Can. J. For. Res. **22**: 1727-1738.

USACE (United States Army Corps of Engineers). 2005. Final report: known and potential environmental effects of oil and gas drilling activity in the Great Lakes. Chicago District. (http://www.lrc.usace.army.mil/GrtLakes/OilGas/report.html). Accessed December 31, 2007.

USACE (United States Army Corps of Engineers). 2006. Great Lakes water level table for Lake Michigan/Huron: 1918-2006. (online). Detroit District. (http://www.lre.usace.army.mil/greatlakes/hh/greatlakeswaterlevels/historicdata/greatlakeshydrographs/). Accessed February 25, 2008.

US Census Bureau. 2000. Census 2000 Summary File 1. (http://www.census.gov/). Accessed May 3, 2007.

US Census Bureau. 2001. TIGER/Line Files, Redistricting Census 2000. Accessed through the ESRI Geography Network at (http://arcdata.esri.com/data/tiger2000/tiger_download.cfm). Accessed May 3, 2007.

US Census Bureau. 2007. United States census 2000. (http://www.census.gov/main/www/cen2000.html). Accessed October 16, 2007.

USDA (United States Department of Agriculture). 2002. 2002 census of agriculture. Volume 1, Chapter 2: Michigan county level data. National Agricultural Statistics Service. (http://www.nass.usda.gov/census/census02/volume1/mi/index2.htm) Accessed October 6, 2008.

USDA (United States Department of Agriculture). 2004. 2003 Chemical Use Summaries for Fruit and Field Crops-Michigan. National Agricultural Statistics Service. (http://www.nass.usda.gov/mi/stats04/chemuse.pdf). Accessed August 29, 2007.

USDA (United States Department of Agriculture) Animal and Plant Health Inspection Service. 2009. Cooperative emerald ash borer project: EAB locations in Illinois, Indiana, Maryland, Michigan, Missouri, Ohio, Pennsylvania, Virginia, Wisconsin, West Virginia, and Canada. (online). Romulus, MI. (http://www.emeraldashborer.info/files/MultiState_EABpos.pdf). Accessed February 9, 2009.

USDA ERS (United States Department of Agriculture Economic Research Service). 2004. Final 2004 Typology Codes. (http://www.ers.usda.gov/Data/TypologyCodes/). Accessed May 15, 2007.

USDA-Forest Service. 2003. Forest Health Protection. Forest insect and disease conditions in the United States, 2002. Washington, D.C.

USDA-Forest Service. 2008. List of state and counties with known hemlock woolly adelgid infestations. Morgantown, WV. (http://na.fs.fed.us/fhp/hwa/infestations/hwa_infestations07.pdf). Accessed February 9, 2009.

US Department of Transportation. 2005. Industry survey series: Great Lakes operators 2005. Washington, DC. (http://marad.dot.gov/documents/Great_Lakes_Operators.pdf). Accessed December 27, 2008.

USEPA (United States Environmental Protection Agency). 1977a. National secondary drinking water regulations. Federal Register, V.42, Part 1 p. 17143-17147.

USEPA (United States Environmental Protection Agency). 1977b. National interim primary drinking water regulations. US Gov. Printing Office, 139 pp.

USEPA (United States Environmental Protection Agency). 1986. Quality Criteria for Water 1986. EPA 440/5-86-001. (http://www.epa.gov/waterscience/criteria/goldbook.pdf). Accessed October 9, 2007.

USEPA (United States Environmental Protection Agency). 1999. Commercial marine activity for Great Lake and inland river ports in the United States: final report. EPA420-R-99-019. (http://www.epa.gov/otaq/models/nonrdmdl/c-marine/r99019.pdf). Accessed July 23, 2007.

USEPA (United States Environmental Protection Agency). 2000. Ambient water quality criteria recommendations: information supporting the development of state and tribal nutrient criteria for lakes and reservoirs in nutrient ecoregion VII. EPA-822-B-00-009. (http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/lakes/lakes_7.pdf). Accessed May 14, 2007.

USEPA (United States Environmental Protection Agency). 2001a. Ambient water quality criteria recommendations: information supporting the development of state and tribal nutrient criteria for rivers and streams in nutrient ecoregion VII. EPA 822-B-00-018. Washington, D.C. (http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/rivers/rivers_7.pdf). Accessed February 4, 2008.

USEPA (United States Environmental Protection Agency). 2001b. Phosmet IRED Facts. (http://www.epa.gov/oppsrrd1/REDs/factsheets/phosmet_fs.htm). Accessed August 29, 2007.

USEPA (United States Environmental Protection Agency). 2002. Draft regulatory support document: control of emissions from compression-ignition marine diesel engines at or above 30 liters per cylinder. EPA420-D-02-002. (http://www.epa.gov/otaq/regs/nonroad/marine/ci/d02002.pdf) Accessed July 23, 2007.

USEPA (United States Environmental Protection Agency). 2004. Regulatory update: overview of EPA's emission standards for marine engines. EPA420-F-04-031. (http://www.epa.gov/otaq/regs/nonroad/marine/420f04031.pdf). Accessed July 23, 2007.

USEPA (United States Environmental Protection Agency). 2005c. Vessel sewage discharge program. (online) (http://www.epa.gov/owow/oceans/regulatory/vessel_sewage/). Accessed July 8, 2007.

USEPA (United States Environmental Protection Agency). 2006a. Lake Michigan Mass Balance Study-Overview (online). (http://www.epa.gov/med/grosseile_site/LMMBP/). Accessed June 26, 2007.

USEPA (United States Environmental Protection Agency). 2006b. Azinphos-Methyl Phaseout. (http://www.epa.gov/oppsrrd1/reregistration/azm/phaseout_fs.htm). Accessed August 29, 2007.

USEPA (United States Environmental Protection Agency). 2006c. Great Lakes National Program Office environmental indicators: trophic state of the Great Lakes (online). (http://www.epa.gov/glnpo/glindicators/water/trophicb.html). Accessed September 10, 2007.

USEPA (United States Environmental Protection Agency). 2006d. Great Lakes Environmental Database (GLENDA). (online) (http://www.epa.gov/glnpo/monitoring/data_proj/glenda/index.html). Accessed October 2, 2007.

USEPA (United States Environmental Protection Agency). 2007a. Envirofacts data warehouse (online). (http://www.epa.gov/enviro/). Accessed March 27, 2007.

USEPA (United States Environmental Protection Agency). 2007b. National emission inventory (NEI) database for criteria and hazardous air pollutants (online). (http://www.epa.gov/air/data/neidb.html). Accessed March 22, 2007.

USEPA (United States Environmental Protection Agency). 2007c. Clean air status and trends network Hoxeyville (HOX148) (online). (http://www.epa.gov/castnet/sites/hox148.html) Accessed June 22, 2007.

USEPA (United States Environmental Protection Agency) and Environment Canada. 2007. State of the Great Lakes 2007 (draft) (online). (http://www.epa.gov/grtlakes/solec/). Accessed September 25, 2007.

USEPA (United States Environmental Protection Agency) and Environment Canada. 2008. State of the Great Lakes 2009 (draft) (online). (http://solecregistration.ca/en/indicator_reports.asp). Accessed December 8, 2008.

USEPA Region 5 (United States Environmental Protection Agency Region 5). 1992. Clean Lakes Program: Glen Lake, Leelanau County, Michigan. Final Report, Phase 1 Diagnostic/Feasibility Study.

USEPA Region 5 (United States Environmental Protection Agency Region 5). 2000. Inland sensitivity atlas: northern Michigan. USEPA Region 5, Chicago, IL.

USFWS (United States Fish and Wildlife Service). 1994. National wetlands inventory data. St. Petersburg, FL. (http://www.dnr.state.mi/spatialdatalibrary/metadata/NWI_Data.htm). Accessed March 15, 2007.

USGAO (United States General Accounting Office). 2000. Marine pollution: progress made to reduce marine pollution by cruise ships, but important issues remain. GAO/RCED-00-48. (http://www.gao.gov/new.items/rc00048.pdf). Accessed July 17, 2007.

USGS (United States Geological Survey) EROS Data Center. 1999. National Elevation Dataset. Sioux Falls, SD. Accessed from the National Map Seamless Server (http://seamless.usgs.gov) January 29, 2007.

USGS (United States Geological Survey). Great Lakes Science Center. 2000. Round goby: an exotic fish in the Great. Ann Arbor, MI. (http://www.glsc.usgs.gov/_files/factsheets/2000-1%20Round%20Goby.pdf). Accessed December 11, 2007.

USGS (United States Geological Survey). 2003. Great Lakes regional aquatic gap analysis-preserving biodiversity in the Great Lakes basin. GLSC Fact Sheet 2003 -1. Great Lakes Science Center. Ann Arbor, MI. (http://www.glsc.usgs.gov/_files/factsheets/2003-1%20Great%20Lakes%20Regional%20Aquatic%20GAP.pdf). Accessed September 11, 2007.

USGS (United States Geological Survey). 2005. Water science for schools. Water Q and A: water use at home. Online. (http://ga.water.usgs.gov/edu/qahome.html). Accessed October 29, 2007.

USGS (United States Geological Survey). 2007a. NAS-Nonindigenous aquatic species database (online). (http://nas.er.usgs.gov/queries). Accessed November 27, 2007.

USGS (United States Geological Survey) National Wildlife Health Center. 2007b. Quarterly Wildlife Mortality Report. Madison, WI. (http://www.nwhc.usgs.gov/publications/quarterly_reports/2007_qtr_2.jsp) . Accessed January 7, 2008.

Uzarski, D.G., T.M. Burton, M.J. Cooper, J.W. Ingram, and S.T.A. Timmermans. 2005. Fish habitat use within and across wetland classes in coastal wetlands of the five Great Lakes: development of a fish-based index of biotic integrity. J. Great Lakes Res. **31** (Supplement 1): 171-187.

Uzarski, D.G., T.M. Burton, and J.A. Genet. 2004. Validation and performance of an invertebrate index of biological integrity for Lakes Huron and Michigan fringing wetlands during a period of lake level decline. Aquatic Ecosystem Health and Management **7**(**2**): 269-288.

Vana-Miller, D.L. 2002. Water resources management plan, Sleeping Bear Dunes National Lakeshore, Michigan. NPS, Fort Collins, CO. (http://www.nature.nps.gov/water/management_plans/slbe_final_screen.pdf). Accessed May 15, 2007.

Van Deelen, T.R., K.S. Pregitzer, and J.B. Haufler. 1996. A comparison of presettlement and present-day forests in two northern Michigan deer yards. Am. Midl. Nat. **135**:181-194.

Vellend, M. 2003. Habitat loss inhibits recovery of plant diversity as forests regrow. Ecology **84**:1158-1164.

Vent, M.H. 1973. South Manitou Island: from pioneer settlement to national park. Goodway. Springfield, VA. 105 pp.

Villalba, R., T.T. Veblen, and J. Ogden. 1994. Climatic influences on the growth of subalpine trees in the Colorado Front Range. Ecology **75**:1450-1462.

Villalba, R. and T.T. Veblen. 1998. Influences of large-scale climatic variability on episodic tree mortality in northern Patagonia. Ecology **79**:2624-2640.

Volker, R., and S.G. Smith. 1965. Changes in the aquatic vascular flora of Lake East Okoboji in historic times. Iowa Acad. Sci. **72**:66-72.

Voss, E.G. 1972. Michigan flora. Part I. Gymnosperms and monocots. Bull. Cranbrook Inst. Sci. **55** and Univ. Michigan Herbarium.

Voss, E.G. 1985. Michigan Flora. Part II Dicots (Saururaceae-Cornaceae). Cranbrook Inst. Sci. Bull. **59** and Univ. Michigan Herb. 488p.

Wainhouse, D. and I.G. Gate. 1988. The beech scale. Pages 67-85 *in* A.A. Berryman (ed.). Dynamics of forest insect populations. Plenum Press, New York, NY.

Walker, B.R. 1999. A biological survey of the Platte River system, Benzie County, August 3-5, 1998. Staff Report MI/DEQ/SWQ-99/083. Surface Water Quality Division, MDEQ, Lansing, MI.

Walker, K. 2002. How will climate change affect the potential distribution of individual tree species in the Great Lakes region? (Great Lakes regional assessment findings). Presentation at Climate change and terrestrial ecosystems of the Great Lakes region: the potential impacts and what we can do. Great Lakes Regional Assessment Workshop June 21, 2002, Minneapolis, MN. (http://www.geo.msu.edu/glra/workshop/04landwkshop/wkshp.day.htm). Accessed March 25, 2008.

Wallbom, T. and G. Larson. 1998. Surficial geology of the Glen Haven, Glen Arbor, Good Harbor Bay, Empire, Burdickville, and Beulah 7.5 minute quads, Leelanau and Benzie counties, Michigan. Michigan State University, East Lansing, MI.

Wallbom, T.E. and G.J. Larson. 1999. Surficial geology of Sleeping Bear Dunes National Lakeshore, Lake Michigan: a product of the USGS-EDMAP Program: Geological Society of America Abstracts with Programs **31**(**5**):A-78.

Walther, G, E. Post, P. Convey, A. Menzel, C. Parmeson, T.J. Beebee, J. Fromentin, O. Voegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. Nature **416**:389-95.

Ward, J.S., M.E. Montgomery, C.A. Cheah, B.P. Onken and R.S. Cowles. 2004. Eastern hemlock forests: guidelines to minimize the impacts of hemlock woolly adelgid. NA-TP-03-04. USDA-Forest Service, Northeastern Area State and Private Forestry, Morgantown, WV.

Warren, G. 2005. Nutrients. In M.E. Holey and T.N. Trudeau (eds.). The state of Lake Michigan in 2000. Special Publication 05-01. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/pubs/SpecialPubs/Sp05_1.pdf). Accessed November 6, 2007.

Warren, G.J. and R.G. Kreis. 2005. Recent and long-term nutrient trends in Lake Michigan. In T. Edsall and M. Munawar (eds.). State of Lake Michigan: ecology, health and management. Ecovision World Monograph Series. Aquatic Ecosystem Health and Management Society. Burlington, Ontario.

Waterman, W. 1922. Development of plant communities of a sand ridge region in Michigan. Bot. Gaz. **74**:1-31.

Watkins, R.Z., J. Chen, J. Pickens, and K.D. Brosofske. 2003. Effects of forest roads on understory plants in a managed hardwood landscape. Cons. Biol. **17**:411-19.

WDNR (Wisconsin Department of Natural Resources). 1992. Wisconsin County Boundaries. Madison, WI.

WDNR (Wisconsin Department of Natural Resources). 2007. Joint Legislative Hearing on Viral Hemorrhagic Septicemia, November 7, 2007, Testimony of the Wisconsin Department of Natural Resources. Madison, WI. (http://dnr.wi.gov/fish/vhs/vhs_hearingtestimony_11072007.pdf). Accessed January 15, 2008.

WDNR (Wisconsin Department of Natural Resources). 2008. Spotted knapweed (*Centaurea stoebe Lamarck ssp. micranthos (Gugler) Hayek syn. C. biebersteinii, formally C. maculosa*). Online factsheet. Madison, WI. (http://dnr.wi.gov/invasives/fact/pdfs/knapweedFactsheet.pdf). Accessed February 9, 2009.

Weber, C.R, J.G. Cohen, and M.A. Kost. 2007. Natural community abstract for Northern Hardwood Swamp. Michigan Natural Features Inventory, Lansing, MI. 8 pp. (http://web4.msue.msu.edu/mnfi/abstracts/ecology/Northern_hardwood_swamp.pdf). Accessed October 11, 2008.

Webster, C.R. and G.R. Parker. 2000. Evaluation of *Osmorhiza claytonii*, *Arisaema triphyllum* and *Actaea pachypoda* as potential indicators of white-tailed deer overabundance. Nat. Areas J. **20**:176-88.

Weeks, D.P. and R.J. Andrascik. 1998. Voyageurs National Park, Minnesota, Water Resources Scoping Report. Technical Report NPS/NRWRS/NRTR-98/201. Water Resources Division, National Park Service, Department of the Interior. Denver, CO.

Welch, A.H., D.B. Westjohn, D.R. Helsel, and R.B. Wanty. 2000. Arsenic in ground water of the United States: occurrence and geochemistry. Ground Water **38**(**4**): 589-604.

Wells, L. and A.L. McLain. 1973. Lake Michigan: man's effects on native fish stocks and other biota. Report No. 20. Great Lakes Fishery Commission, Ann Arbor, MI. (http://www.glfc.org/pubs/TechReports/Tr20.pdf). Accessed December 17, 2007.

Wesander, D.L. and D.F. Clapp. 2007. Charter boat effort and fish harvest from the Michigan waters of the Great Lakes, 2006. MDNR Charlevoix Fisheries Research Station. (http://www.michigan.gov/documents/dnr/2006_annual-report_201094_7.pdf). Accessed December 17, 2007.

Westjohn, D.B. and T.L. Weaver. 1998. Hydrogeologic framework of the Michigan Basin regional aquifer system. Professional Paper 1418. USGS, Denver, CO.

Wetzel, R. 1975. Limnology. W.B. Saunders Co. Philadelphia, PA.

Wetzel. R.G. 2001. Limnology. Lake and river ecosystems, 3rd ed. Academic Press. San Diego, CA. 1006 pp.

Wheeler, K. and J. Nauright. 2006. A global perspective on the environmental impact of golf. Sport in Society **9** (**3**): 427-443. (http://www.bvihcg.com/images/beef/golf_environment.pdf). Accessed September 18, 2007.

Whelan, G.E. 1999. Managing effluents from an intensive fish culture facility: the Platte River State Fish Hatchery case history. Appendix 7 in Addressing concerns for water quality impacts from large-scale Great Lakes aquaculture. Based on a roundtable co-hosted by the Habitat Advisory Board of the Great Lakes Fishery Commission and the Great Lakes Water Quality Board of the International Joint Commission, August, 1999. (http://www.ijc.org/php/publications/html/aquaculture/). Accessed November 26, 2007.

Whelan, G. 2007. Viral Hemorrhagic Septicemia (VHS) Briefing Paper, August 1, 2007. MDNR, Lansing, MI. (http://www.michigan.gov/documents/dnr/Viral-Hemorrhagic-Septicemia-Fact-Sheet-11-9-2006_178081_7.pdf). Accessed January 15, 2008.

White, D. 1987. Analysis of the limnology of four streams (Platte River, Crystal River, Shalda Creek, Otter Creek) in the Sleeping Bear Dunes National Lakeshore based on macroinvertebrate fauna. NPS, Sleeping Bear Dunes National Lakeshore. Empire, MI.

White, P.S. 1979. Pattern, process and natural disturbance in vegetation. Bot. Rev. **45**(**3**):229-299.

Whitman, R., L. Last, and P. Gerovac. 1994. Limnological characteristics of selected lakes and streams of Sleeping Bear Dunes National Lakeshore inspected during summer 1994. Final Report, National Park Service Contracts DI6620-R041 and DI6620-R040. National Biological Service, Lake Michigan Ecological Station, Porter, IN. 20 pp.

Whitman, R. 2000. Inspect, assess and monitor inland lakes of Great Lakes cluster parks. NPS, Sleeping Bear Dunes National Lakeshore, Empire, MI.

Whitman, R.L., B. Davis, and M.L. Goodrich. 2002a. Study of the application of limnetic zooplankton as a bioassessment tool for lakes of Sleeping Bear Dunes National Lakeshore. USGS Lake Michigan Ecological Research Station. Porter, IN. (http://www.glsc.usgs.gov/_files/reports/InlandLakesZooplankton.pdf). Accessed February 26, 2008.

Whitman, R.L., M.B. Nevers, L.L. Last, T.G. Horvath, M.L. Goodrich, S.M. Mahoney, and J.A. Nefczyk. 2002b. Status and trends of selected inland lakes of the Great Lakes cluster National Parks. Report submitted to NPS Midwest Region and Great Lakes Cluster National Parks in fulfillment of Interagency Agreement #14431A603097017. 310 pp. USGS Great Lakes Science Center, Ann Arbor, MI. (http://www.glsc.usgs.gov/_files/reports/InlandLakesReport.pdf). Accessed September 23, 2008.

Whitman, R.L., D.A. Shively, H. Pawlik, M.B. Nevers, and M.N. Byappanahalli. 2003. Occurrence of *Escherichia coli* and enterococci in Cladophora (Chlorophyta) in nearshore water and beach sand of Lake Michigan. Applied and Environmental Microbiology **69**(**8**): 4714-4719.

Whitney, G.G. 1986. Relation of Michigan's presettlement pine forests to substrate and disturbance history. Ecology **67**:1548-1559.

Whitney, G.G. 1987. An ecological history of the Great Lakes forest of Michigan. J. Ecol. **75**:667-684.

Whitney, H.E. and W.C. Johnson. 1984. Ice storms and forest succession in southwestern Virginia. Bulletin Torrey Botanical Club **111**(**4**):429-437.

Wiese, F. 2002. Seabirds and Atlantic Canada's ship-source oil pollution: impacts, trends and solutions. World Wildlife Fund Canada, Toronto, Canada. (http://wwf.ca/AboutWWF/WhatWeDo/ConservationPrograms/RESOURCES/PDF/SeabirdsReport.pdf). Accessed July 17, 2007.

Wilcox, D.A., T.A. Thompson, R.K. Booth, and J.R. Nicholas. 2007, Lake-level variability and water availability in the Great Lakes. Circular 1311, 25 p. U.S. Geological Survey, Reston, VA. (http://pubs.usgs.gov/circ/2007/1311/). Accessed January 27, 2009.

Williamson, C.E., W. Dodds, T.K. Kratz, and M.A. Palmer. 2008. Lakes and streams as sentinels of environmental change in terrestrial and atmospheric processes. Front. Ecol. Environ. **6**(**5**):247-54.

Williams, J., S.T. Jackson, and J.E. Kutzbach. 2007. Projected distributions of novel and disappearing climates by 2100 AD. Proc. Nat. Acad. Sci. **104**:5738-42.

Wisconsin Sea Grant. 2002. White perch (online). Wisconsin Sea Grant, UW-Madison, Madison, WI. (http://www.seagrant.wisc.edu/greatlakesfish/fwhiteperch1.html). Accessed December 11, 2007.

Witter, J.A., J.L. Stoyenoff, H.A. Petrillo, J.L. Yocum and J.I. Cohen. 2005. Effects of beech bark disease on trees and ecosystems. Pages 28-35 *in* C.A. Evans, J.A. Lucas, and M.J. Twery. Beech Bark Disease: Proceedings of the Beech Bark Disease Symposium. Gen. Tech. Rep. NE-331. USDA-Forest Service, Newtown Square, PA. (http://treesearch.fs.fed.us/pubs/20356). Accessed September 28, 2008.

Wolf, A.T., L. Parker, G. Fewless, K. Corio, J. Sundance. R. Howe, and H. Gentry. 2008. Impacts of summer versus winter logging on understory vegetation in the Chequamegon-Nicolet National Forest. For. Ecol. Mngt. **254**:34-45.

Woods, K.D. 1993. Effects of invasion by *Lonicera tatarica* L. on herbs and tree seedlings in four New England forests. Amer. Midl. Nat. **130**:62-74.

Worldwatch Institute. 2004. Matters of scale-Planet Golf. World Watch magazine, March/April 2004. Washington, D.C. (http://www.worldwatch.org/node/797). Accessed September 18, 2007.

Wuenscher, J.E. and T.T. Kozlowski. 1971. Relationship of gas-exchange resistance to tree seedling ecology. Ecology **52**:1016-23.

Yorks, T.E., J.C. Jenkins, D.J. Leopold, D.J. Raynal, and D.A. Orwig. 2000. Influences of eastern hemlock mortality on nutrient cycling. Pages 126-133 *in* K.A. McManus, K.S. Shields, and D.R. Souto (eds.) Proceedings: symposium on sustainable management of hemlock ecosystems in eastern North America. Gen. Tech. Rep. NE-267. USDA-Forest Service Northeastern Research Station, Newtown Square, PA. (http://www.treesearch.fs.fed.us/pubs/4141). Accessed September 30, 2008.

Zaccherio, M.T. and A.C. Finzi. 2007. Atmospheric deposition may affect northern hardwood forest composition by altering soil nutrient supply. Ecol. Appl. **17**:1929-1941.

Zak, D.R., W.E. Holmes, and K.S. Pregitzer. 2007. Atmospheric CO_2 and O_3 alter the flow of N^{15} in developing forests ecosystems. Ecology **88**:2630-2639.

Zhang, Q., K.S. Pregitzer, and D.D. Reed. 2000. Historical changes in the forests of the Luce District of Upper Peninsula of Michigan. Am. Midl. Nat. **143**:94-110.

Zuccharino-Crowe, C. (ed). 2007. Botulism in the Great Lakes-frequently asked questions. USEPA Great Lakes National Program Office and Michigan Sea Grant. East Lansing, MI. (http://www.miseagrant.umich.edu/habitat/avian-botulism-faq.html). Accessed January 7, 2008.

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National Marine Fisheries Service, Fisheries Statistics Division, Silver Springs, MD. (http://www.st.nmfs.noaa.gov/st1/commercial/landings/gl_query.html). Accessed November 6, 2007.

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Schultz, G. US Coast Guard. GSchultz@D14.uscg.mil. Also available at http://www.glc.org/irps/irps/docs/jan17meeting.pdf, Accessed July 10, 2007.

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Appendix A. Sources of data for base map and notes on map content development.

All maps and associated geoprocessing were done with the ArcGIS 9.2 software by Environmental Systems Research Institute, Inc. (ESRI 2006). Maps are shown in the NAD 1983 UTM Zone 16N coordinate system. Spatial data obtained in other datums or coordinate systems were re-projected using ArcGIS. GIS data obtained from the Michigan Center for Geographic Information Data Library were typically in the Michigan GeoRef coordinate system based on the NAD 1983 datum and an oblique mercator projection.

Base map features used on many of the maps were obtained as follows. Michigan county, city, and village boundaries, minor civil divisions (townships), lake and stream hydrography, and US/state highways are the 1:24k Michigan Geographic Framework, version 6b (MCGI 2006). Wisconsin counties are from Wisconsin County Boundaries (WDNR 1992). When local roads are shown, the road network is based on the NPS roads layer (NPS 1997a) with minor editing, including onscreen digitization of the revised Pierce Stocking Scenic Drive. The SLBE park boundary is based on the NPS boundary layer (NPS 1999a). This boundary file provided the inland boundary and ¼ mile extension into Lake Michigan. The SLBE Lake Michigan shoreline boundary and separate land/submerged park polygon areas were created by unioning the NPS boundary and the Michigan Framework county layer. Terrain layers are based on the 10 meter National Elevation Dataset (USGS 1999).

The regional map insert in Figure 1 utilized States, Provinces, and US_Lakes layers from ESRI Data & Maps (ESRI 2002). The upper Lake Michigan insert utilized Michigan Framework counties, Wisconsin County Boundaries, and a Lake Michigan layer created from NOAA electronic navigation charts (NOAA 2007b,c).

Although not used directly on any maps, digital version of the USGS topographic maps (DRGs) and airphotos (DOQs) were used to verify other data, serve as a base for digitization, and as a general reference for locating features as noted below. County based DRGs and 1998/2005 DOQs were obtained from the Michigan Center for Geographic Information (http://www.mcgi.state.mi.us/mgdl/) in January and September, 2007.

Data sources are listed for the specific content on most maps. Digital versions (GIS-ready) of the source data were used when possible. When GIS layers were not available, new layers were developed from available spatial information. The generalized Port Oneida Historic District layer in Figure 4 was cut from the park polygon layer based on the map at http://www.nps.gov/slbe/planyourvisit/povirtualtour.htm. Published lat/long or UTM coordinates were the basis for the Manitou Passage Bottomland Preserve layer (Figure 2), Historic Fishing Sites and Current Lake Trout Refuge layers (Figure 13), Open Lake Water Quality Sites layer (Figure 15), Amphibians layer (Figure 26), Air Releases (Figure 46), Air Monitoring Sites (Figure 47), LUST Sites (Figure 55), and the NPS sewage disposal system layer (Figure 56). In addition, the spatial content of some layers was developed or supplemented using addresses, DOQs, PLSS descriptions, county parcel maps, land use plans, the NPS historic buildings and structures layer, related mapped features such as campgrounds and trailheads, and web search engine maps. These layers include Air Releases (Figure 46), ERD Sites (Figure 55), and the NPS sewage disposal system and OSDS layers (Figure 56). A location method attribute field was added to these layers.

Some layers were derived or modified using basic ArcGIS geoprocessing and editing tools. Many of the layers were obtained as county area layers, and these were generally combined into one layer using the merge tool. The Lake Michigan and shipping lanes layers (Figure 50) are merged features from NOAA electronic navigation charts 14901 (south end) and 14902 (north end). As noted above, the union tool was used to create the park polygon layer from the NPS park boundary and the Michigan counties layer. The union tool was also commonly used with area-wide layers and the park boundary layer when statistics for park areas were needed. The wetland layer of Figure 4 and Figure 33 to Figure 40 is a union of the three lowland layers (SSURGO hydric soils, NWI wetlands, and lowlands from the 1978 MDNR Land Use/Land Cover) comprising the 2006 MDEQ Final Wetland Inventory. The watershed population (Figure 6) was created by intersecting census blocks with the watershed boundary. Hillshades to enhance the three dimensional perspective were generated with the Spatial Analyst hillshade tool for the surface elevation grid (many figures), Lake Superior bathymetry (Figure 11) and groundwater elevation grid (Figures 42 and 43). The watershed boundary above the park layer, used on many of the maps, is mostly based on the Michigan watershed boundary data (MDEQ 1998b). Watersheds impacting the park were selected, internal boundaries dissolved, and edge adjustments made based on DRGs and the ArcGIS watershed tool using the 10 meter DEM. The watershed tool was also used to delineate the shallow groundwatersheds (Figures 42 and 43) using the groundwater elevation grid. The town/range grid used in Figure 3 is based on the Michigan statewide town range layer, accessed from the Michigan Center for Geographic Information (http://www.mcgi.state.mi.us/mgdl/) on 12/4/2007. This layer was extensively edited to form a continuous grid rather than follow large bodies of water. The Golf Course layer (Figure 54) was created by digitizing the general extent of developed golf course properties using the DOQs as a base. A list of golf courses and general locations were developed from web sites, such as www.worldgolf.com.

Layer symbolization represents our interpretation or application of the data.

A complete list of GIS layers, sources and metadata is included as Appendix B.

Appendix B. Description of GIS layers, sources, and metadata for maps used in the preparation of this report.

Layer	Type	General Source	Description	Metadata File
10mDEM	grid	USGS	1/3 arc second (10 meter) Digital Elevation Model data for the SLBE area	DEM_10m.html
Air_Monitoring	point	various	air quality monitoring stations pertinent to the SLBE area	Air_Monitoring.xls
Air_Releases	point	various	facilities on the USEPA AIRS/AFS air release list for the SLBE area	Air_Releases.xls
amphibians	point	Bowen and Beever	2007 amphibian sampling sites on North and South Manitou Islands	amphibians.xls
cities	polygon	MCGI	subset of the MGF cities layer for the SLBE area	Cities MI DDv6b.pdf
Coastal_CPI	arc	USGS	coastal change potential index for SLBE shorelines	slbe_shore - Coastal Change Potential (CPI) Assessment of Sleeping Bear Dunes National Lakeshore.htm
Counties_MI	polygon	MCGI	MGF county layer for the state of Michigan	Counties MI DDv6b.pdf
Counties_WI	polygon	WDNR	county layer for the state of Wisconsin	WI_county_boundaries.htm
county_arc	arc	MCGI	arc version of the county_poly layer	Counties MI DDv6b.pdf
county_poly	polygon	MCGI	subset of the MGF county layer for the 14 northwest lower Michigan counties	Counties MI DDv6b.pdf
Critical_Dune_Areas	polygon	MDEQ	critical dunes for Benzie and Leelanau Counties	critical_dune_area_benzie.htm, critical_dune_area_leelanau.htm
ERD	point	various	MDEQ hazardous materials discharge sites in the SLBE area	ERD.xls
ESI	arc	EPA	shoreline sensitivity classification extracted for SLBE shorelines	Inland_Sensitivity_Atlas.HTM
Facility_Assets	point	NPS-SLBE	SLBE pit and vault toilets, quarters, wastewater treatment systems, and water systems	SLBE_Facility_Assets.xls
Fish_poly	polygon	Dawson-MDNR	historic lake trout spawning and current lake trout refuge sites in the SLBE area	SLBE Fish Locations.xls, Lake Trout Refuge.xls
Fish_pt	point	Dawson	historic lake trout spawning sites in the SLBE area	SLBE Fish Locations.xls

MCGI = Michigan Center for Geographic Information (http://www.michigan.gov/cgi)
MGF = Michigan Geographic Framework — michigan_geographic_framework.html

Indicates significant geoprocessing and modification of source GIS data

Appendix B. Description of GIS layers, sources, and metadata for maps used in the preparation of this report (continued).

Layer	Type	General Source	Description	Metadata Files
GAP_Stewardship	polygon	MCGI	SLBE area subset of the MDNR Michigan (Lower Peninsula) GAP Land Stewardship coverage	gap_stewardship_lp.htm
GenSoilMap	polygon	NRCS	SLBE area subset of the National Soil Map (statsgo) attributed with the mapunit and muaggatt tables	Digital General Soil Map of US Metadata.pdf
golf_courses	polygon	various	generalized map of golf courses in the SLBE area	--
Groundwater_Nitrate	point	MDEQ	MDEQ nitrate data for groundwater samples in the SLBE area	deq-wd-gws-ciu-benzie-no3.pdf, deq-wd-gws-ciu-leelanau-no3.pdf
GW_Contours_arc	arc	MCGI	10 foot contours of groundwater elevation in the SLBE area	benz_con_10.shp.xml, leel_con_10.shp.xml, gran_con_10.shp.xml
GW_shed_arc	arc	derived	a delineation of the shallow groundwater-shed using ArcGIS tools and the GW_tab30 layer	--
GW_shed_poly	polygon	derived	polygon version of the GW_shed_arc layer	--
GW_tab30	grid	MCGI	a composite of county based 30 meter groundwater table elevation grids for the SLBE three county area	Benzie_WT_metadata.xml, GrandTraverse_WT_metadata.xml, Leelanau_WT_metadata.xml
GW_tab_HS	grid	derived	Groundwater Table hillshade created in ArcGIS using the GW_tab30 layer	--
Hillshade_10m	grid	derived	Ground surface elevation hillshade created in ArcGIS using the 10mDEM layer	--
Hillshade_2x	grid	derived	Ground surface elevation hillshade created in ArcGIS using the 10mDEM layer (2X vertical exaggeration)	--
Hillshade_4x	grid	derived	Ground surface elevation hillshade created in ArcGIS using the 10mDEM layer (4X vertical exaggeration)	--
Historic_Sites	point	NPS	historic buildings and structures layer for SLBE	NPS_histbldg.xml

MCGI = Michigan Center for Geographic Information (http://www.michigan.gov/cgi) michigan_geographic_framework.html
MGF = Michigan Geographic Framework

Indicates significant geoprocessing and modification of source GIS data

Appendix B. Description of GIS layers, sources, and metadata for maps used in the preparation of this report (continued).

Layer	Type	General Source	Description	Metadata Files
hydro_arc	arc	NPS	hydrologic line features in the SLBE area	NPS_Hydro.xml
hydro_arc_MI	arc	MCGI	the MGF hydrologic line features in the SLBE area	Hydrography DDv6b MI.pdf
hydro_arc_MI_SLBE	arc	MCGI	the MGF hydrologic line features in SLBE; river centerlines and SLBE boundary shoreline ownership added	Hydrography DDv6b MI.pdf
hydro_poly	polygon	NPS	hydrologic area features in the SLBE area	NPS_Hydro.xml
hydro_poly_MI	polygon	MCGI	the MGF hydrologic area features in the SLBE area	Hydrography Poly DDv6b.pdf
hydro_pt	point	NPS	hydrologic point features in the SLBE area	NPS_Hydro_pt.xml
IFMAP_3Co	grid	MCGI	subset of the MDNR IFMAP/GAP Lower Peninsula land cover for the SLBE area	IFMAP_lp_landcover.htm
IFMAP_Park	grid	MCGI	subset of the MDNR IFMAP/GAP Lower Peninsula land cover for SLBE	IFMAP_lp_landcover.htm
L_Mich_Depth	grid	MCGI	a 60 meter water depth grid for Lake Michigan	--
L_Mich_ENC_Signal	point	NOAA	ENC signal light features from charts 14901 and 14902	NOAA_ENC_download.TXT
L_Mich_Hillshade	grid	derived	Lake Michigan depth hillshade created in ArcGIS using the L_Mich_Depth grid layer	--
L_Michigan	polygon	NOAA	polygon version of the L_Michigan_Coastline layer	NOAA_ENC_download.TXT
L_Michigan_Coastline	arc	NOAA	merged and cleaned ENC coastline features from charts 14901 and 14902	NOAA_ENC_download.TXT
L_Michigan_Contours	arc	GLIN	5 meter contours of Lake Michigan depth	lake_michigan_bathymetry.xml
Land_Use_1978	polygon	NPS	subset of MDNR 1978 land use files for SLBE	NPS_Land_Use_1978.xml
LandTypeAssociations	polygon	MCGI	the MI Natural Features Inventory Landtype Associations of Northern Michigan Section VII	lta_sec7_metadata.htm
LUST	point	various	MDEQ leaking underground storage sites in the SLBE area	LUST.xls

MCGI = Michigan Center for Geographic Information (http://www.michigan.gov/cgi) — michigan_geographic_framework.html
MGF = Michigan Geographic Framework

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Appendix B. Description of GIS layers, sources, and metadata for maps used in the preparation of this report (continued).

Layer	Type	General Source	Description	Metadata Files
Manitou_Passage_ bottomland_preserve	polygon	legislation	spatial extent of the Manitou Passage Bottomland Preserve	manitou_Passage_Bottomland_ Preserve.txt
mask_arc	arc	derived	a general upland/Lake Michigan mask layer for the SLBE area created from the MGF Counties_MI layer	--
mask_poly	polygon	derived	the polygon version of the mask_arc layer	--
mask_poly_3co_area	polygon	derived	an upland/Lake Michigan mask layer for the SLBE three county area created from the MGF Counties_MI layer	--
MCD_3co	polygon	MCGI	subset of the MGF minor civil divisions layer (townships and Traverse City) for the SLBE three county area	MCD DDv6b.pdf
NPS_Veg	polygon	NPS	the NPS 1999 (1983-1986) vegetation map for SLBE	NPS_veg.xml
OSDS	point	various	MDEQ permitted onsite sewage disposal systems in the SLBE area	OSDS.xls
park_arc	arc	NPS-MCGI	SLBE boundaries (union of the NPS park boundary layer and the MGF Counties layer for L Michigan shorelines)	NPS_park_boundary, Counties MI DDv6b.pdf
park_land_status_tracts	polygon	NPS	land status (ownership) for SLBE	NPS_tracts.xml
park_poly	polygon	NPS-MCGI	polygon version of the park_arc layer	NPS_park_boundary, Counties MI DDv6b.pdf
Population	polygon	census	block level map of census summary file 1 intersected with the watershed_park_poly layer	TIGER_2000Census_meta.txt
Port_Oneida	polygon	NPS-SLBE	generalization of the historic district map on the SLBE web site (http://www.nps.gov/slbe/planyourvisit/povirtualtour.htm)	--
Provinces	polygon	ESRI	general Canadian Province layer	ESRI_province.shp.xml

MCGI = Michigan Center for Geographic Information (http://www.michigan.gov/cgi)

MGF = Michigan Geographic Framework — michigan_geographic_framework.html

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Appendix B. Description of GIS layers, sources, and metadata for maps used in the preparation of this report (continued).

Layer	Type	General Source	Description	Metadata Files
Quaternary_Geology	polygon	USGS	subset of the Quaternary Geologic Atlas of the United States for the SLBE area	Quaternary Geologic Map of the Lake Superior 4x6 Quadrangle, US and Canada.htm
roads	arc	NPS	updated NPS roads layer for the SLBE area	NPS_roads.xml
Roads_US_State	arc	MCGI	the MGF All Roads layer selected for US and state highways (FCC=A21) in the SLBE area	All Roads MI DDv6b.pdf
Shipping_Lanes	arc	NOAA	merged and cleaned ENC track and ferry line features from charts 14901 and 14902	NOAA_ENC_download.TXT
Shipping_Lanes_direction	point	NOAA	direction of recommended track lines based on description and orientation information in the Shipping_Lanes layer	NOAA_ENC_download.TXT
SLBE_Annotation	annotation		common map annotation created in ArcGIS suitable for map scales 1:200,000 to 1:325,000	--
States	polygon	ESRI	small scale general US state layer	ESRI_states.shp.xml
TR_grid_arc	arc	MCGI	edited version of the MI statewide_plss_town_range layer cut to the larger SLBE area	statewide_plss_town_range.htm
TR_grid_poly	polygon	MCGI	polygon version of TR_grid_arc	statewide_plss_town_range.htm
US_Lakes	polygon	ESRI	small scale general US lake layer	ESRI_lakes.shp.xml
villages	polygon	MCGI	subset of the MGF Villages layer for the SLBE area	Villages MI DDv6b.pdf
Water_Qual_Open_Lake	point	GLENDA-NPS	GLENDA and Horizon Lake Michigan water quality sampling sites in the SLBE area	SLBE open lake sites.xls
Water_Quality	point	NPS	NPS water quality sampling in SLBE	NPS_Water_quality.xml
Water_Wells	point	MDEQ	the MI well logic database for the SLBE area with minor edits	wwells_readme.txt
watershed_above_arc	arc	derived	arc version of watershed_park_poly only for the outer boundary of the watershed areas upgradient of SLBE	--

MCGI = Michigan Center for Geographic Information (http://www.michigan.gov/cgi) michigan_geographic_framework.html
MGF = Michigan Geographic Framework

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Appendix B. Description of GIS layers, sources, and metadata for maps used in the preparation of this report (continued).

Layer	Type	General Source	Description	Metadata Files
watershed_park_poly	polygon	derived	SLBE and watershed areas upgradient of SLBE	--
watersheds_arc	arc	MCGI	arc version of the watersheds_poly layer	watershed24k_metadata.htm
watersheds_poly	polygon	MCGI	subset of the MDEQ watershed layer for the SLBE area	watershed24k_metadata.htm
Wetlands	polygon	MDEQ	union of Benzie and Leelanau Counties Final Wetland Inventory layers (hydric soils, 1978 landuse lowlands, NWI) cut for SLBE	Final_Wetland_Inventory_ Benzie.pdf, Final_Wetland_Inventory_ Leelanau.pdf
WI_MI_Boundary	arc	WDNR	the Wisconsin Upper Michigan boundary extracted from the Counties_WI layer	WI_county_boundaries.htm

MCGI = Michigan Center for Geographic Information (http://www.michigan.gov/cgi) michigan_geographic_framework.html
MGF = Michigan Geographic Framework

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Appendix C. Federal and state endangered and threatened species in SLBE (MNFI 2006).

Type	Scientific name	Common name	Habitat
Federal- and State-Endangered			
	Charadrius melodus	Piping plover	Dunes
	Mimulus glabratus var. *michiganensis*	Michigan monkey-flower	Lakeshore
Federal- and State-Threatened			
	Cirsium pitcheri	Pitcher's thistle	Dunes
	Haliaeetus leucocephalus	Bald eagle*	Aquatic environments
State-Endangered			
	Asio flammeus	Short-eared owl	Emergent wetlands
	Rallus elegans	King rail	Freshwater marshes
	Dendroica discolor	Prairie warbler	Dunes
	Castanea dentata	American chestnut	Oak forests
State-Threatened	*Buteo lineatus*	Red-shouldered hawk	Forested floodplain
	Falco columbarius	Merlin	Dunes
	Pandion haliaetus	Osprey	Aquatic environments
	Ixobrychus exilis	Least bittern	Freshwater marshes
	Sterna caspia	Caspian tern	Dunes, coastal wetlands
	Sterna hirundo	Common tern	Dunes, coastal wetlands
	Ammodramus henslowii	Henslow's sparrow	Grasslands
	Acipenser fulvescens	Lake sturgeon	Offshore waters
	Coregonus artedi	Cisco/lake herring	Offshore waters
	Berula erecta	Cutleaf waterparsnip	Springs
	Panax quinquefolius	American ginseng	Rich woods
	Artemisia ludoviciana	Louisiana sagewort	Dunes, dry prairies
	Carex oligocarpa	Eastern few-fruit sedge	Rich woods
	Carex platyphylla	Broad-leaved sedge	Dry northern hardwoods
	Bromus pumpellianus	Pumpelly's brome grass	Perched dunes
	Pterospora andromedea	Giant pinedrops	Dry conifer forests
	Botrychium campestre	Iowa moonwort	Perched dunes
	Botrychium hesperium	Western moonwort	Dunes
	Calypso bulbosa	Fairy-slipper	Coniferous forests
	Triphora trianthophora	Three birds orchid	Rich woods
	Asplenium rhizophyllum	Walking fern	Dolomite boulders
	Asplenium trichomanes-ramosum	Brightgreen spleenwort	Calcareous cliffs
	Orobanche fasciculata	Clustered broomrape	Dunes
		proposed federal delisting	

Appendix D. Plants of Sleeping Bear Dunes National Lakeshore mentioned in this report.

Nomenclature for plant names in this report generally follows that of Hazlett (1986, 1989, 1991). Hazlett (1991) generally followed Lellinger (1985) for ferns and fern allies, and Gleason and Cronquist (1963) for those groups not covered by Voss (1972, 1985). Common names used by Hazlett for some species followed Peterson and McKenny (1968), and synonomy for orchids followed Case (1987).

We checked for current preferred genus and species names at the USDA PLANTS database (NRCS 2008). Common names used by Hazlett were maintained unless conflicts arose (two scientific names with the same common name), in which case the common name from the PLANTS database was used, with the preferred Michigan common name where available. Some plants listed by Hazlett appear to have no current scientific or common names; these are marked with a question mark. All plant species were checked against the SLBE lists of native and non-native plants (NPSpecies 2007); those that could not be matched are marked with an asterisk.

Common Name	**Scientific Name**
a cotton-grass*	*Eriophorum virgatum* (?)
a goldenrod*	*Solidago gramineus* (?)
a sphagnum moss	*Sphagnum magellanicum*
a touch-me-not*	*Impatiens balsamea* (?)
adder's tongue	*Erythronium americanum* Ker Gaul
American elm	*Ulmus americana* L.
American germander	*Teucrium canadense* L.
American starflower	*Trientalis borealis* Raf. ssp. *borealis*
American yew	*Taxus canadensis* Marshall
aspen	*Populus* spp.
Austrian pine	*Pinus nigra* Arnold
autumn olive	*Elaeagnus umbellata* Thunb.
baby's breath	*Gypsophila paniculata* L.
bald spike rush	*Eleocharis erythropoda* Stuedel
balsam fir	*Abies balsamea* (L.) Mill.
balsam groundsel	*Packera paupercula* (Michx.) A. Löve & D. Löve
Baltic rush	*Juncus balticus* Willd.
baneberry	*Actaea* sp. L.
barberry*	*Berberis* spp. L.
bearberry	*Arctostaphylos uva-ursi* (L.) Spreng.
basswood	*Tilia americana* L.
beach heather	*Hudsonia tomentosa* Nutt. var. *tomentosa*
beaked hazelnut	*Corylus cornuta* Marsh.
beech	*Fagus grandifolia* Ehrh.
big-tooth aspen	*Populus grandidentata* Michx.
bitter dock	*Rumex obtusifolius* L.
black ash	*Fraxinus nigra* Marshall
black birch*	*Betula lenta*
black cherry	*Prunus serotina* Ehrh.
black huckleberry	*Gaylussacia baccata* (Wang.) K. Koch
black locust	*Robinia pseudoacacia* L.
black oak	*Quercus velutina* Lam.
black spruce	*Picea mariana* (Miller) BSP
bladder campion	*Silene latifolia* Poir. ssp. *alba* (Mill.) Greuter & Burdet
bladder fern	*Cystopteris bulbifera* (L.) Bernh.
blue bead lily	*Clintonia borealis* (Aiton) Raf.

Appendix D. Plants of Sleeping Bear Dunes National Lakeshore mentioned in this report (continued).

Common Name	**Scientific Name**
blue joint	*Calamagrostis canadensis* (Michaux) Beauv.
blue lyme grass	*Leymus arenarius* L.
blue spruce	*Picea pungens* Engelm.
blunt leaved orchid	*Platanthera obtusata* (Banks ex Pursh) Lindl.
bog birch	*Betula pumila* L.
bog candle	*Platanthera dilatata* (Pursh) Lindl. ex Beck
bog laurel	*Kalmia polifolia* (Wang.)
bog-rosemary	*Andromeda glaucophylla* Link
boneset	*Eupatorium perfoliatum* L.
bottlebrush sedge	*Carex hystericina* Willd.
bouncing-bet	*Saponaria officinalis* L.
broad beech fern	*Phegopteris hexagonoptera* (Michx.) Fée
broadleaf pondweed	*Stuckenia pectinata* (L.) Böerner
buckbean	*Menyanthes trifoliata* L.
buckthorn*	*Rhamnus* sp. L.
bulrushes	*Scirpus* spp.
bunchberry	*Cornus canadensis* L.
Canada mayflower	*Maianthemum canadense* Desf.
Canada thistle	*Cirsium arvense* (L.) Scop.
cardinal flower	*Lobelia cardinalis* L.
chair maker’s rush	*Schoenoplectus americanus* (Pers.) Volkart ex Schinz & R. Keller
chokeberry*	*Aronia prunifolia* (Marsh) Rehder
chokecherry	*Prunus virginiana* L.
cinnamon fern	*Osmunda cinnamomea* L.
Clinton’s wood fern	*Dryopteris clintoniana* (D. C. Eaton) Powell
clubmoss	*Lycopodium* spp. L.
common bladderwort	*Utricularia macrorhiza* Leconte
common cattail	*Typha latifolia* L.
common duckweed	*Lemna minor* L.
common skullcap	*Scutellaria galericulata* L.
common spikerush	*Eleocharis palustris* (L.) Roem. & Schult. var. *palustris*
coontail	*Ceratophyllum demersum* L.
creeping juniper	*Juniperus horizontalis* Moench
creeping snowberry	*Gaultheria hispidula* (L.) Muhl
creeping spearwort	*Ranunculus flammula* L. var. *filiformis* (Michx.) Hook.
crested shield fern	*Dryopteris cristata* (L.) A. Gray
curly leaf pondweed	*Potamogeton crispus* L.
cutleaf waterparsnip	*Berula erecta* (Hudson) Cov.
deadly nightshade	*Solanum dulcamara* L.
Douglas-fir*	*Pseudotsuga* spp. Carrière
duck-potato	*Sagittaria latifolia* Willd.
dwarf enchanter’s-nightshade	*Circaea alpina* L.
early coralroot	*Corallorhiza trifida* Chat.
eastern leatherwood	*Dirca palustris* L.
eastern marsh fern	*Thelypteris palustris* Schott
eelgrass	*Vallisneria* sp. L.
elk sedge	*Carex garberi* Fernald.
elliptic spikerush	*Eleocharis elliptica* Kunth
elodea	*Elodea canadensis* Michaux
Eurasian water-milfoil	*Myriophyllum spicatum* L.

Appendix D. Plants of Sleeping Bear Dunes National Lakeshore mentioned in this report (continued).

Common Name	Scientific Name
European fly honeysuckle	*Cirsium palustre* (L.) Scop.
European marsh thistle	*Lonicera xylosteum* L.
fascicled (clustered) broom-rape	*Orobanche fasciculata* Nutt.
fen orchid	*Liparis loeselii* (L.) Richard
fineleaf pondweed	*Stuckenia filiformis* (Pers.) Böerner ssp. *filiformis*
flatstem pondweed	*Potamogeton zosterformis* Fern.
floating pondweed	*Potamogeton natans* L.
fowl manna grass	*Glyceria striata* (Lam.) Hitchc.
Fries' pondweed	*Potamogeton friesii* Rupr.
fringed polygala	*Polygala paucifolia* Willd.
fringed willow-herb	*Epilobium ciliatum* Raf.
garlic mustard	*Alliaria petiolata* (M. Bieb) Cavara & Grande
glossy buckthorn	*Rhamnus frangula* L.
golden saxifrage	*Chrysosplenium americanum* Hooker.
goldthread	*Coptis trifolia* (L.) Salisb.
grass-leaved goldenrod	*Euthamia graminifolia* (L.) Nutt. var. *graminifolia*
greater duckweed	*Spirodela polyrhiza* (L.) Schleiden
hard-stem bulrush	*Scirpus acutus* Bigelow
hemlock (eastern hemlock)	*Tsuga canadensis* (L.) Carrière
hidden-fruited bladderwort	*Utricularia geminiscapa* Benj.
Hill's pondweed*	*Potamogeton hillii* Morong
honeysuckle, bush honeysuckle	*Lonicera* spp.
hooded lady's-tresses	*Spiranthes romanzoffiana* Cham
hooked crowfoot	*Ranunculus recurvatus* Poiret
hornwort	*Typha* x *glauca* Godr.
hybrid cattail	*Ceratophyllum* sp. L.
Illinois pondweed	*Potamogeton illinoensis* Morong
inland sedge	*Carex interior* Bailey
ironwood	*Ostrya virginiana* (Mill.) K. Koch
jack pine	*Pinus banksiana* Lamb.
jack-in-the-pulpit	*Arisaema triphyllum* (L.) Schott
Jimson-weed	*Datura stramonium* L.
Joe-Pye-weed	*Eupatorium maculatum* L.
Kalm's St. John's-wort	*Hypericum kalmianum* L.
knotted rush	*Juncus nodosus* L.
knotweed	*Polygonum* sp. L.
lady fern	*Athyrium filix-femina* (L.) Roth
lady's thumb	*Polygonum persicaria* L.
larch (tamarack)	*Larix laricina* (Du Roi) K. Koch
large yellow sedge	*Carex flava* L.
largeleaf pondweed	*Potamogeton amplifolius* Tuckerman
larger Canadian St. John's–wort	*Hypericum majus* (A. Gray) Britton
leafy pondweed	*Potamogeton foliosus* Raf.
leafy spurge	*Euphorbia esula* L.
leather-leaf	*Chamaedaphne calyculata* (L.) Moench
lesser bladderwort	*Utricularia minor* L.
lombardy poplar	*Populus nigra* L.
longhair sedge	*Carex comosa* Boott
mad dog skullcap	*Scutellaria lateriflora* L.
maple-leaf viburnum	*Viburnum acerifolium* L.
mare's-tail	*Hippuris vulgaris* L.

Appendix D. Plants of Sleeping Bear Dunes National Lakeshore mentioned in this report (continued).

Common Name	Scientific Name
marram grass (beach grass)	*Ammophila breviligulata* Fern.
marsh arrow grass	*Triglochin palustre* L.
marsh bellflower	*Campanula aparinoides* Pursh
marsh cinquefoil	*Comarum palustre* L.
marsh marigold	*Caltha palustris* L.
marsh St. John's-wort	*Triadenum fraseri* (Spach) Gl
mat panic grass	*Dichanthelium acuminatum* (Sw.) Gould & C.A. Clark var. *fasciculatum* (Torr.) Freckmann
meadowsweet	*Spiraea alba* Du Roi
Michigan holly	*Ilex verticillata* (L.) Gray
Michigan monkey-flower	*Mimulus glabratus* var. *michiganensis* (Pennell) Fassett
moonwort	*Botrychium* spp.
Morrow's honeysuckle	*Lonicera morrowii* A. Gray
mountain maple	*Acer spicatum* Lam.
mountain wood-sorrel	*Oxalis montana* Raf.
muskgrass	*Chara* spp., *Chara vulgaris*
naked miterwort	*Mitella nuda* L.
narrowleaf pondweed	*Potamogeton strictifolius* Benn.
narrow-leaved bur-reed*	*Sparganium emersum Rehmann*
narrow-leaved cattail	*Typha angustifolia* L.
narrow-panicle rush	*Juncus brevicaudatus* (Englelm.) Fern.
nodding water-nymph	*Najas flexilis* Willd.
northern bugleweed	*Lycopus uniflorus* Michaux
northern green orchid	*Platanthera aquilonis* Sheviak
northern red oak	*Quercus rubra* L.
northern reedgrass	*Calamagrostis stricta* (Timm) Koeler ssp. *inexpansa* (A. Gray) C.W. Greene
Norway spruce	*Picea abies* (L.) Karst.
oak fern	*Gymnocarpium dryopteris* (L.) Newm.
Oakes' pondweed	*Potamogeton oaksianus* Robbins
Ontario lobelia	*Lobelia kalmii* L.
Oriental bittersweet	*Celastrus orbiculatus* Thunb.
ostrich fern	*Matteucia struthiopteris* (L.) Todaro
partridgeberry	*Mitchella repens* L.
peat moss	*Sphagnum* spp.
periwinkle	*Vinca minor* L.
pickerel weed	*Pontederia* spp. L.
pin cherry	*Prunus pensylvanica* L. f.
Pitcher's thistle	*Cirsium pitcheri* (Torrey) Torrey & A. Gray
pitcher-plant	*Sarracenia purpurea* L.
prairie moonwort	*Botrychium campestre* W.H.Wagner & Farrar
purple avens	*Geum rivale* L.
purple loosestrife	*Lythrum salicaria* L.
purple-stem beggar-ticks	*Bidens connata* Muhl.
pussy willow	*Salix discolor* Muhl.
quaking aspen	*Populus tremuloides* Michx.
rannoch-rush	*Scheuchzeria palustris* L.
raspberries	*Rubus* sp.
rattlesnake fern	*Botrychium virginianum* (L.) Sw.
rattlesnake mannagrass	*Glyceria canadensis* (Michaux) Trin.
red elderberry	*Sambucus racemosa* L. subs *pubens* (Michaux.) House var. *pubens* (Michx.) Koehne

Appendix D. Plants of Sleeping Bear Dunes National Lakeshore mentioned in this report (continued).

Common Name	Scientific Name
red maple	*Acer rubrum* L.
red pine	*Pinus resinosa* Aiton
red-osier dogwood	*Cornus sericea* ssp. *sericea*
reed	*Phragmites australis* (Cav.) Steudel
reed canary grass*	*Phalaris arundinacea* L.
Richardson's pondweed	*Potamogeton richardsonii* (A. Bennett) Rydb.
Robbins' pondweed	*Potamogeton robbinsii* Oakes
royal fern	*Osmunda regalis* L.
rushes	*Juncus* spp.
sage willow	*Salix candida* Willd.
sand cherry	*Prunus pumila* L.
sand reed grass (dune reed)	*Calamovilfa longifolia* (Hook.) Scribn.
sandbar willow	*Salix exigua* Nutt.
scarlet oak	*Quercus coccinea* Münchh
Scots pine	*Pinus sylvestris* L.
sea rocket	*Cakile edentula* (Bigelow) Hook.
seaside spurge	*Chamaesyce polygonifolia* (L.) Small
sedges	*Carex* spp.
sensitive fern	*Onoclea sensibilis* L.
serviceberry	*Amelanchier* spp. Medik.
short-headed rush	*Juncus brachycephalus* (Engelm.) Buch.
shortspike water-milfoil	*Myriophyllum sibiricum* Kom.
showy fly honeysuckle	*Lonicera x bella* Zabel
showy lady-slipper	*Cypripedium reginae* Walter
shrubby cinquefoil	*Dasiphora fruticosa* (L.) Rydb. *ssp. floribunda* (Pursh) Kartesz
silky dogwood	*Cornus amomum* Miller
silverweed	*Argentina anserina* (L.) Rydb.
small bur-reed	*Sparganium minimum* (Hartman) Fries
small cranberry	*Vaccinium oxycoccos* L.
small pondweed	*Potamogeton pusillus* L. ssp. *tenuissimus*
small purple-fringed orchid	*Platanthera psycodes* (L.) Lindl.
southern blue flag	*Iris virginica* L.
speckled alder	*Alnus incana* (L.) Moench ssp. *rugosa* (Du Roi) R.T. Clausen
spotted knapweed	*Centaurea* spp. L.
spotted touch-me-not	*Impatiens capensis* Meerb.
spotted water-hemlock	*Cicuta maculata* L.
spring beauty	*Claytonia caroliniana* Michx.
star duckweed	*Lemna trisulca* L.
stinging nettle	*Urtica dioica* L.
striped coralroot	*Corallorhiza striata* Lindley
striped maple	*Acer pensylvanicum* L.
sugar maple	*Acer saccharum* Marsh.
sundew	*Drosera rotundifolia* L.
swamp loosestrife	*Decodon verticillatus* (L.) Ell
swamp milkweed	*Asclepias incarnata* L.
swamp rose	*Rosa palustris* Marshall
swamp-candle	*Lysimachia terrestris* (L.) BSP.
sweet gale	*Myrica gale* L.
sweet low blueberry	*Vaccinium angustifolium* Aiton
sweet white violet	*Viola blanda* Willd.
sweetroot	*Osmorhiza* spp. Raf.

Appendix D. Plants of Sleeping Bear Dunes National Lakeshore mentioned in this report (continued).

Common Name	Scientific Name
switch grass	*Panicum virgatum* L.
tape-grass	*Vallisneria americana* Michaux
Tatarian honeysuckle	*Lonicera taterica* L.
teasels*	*Dipsacus* sp. L.
thinleaf cottonsedge	*Eriophorum viridicarinatum* (Engelm.) Fern.
three-birds orchid	*Triphora trianthophora* (Sw.) Rydb.
three-leaf Solomon's seal	*Maianthemum trifolium* (L.) Sloboda
three-way sedge	*Dulichium arundinaceum* (L.) Britton
tree of heaven	*Ailanthus altissima* (Mill.) Swingle
trillium	*Trillium* spp. L.
tufted loosestrife	*Lysimachia thyrsiflora* L.
turtle-head	*Chelone glabra* L.
twig-rush	*Cladium mariscoides* (Muhl.) Torrey
twinflower	*Linnaea borealis* L.
twoleaf water-milfoil	*Myriophyllum heterophyllum* Michaux
variableleaf pondweed	*Potamogeton gramineus* L.
variegated yellow pond lily	*Nuphar lutea* (L.) Sm. ssp. *variegata* (Durand) E.O. Beal
velvet-leaf blueberry	*Vaccinium myrtilloides* Michaux
water dock*	*Rumex verticillatus* L.
water horehound	*Lycopus americanus* Muhl.
water horsetail	*Equisetum fluviatile* L.
water sedge	*Carex aquatilis* Wahlenb.
water smartweed	*Polygonum amphibium* L.
water star-grass	*Heteranthera dubia* (Jacq.) MacM.
watercress	*Nasturtium officinale* R.Br
water-hemlock	*Cicuta* sp.
water-marigold	*Megalodonta beckii* (Torr.) Greene
water-meal	*Wolffia punctata*
water-parsnip	*Sium suave* Walter
water-shield	*Brassenia schreberi* J.F. Gmelin
wheat sedge	*Carex atherodes* Sprengel
white ash	*Fraxinus americana* L.
white birch	*Betula papyrifera* Marsh.
white cedar	*Thuja occidentalis* L.
white oak	*Quercus alba* L.
white pine (eastern white pine)	*Pinus strobus* L.
white spruce	*Picea glauca* (Moench) Voss
white sweet clover	*Melilotus alba* Medikus, orth. var.
white water crowfoot	*Ranunculus longirostris* Godron
white water lily	*Nymphaea odorata* Aiton
whitestem pondweed	*Potamogeton praelongus* Wulfen
wild black current	*Ribes americanum* Miller
wild gooseberry	*Ribes cynosbati* L.
wild leek	*Allium tricoccum* Aiton
wild mint	*Mentha arvensis* L.
wild parsnip	*Pastinaca sativa* L.
wild strawberry	*Fragaria virginiana* Miller
willows	*Salix* spp.
witch hazel	*Hamamelis virginiana* L.
wool-grass	*Scirpus cyperinus* (L.) Kunth
wooly-fruit sedge	*Carex lasiocarpa* Ehrh.

Appendix D. Plants of Sleeping Bear Dunes National Lakeshore mentioned in this report (continued).

Common Name	**Scientific Name**
wormwood	*Artemisia campestris* L.
yellow archangel	*Lamiastrum galeobdolon* (L.) Ehrend. & Polatschek
yellow avens	*Geum aleppicum* Jacq.
yellow birch	*Betula alleghaniensis* Britton
yellow monkeyflower	*Mimulus glabratus* Kunth var. *jamesii* (Torr. & A. Gray ex Benth.) A. Gray
yellow rocket	*Barbarea vulgaris* R. Br.

Appendix E. Fishes of Lake Michigan (Eshenroder et al. 1995) and of SLBE inland waters (Kelly and Price 1979; Fessell 2007).

Family	Scientific Name	Common Name
Petromyzontidae	*Ichthyomyzon castaneus**	chestnut lamprey
	*Ichthyomyzon fossor**	northern brook lamprey
	*Ichthyomyzon unicuspis**	silver lamprey
	*Lampetra lamottei**	American brook lamprey
	Petromyzon marinus#*	sea lamprey (A)
Polyodontidae	*Polydon spathula*	paddlefish (E)
Acipenseridae	*Acipenser fulvescens#*	lake sturgeon
Lepisosteidae	*Lepisosteus osseus**	longnose gar
	Lepisosteus platostomus	shortnose gar (A)
Amiidae	*Amia calva**	bowfin
Anguillidae	*Anguilla rostrata*	American eel (A)
Hiodontidae	*Hiodon tergisus*	mooneye
Clupeidae	*Alosa pseudoharengus*#*	alewife (A)
	Dorosoma cepedianum	gizzard shad
Salmonidae (Salmoninae)	*Oncorhynchus gorbuscha*	pink salmon (A)
	Oncorhynchus kisutch#*	coho salmon (P)
	Oncorhynchus tshawytscha#*	chinook salmon (P)
	Oncorhynchus mykiss#*	steelhead (P)
	Salmo salar#	Atlantic salmon (P)
	Salmo trutta#*	brown trout (P)
	Salvelinus fontinalis#*	brook trout
	Salvelinus namaycush#*	lake trout
	*Salvelinus fontinalis x namaycush**	splake
	Thymallus arcticus	arctic grayling (E)
Salmonidae (Coregoninae)	*Coregonus clupeaformis#*	lake whitefish
	Coregonus artedi#*	lake herring (cisco)
	Coregonus hoyi#	bloater
	Coregonus johannae	deepwater cisco (E)
	Coregonus kiyi	kiyi (E)
	Coregonus nigripinnis	blackfin cisco (E)
	Coregonus reighardi	shortnose cisco (E)
	Coregonus zenithicus	shortjaw cisco (E)
	Prosopium cylindraceum#	round whitefish
Osmeridae	*Osmerus mordax*#*	rainbow smelt (A)
Umbridae	*Umbra limi**	central mudminnow
Esocidae	*Esox americanus*	grass pickerel
	*Esox lucius**	northern pike
	*Esox lucius x Esox masquinongy**	tiger muskie
	*Esox masquinongy**	muskellunge
Cyprinidae	*Phoxinus eos**	northern redbelly dace
	Couesius plumbeus#*	lake chub
	Ctenopharyngodon idella	grass carp
	Cyprinus carpio#*	carp

P=Planned introduction A=Accidental introduction E=Extinct
*found in SLBE inland waters #found in SLBE nearshore waters

Appendix E. Fishes of Lake Michigan (Eshenroder et al. 1995) and of SLBE inland waters (Kelly and Price 1979; Fessell 2007) (continued).

Family	Scientific Name	Common Name
Cyprinidae (continued)	*Carassius auratus*	goldfish (A)
	Margariscus margarita	pearl dace
	*Nocomis bigutatus**	hornyhead chub
	*Notemigonus crysoleucas**	golden shiner
	Notropis atherinoides#*	emerald shiner
	Notropis cornutus#*	common shiner
	*Notropis heterodon**	blackchin shiner
	*Notropis heterolepis**	blacknose shiner
	Notropis hudsonius#*	spottail shiner
	*Notropis rubellus**	rosyface shiner
	Notropis spilopterus	spotfin shiner
	Notropis stramineus#*	sand shiner
	*Notropis volucellus**	mimic shiner
	Pimephales notatus#*	bluntnose minnow
	Pimephales promelas	fathead minnow
	Rhinichthys cataractae#*	longnose dace
	*Rhinichthys atratulus**	blacknose dace
	*Semotilus atromaculatus**	creek chub
Catostomidae	*Carpiodes cyprinus*	quillback
	Catostomus catostomus#*	longnose sucker
	Catostomus commersoni#*	white sucker
	Hypentelium nigricans	northern hogsucker
	Erimyzon sucetta	lake chubsucker
	Ictiobus niger	black buffalo
	*Moxostoma anisurum**	silver redhorse
	Moxostoma erythrurum#	golden redhorse
	Moxostoma valenciennesi	greater redhorse
	*Moxostoma macrolepidotum**	shorthead redhorse
Ictaluridae	*Ictalurus natalis**	yellow bullhead
	*Ictalurus melas**	black bullhead
	*Ictalurus nebulosus**	brown bullhead
	Ictalurus punctatus#*	channel catfish
Percopsidae	*Percopsis omiscomaycus#*	troutperch
Gadidae	*Lota lota#*	burbot
Cyprinodontidae	*Fundulus diaphanus**	banded killifish
Atherinidae	*Labidesthes sicculus**	brook silverside

P=Planned introduction A=Accidental introduction E=Extinct
*found in SLBE inland waters #found in SLBE nearshore waters

Appendix E. Fishes of Lake Michigan (Eshenroder et al. 1995) and of SLBE inland waters (Kelly and Price 1979; Fessell 2007) (continued).

Family	Scientific Name	Common Name
Gasterosteidae	*Culaea inconstans**	brook stickleback
	Gasterosteus aculeatus	threespine stickleback (A)
	Pungitius pungitius#	ninespine stickleback
Percichthyidae	*Morone americana**	white perch (A)
	Morone chrysops	white bass
Centrarchidae	*Ambloplites rupestris**	rock bass
	*Lepomis cyanellus**	green sunfish
	*Lepomis gibbosus**	pumpkinseed
	*Lepomis macrochirus**	bluegill
	*Lepomis megalotis**	longear sunfish
	Micropterus dolomieu#*	smallmouth bass
	*Micropterus salmoides**	largemouth bass
	Pomoxis annularis	white crappie
	*Pomoxis nigromaculatus**	black crappie
Percidae	*Perca flavescens*#*	yellow perch
	Sander canadense	sauger
	Sander vitreus#*	walleye
	*Etheostoma exile**	Iowa darter
	*Etheostoma flabellare**	fantail darter
	Etheostoma nigrum#*	Johnny darter
	*Percina caprodes**	logperch
	*Percina maculata**	blackside darter
Sciaenidae	*Aplodinotus grunniens*	freshwater drum
Gobiidae	*Neogobius melanostomus#*	round goby (A)
Cottidae	*Cottus bairdi**	mottled sculpin
	Cottus cognatus#*	slimy sculpin
	Cottus ricei#	spoonhead sculpin
	Myoxocephalus thompsoni#	deepwater sculpin

P=Planned introduction A=Accidental introduction E=Extinct
*found in SLBE inland waters #found in SLBE nearshore waters

Appendix F. Exotic aquatic species in the Lake Michigan and Betsie-Platte watersheds (USGS 2007a).

4060200 Lake Michigan

Type	Family	Scientific name	Common name	Native habitat	Origin
Algae	Biddulphiaceae	*Biddulphia laevis*	diatom	Marine	Exotic
Algae	Stephanodiscaceae	*Cyclotella atomus*	diatom	Marine	Exotic
Algae	Stephanodiscaceae	*Cyclotella cryptica*	diatom		Exotic
Algae	Stephanodiscaceae	*Cyclotella pseudostelligera*	diatom		Exotic
Algae	Stephanodiscaceae	*Cyclotella woltereki*	diatom	Freshwater	Unknown
Algae	Fragilariaceae	*Diatoma ehrenbergii*	diatom		Exotic
Algae	Ulvaceae	*Enteromorpha flexuosa*	green alga	Freshwater	Unknown
Algae	Sphacelariaceae	*Sphacelaria fluviatilis*	brown alga	Marine	Exotic
Algae	Sphacelariaceae	*Sphacelaria lacustris*	brown alga	Marine	Exotic
Algae	Stephanodiscaceae	*Stephanodiscus binderanus*	diatom	Brackish	Exotic
Algae	Stephanodiscaceae	*Stephanodiscus subtilis*	diatom	Marine	Exotic
Annelids-Oligochaetes	Tubificidae	*Branchiura sowerbyi*	a tubificid worm	Freshwater-Marine	Exotic
Annelids-Oligochaetes	Naididae	*Ripistes parasita*	an oligochaete	Marine	Exotic
Arthropoda	Erirhinidae	*Tanysphyrus lemnae*	duckweed/aquatic weevil	Freshwater	Exotic
Bacteria	Pseudomonadaceae	*Aeromonas salmonicida*	furunculosis, ulcer disease, erythrodermatitis	Freshwater-Marine	Exotic
Bacteria	Corynebacteriaceae	*Renibacterium (Corynebacterium) salmoninarum*	bacterial kidney disease (BKD), Dee disease	Freshwater-Marine	Exotic
Coelenterates-Hydrozoans	Clavidae	*Cordylophora caspia*	freshwater hydroid	Freshwater-Marine	Exotic
Crustaceans-All		*Heteropsyllus nr. nunni*	harpacticoid copepod	Unknown	Unknown
Crustaceans-Amphipods	Gammaridae	*Echinogammarus ischnus*	an amphipod	Freshwater	Exotic
Crustaceans-Amphipods	Gammaridae	*Gammarus fasciatus*	freshwater shrimp	Freshwater	Native Transplant
Crustaceans-Amphipods	Gammaridae	*Gammarus tigrinus*	amphipod	Brackish	Native Transplant
Crustaceans-	Cercopagidae	*Bythotrephes longimanus*	spiny water flea	Freshwater	Exotic

Cladocerans

Appendix F. Exotic aquatic species in the Lake Michigan and Betsie-Platte watersheds (USGS 2007a) (continued).

4060200 Lake Michigan

Type	**Family**	**Scientific name**	**Common name**	**Native habitat**	**Origin**
Crustaceans-Cladocerans	Cercopagidae	*Cercopagis pengoi*	fish-hook water flea	Freshwater	Exotic
Crustaceans-Cladocerans	Daphnidae	*Daphnia lumholtzi*	water flea	Freshwater	Exotic
Crustaceans-Cladocerans	Bosminidae	*Eubosmina coregoni*	water flea	Freshwater	Exotic
Crustaceans-Cladocerans	Bosminidae	*Eubosmina maritima*	a cladoceran	Freshwater	Exotic
Crustaceans-Copepods	Temoridae	*Eurytemora affinis*	a calanoid copepod	Freshwater-Marine	Native Transplant
Crustaceans-Copepods	Canthocamptidae	*Heteropsyllus nunni*	a harpacticoid copepod	Freshwater	Exotic
Crustaceans-Copepods	Ameiridae	*Nitokra hibernica*	a harpacticoid copepod	Freshwater	Exotic
Crustaceans-Copepods	Diosaccidae	*Schizopera borutzkyi*	a harpacticoid copepod	Marine	Exotic
Crustaceans-Mysids	Mysidae	*Hemimysis anomala*	bloody red shrimp	Freshwater	Exotic
Ectoprocts	Vesiculariidae	*Lophopodella carteri*	freshwater bryozoan	Freshwater	Exotic
Fishes	Clupeidae	*Alosa chrysochloris*	skipjack herring	Freshwater-Marine	Native Transplant
Fishes	Clupeidae	*Alosa pseudoharengus*	alewife	Freshwater-Marine	Native Transplant
Fishes	Clupeidae	*Alosa sapidissima*	American shad	Freshwater-Marine	Native Transplant
Fishes	Amiidae	*Amia calva*	bowfin	Freshwater	Native Transplant
Fishes	Gobiidae	*Apollonia (Neogobius) melanostomus*	round goby	Freshwater	Exotic
Fishes	Cyprinidae	*Carassius auratus*	goldfish	Freshwater	Exotic
Fishes	Catostomidae	*Carpiodes cyprinus*	quillback	Freshwater	Native Transplant
Fishes	Salmonidae	*Coregonus clupeaformis*	lake whitefish	Freshwater	Native Transplant
Fishes	Cyprinidae	*Ctenopharyngodon idella*	grass carp	Freshwater	Exotic
Fishes	Cyprinidae	*Cyprinella lutrensis*	red shiner	Freshwater	Native Transplant
Fishes	Cyprinidae	*Cyprinus carpio*	common carp	Freshwater	Exotic
Fishes	Clupeidae	*Dorosoma cepedianum*	gizzard shad	Freshwater-Marine	Native Transplant
Fishes	Gasterosteidae	*Gasterosteus aculeatus*	threespine stickleback	Marine	Native Transplant

Fishes	Percidae	*Gymnocephalus cernuus*	ruffe	Freshwater	Exotic

Appendix F. Exotic aquatic species in the Lake Michigan and Betsie-Platte watersheds (USGS 2007a) (continued).

4060200 Lake Michigan

Type	**Family**	**Scientific name**	**Common name**	**Native habitat**	**Origin**
Fishes	Lepisosteidae	*Lepisosteus platostomus*	shortnose gar	Freshwater	Native Transplant
Fishes	Moronidae	*Morone americana*	white perch	Freshwater	Native Transplant
Fishes	Salmonidae	*Oncorhynchus gorbuscha*	pink salmon	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Oncorhynchus kisutch*	coho salmon	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Oncorhynchus mykiss irideus*	coast rainbow trout	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Oncorhynchus nerka*	kokanee sockeye	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Oncorhynchus tshawytscha*	Chinook salmon	Freshwater-Marine	Native Transplant
Fishes	Osmeridae	*Osmerus mordax*	rainbow smelt	Freshwater-Marine	Native Transplant
Fishes	Percidae	*Percina shumardi*	river darter	Freshwater	Native Transplant
Fishes	Petromyzontidae	*Petromyzon marinus*	sea lamprey	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Salmo salar*	Atlantic salmon	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Salmo trutta*	brown trout	Freshwater-Marine	Exotic
Fishes	Salmonidae	*Salmo x Salvelinus trutta x fontinalis*	tiger trout	Freshwater	Exotic Hybrid
Fishes	Salmonidae	*Salvelinus fontinalis x namaycush*	splake	Freshwater	Native Transplant
Fishes	Percidae	*Sander canadense*	sauger	Freshwater	Native Transplant
Mollusks-Bivalves	Corbiculidae	*Corbicula fluminea*	Asian clam	Freshwater	Exotic
Mollusks-Bivalves	Dreissenidae	*Dreissena polymorpha*	zebra mussel	Freshwater	Exotic
Mollusks-Bivalves	Dreissenidae	*Dreissena rostriformis bugensis*	quagga mussel	Freshwater	Exotic
Mollusks-Bivalves	Sphaeriidae	*Pisidium amnicum*	greater European pea/pill clam, pisidiid clam	Freshwater	Exotic
Mollusks-Bivalves	Sphaeriidae	*Pisidium henslowanum*	Henslow peaclam	Freshwater	Exotic
Mollusks-Gastropods	Bithyniidae	*Bithynia tentaculata*	mud bithynia	Freshwater	Exotic
Mollusks-Gastropods	Viviparidae	*Cipangopaludina chinensis malleata*	Chinese mysterysnail	Freshwater	Exotic
Mollusks-Gastropods	Viviparidae	*Cipangopaludina (Bellamya) japonica*	Japanese mysterysnail	Freshwater	Exotic

Appendix F. Exotic aquatic species in the Lake Michigan and Betsie-Platte watersheds (USGS 2007a) (continued).

Type	Family	Scientific name	Common name	Native habitat	Origin
4060200 Lake Michigan					
Mollusks-Gastropods	Lymnaeidae	*Radix auricularia*	big-ear radix	Freshwater	Exotic
Mollusks-Gastropods	Valvatidae	*Valvata piscinalis*	European stream valvata	Freshwater	Exotic
Mollusks-Gastropods	Viviparidae	*Viviparus georgianus*	banded mystery snail	Freshwater	Native Transplant
Plants	Cyperaceae	*Carex acutiformis*	swamp sedge	Freshwater	Exotic
Plants	Onagraceae	*Epilobium parviflorum*	small flowered hairy willow herb	Freshwater	Exotic
Plants	Haloragaceae	*Myriophyllum spicatum*	Eurasian water-milfoil	Freshwater	Exotic
Plants	Asteraceae	*Solidago sempervirens*	seaside goldenrod	Freshwater	Unknown
Protozoans	Myxosomatidae	*Myxobolus cerebralis*	myxosporean parasite, salmonid whirling disease	Freshwater	Exotic
Viruses		*Rhabdovirus carpio*	spring viraemia of carp, SVC	Freshwater	Exotic
4060104 Betsie-Platte					
Coelenterates-Hydrozoans	Olindiidae	*Craspedacusta sowerbyi*	freshwater jellyfish	Freshwater	Exotic
Crustaceans-Amphipods	Gammaridae	*Echinogammarus ischnus*	an amphipod	Freshwater	Exotic
Crustaceans-Cladocerans	Cercopagidae	*Bythotrephes longimanus*	spiny water flea	Freshwater	Exotic
Fishes	Clupeidae	*Alosa pseudoharengus*	alewife	Freshwater-Marine	Native Transplant
Fishes	Cyprinidae	*Cyprinus carpio*	common carp	Freshwater	Exotic
Fishes	Salmonidae	*Oncorhynchus kisutch*	coho salmon	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Oncorhynchus tshawytscha*	Chinook salmon	Freshwater-Marine	Native Transplant
Fishes	Osmeridae	*Osmerus mordax*	rainbow smelt	Freshwater-Marine	Native Transplant
Fishes	Petromyzontidae	*Petromyzon marinus*	sea lamprey	Freshwater-Marine	Native Transplant
Fishes	Salmonidae	*Salmo salar*	Atlantic salmon	Freshwater-Marine	Native Transplant

Appendix F. Exotic aquatic species in the Lake Michigan and Betsie-Platte watersheds (USGS 2007a) (continued).

4060104 Betsie-Platte					
Type	**Family**	**Scientific name**	**Common name**	**Native habitat**	**Origin**
Fishes	Salmonidae	*Salmo trutta*	brown trout	Freshwater-Marine	Exotic
Fishes	Salmonidae	*Salvelinus fontinalis x namaycush*	splake	Freshwater	Native Transplant
Fishes	Salmonidae	*Salvelinus namaycush*	lake trout	Freshwater	Native Transplant
Mollusks-Bivalves	Dreissenidae	*Dreissena polymorpha*	zebra mussel	Freshwater	Exotic
Plants	Iridaceae	*Iris pseudacorus*	yellow iris	Freshwater	Exotic
Plants	Lythraceae	*Lythrum salicaria*	purple loosestrife	Freshwater	Exotic
Plants	Brassicaceae	*Nasturtium officinale*	watercress	Freshwater	Exotic
Plants	Scrophulariaceae	*Veronica beccabunga*	European brooklime	Freshwater	Exotic

Appendix G. Map classes and resolution of conflicts for wetland types in MIRIS and NWI.

Wetland Type	MIRIS	NWI System/	Subsystem/	Class/	Subclass	Hectares	Map Class for this report
Soils	No MIRIS	No NWI				873.667	Soils
Open Water	No MIRIS	Lacustrine	Limnetic	Open Water/Unknown Bottom		205.468	Open water
	No MIRIS	Lacustrine	Limnetic	Unconsolidated Bottom (open water)		150.497	Open water
	No MIRIS	Lacustrine	Littoral	Open Water/Unknown Bottom		23.315	Open water
	No MIRIS	Palustrine		Open Water/Unknown Bottom		15.260	Open water
	No MIRIS	Palustrine		Unconsolidated Bottom (open water)		19.001	Open water
Aquatic Bed	No MIRIS	Palustrine		Aquatic Bed		0.553	Aquatic bed
	Aquatic Bed Wetland	No NWI				61.420	Aquatic bed
	Aquatic Bed Wetland	Palustrine		Emergent		17.162	Conflict
	Aquatic Bed Wetland	Palustrine		Forested (mixed forest)		0.815	Conflict
	Aquatic Bed Wetland	Palustrine		Open Water/Unknown Bottom		0.121	Conflict
	Aquatic Bed Wetland	Palustrine		Scrub-Shrub		17.542	Conflict
Emergent	No MIRIS	Palustrine		Emergent		33.055	Emergent
	Emergent Wetland	No NWI				13.548	Emergent
	Emergent Wetland	Palustrine		Emergent		8.130	Emergent
	Emergent Wetland	Palustrine		Forested (mixed forest)		27.928	Conflict
	Emergent Wetland	Palustrine		Forested (other wooded)	Dead	0.007	Conflict
	Emergent Wetland	Palustrine		Forested (lowland conifers)	Needle-Leaved Evergreen	0.398	Conflict
	Emergent Wetland	Lacustrine	Limnetic	Unconsolidated Bottom (open water)		0.033	Conflict
	Emergent Wetland	Palustrine		Open Water/Unknown Bottom		0.620	Conflict
	Emergent Wetland	Palustrine		Scrub-Shrub		13.640	Conflict
	Emergent Wetland	Palustrine		Scrub-Shrub	Broad-Leaved Deciduous	8.493	Conflict
	Emergent Wetland	Palustrine		Scrub-Shrub	Broad-Leaved Evergreen	0.460	Conflict

Appendix G. Map classes and resolution of conflicts for wetlands in MIRIS and NWI (continued).

Wetland Type	MIRIS	NWI System/	Subsystem/	Class/	Subclass	Hectares	Map Class for this report
Lowland conifers	No MIRIS	Palustrine		Forested (lowland conifers)	Indeterminate Evergreen	3.012	Lowland conifers
	No MIRIS	Palustrine		Forested (lowland conifers)	Needle-Leaved Deciduous	1.496	Lowland conifers
	No MIRIS	Palustrine		Forested (lowland conifers)	Needle-Leaved Evergreen	105.225	Lowland conifers
	Lowland Conifer	No NWI				397.677	Lowland conifers
	Lowland Conifer	Palustrine		Forested (lowland conifers)	Indeterminate Evergreen	8.822	Lowland conifers
	Lowland Conifer	Palustrine		Forested (lowland conifers)	Needle-Leaved Deciduous	14.418	Lowland conifers
	Lowland Conifer	Palustrine		Forested (lowland conifers)	Needle-Leaved Evergreen	40.303	Lowland conifers
	Lowland Conifer	Palustrine		Forested		90.632	Lowland conifers
	Lowland Conifer	Palustrine		Forested	Dead	0.284	Lowland conifers
	Wooded Wetland	Palustrine		Forested (lowland conifers)	Needle-Leaved Evergreen	26.426	Lowland conifers
	Lowland Conifer	Lacustrine	Limnetic	Open Water/Unknown Bottom		0.293	Conflict
	Lowland Conifer	Lacustrine	Limnetic	Unconsolidated Bottom (open water)		0.036	Conflict
	Lowland Conifer	Palustrine		Unconsolidated Bottom (open water)		0.835	Conflict
	Lowland Conifer	Palustrine		Emergent		1.203	Conflict
	Lowland Conifer	Palustrine		Scrub-Shrub		14.828	Conflict
	Lowland Conifer	Palustrine		Scrub-Shrub	Broad-Leaved Deciduous	22.698	Conflict
	Lowland Conifer	Palustrine		Scrub-Shrub	Broad-Leaved Evergreen	0.001	Conflict

Appendix G. Map classes and resolution of conflicts for wetlands in MIRIS and NWI (continued).

Wetland Type	MIRIS	NWI				Hectares	Map Class for this report
		System/	Subsystem/	Class/	Subclass		
Lowland hardwood	No MIRIS	Palustrine		Forested (lowland hardwoods)	Broad-Leaved Deciduous	86.635	Lowland hardwood
	No MIRIS	Palustrine		Forested (lowland hardwoods)	Indeterminate Deciduous	2.256	Lowland hardwood
	Lowland Hardwood	No NWI				166.981	Lowland hardwood
	Lowland Hardwood	Palustrine		Forested (lowland hardwoods)	Broad-Leaved Deciduous	14.259	Lowland hardwood
	Lowland Hardwood	Palustrine		Forested (lowland hardwoods)	Indeterminate Deciduous	17.441	Lowland hardwood
	Lowland Hardwood	Palustrine		Forested		413.325	Lowland hardwood
	Lowland Hardwood	Palustrine		Forested	Dead	5.213	Lowland hardwood
	Wooded Wetland	Palustrine		Forested (lowland hardwoods)	Broad-Leaved Deciduous	7.510	Lowland hardwood
	Lowland Hardwood	Palustrine		Emergent		5.407	Conflict
	Lowland Hardwood	Lacustrine	Limnetic	Open Water/Unknown Bottom		0.250	Conflict
	Lowland Hardwood	Lacustrine	Limnetic	Unconsolidated Bottom (open water)		0.000	Conflict
	Lowland Hardwood	Palustrine		Open Water/Unknown Bottom		0.408	Conflict
	Lowland Hardwood	Palustrine		Unconsolidated Bottom (open water)		1.189	Conflict
	Lowland Hardwood	Palustrine		Scrub-Shrub		34.489	Conflict
	Lowland Hardwood	Palustrine		Scrub-Shrub	Broad-Leaved Deciduous	10.341	Conflict
	Lowland Hardwood	Palustrine		Scrub-Shrub	Broad-Leaved Evergreen	0.077	Conflict
	Lowland Hardwood	Palustrine		Scrub-Shrub	Needle-Leaved Evergreen	0.140	Conflict

Appendix G. Map classes and resolution of conflicts for wetlands in MIRIS and NWI (continued).

Wetland Type	MIRIS	NWI				Hectares	Map Class for this report
		System/	Subsystem/	Class/	Subclass		
Lowland mixed forest	No MIRIS	Palustrine		Forested		396.654	Lowland mixed forest
	Wooded Wetland	Palustrine		Forested (mixed forest)		145.098	Lowland mixed forest
	Lowland Conifer	Palustrine		Forested (lowland hardwoods)	Broad-Leaved Deciduous	22.598	Lowland mixed forest
	Lowland Conifer	Palustrine		Forested (lowland hardwoods)	Indeterminate Deciduous	0.028	Lowland mixed forest
	Lowland Hardwood	Palustrine		Forested (lowland conifers)	Indeterminate Evergreen	4.513	Lowland mixed forest
	Lowland Hardwood	Palustrine		Forested (lowland conifers)	Needle-Leaved Deciduous	0.532	Lowland mixed forest
	Lowland Hardwood	Palustrine		Forested (lowland conifers)	Needle-Leaved Evergreen	29.012	Lowland mixed forest
Shrub/ scrub	No MIRIS	Palustrine		Scrub-Shrub		44.775	Shrub/scrub
	No MIRIS	Palustrine		Scrub-Shrub	Broad-Leaved Deciduous	32.974	Shrub/scrub
	No MIRIS	Palustrine		Scrub-Shrub	Broad-Leaved Evergreen	0.043	Shrub/scrub
	No MIRIS	Palustrine		Scrub-Shrub	Needle-Leaved Evergreen	3.584	Shrub/scrub
	Shrub/Scrub Wetland	No NWI				50.140	Shrub/scrub
	Shrub/Scrub Wetland	Palustrine		Scrub-Shrub		74.874	Shrub/scrub
	Shrub/Scrub Wetland	Palustrine		Scrub-Shrub	Broad-Leaved Deciduous	24.800	Shrub/scrub
	Shrub/Scrub Wetland	Palustrine		Scrub-Shrub	Broad-Leaved Evergreen	1.933	Shrub/scrub
	Wooded Wetland	Palustrine		Scrub-Shrub		5.596	Shrub/scrub
	Wooded Wetland	Palustrine		Scrub-Shrub	Broad-Leaved Deciduous	3.124	Shrub/scrub
	Shrub/Scrub Wetland	Palustrine		Emergent		5.401	Conflict
	Shrub/Scrub Wetland	Palustrine		Forested (lowland hardwoods)	Broad-Leaved Deciduous	3.140	Conflict
	Shrub/Scrub Wetland	Palustrine		Forested (lowland hardwoods)	Indeterminate Deciduous	2.583	Conflict

Appendix G. Map classes and resolution of conflicts for wetlands in MIRIS and NWI (continued).

Wetland Type	MIRIS	NWI				Hectares	Map Class for this report
		System/	Subsystem/	Class/	Subclass		
Shrub/ scrub (cont)	Shrub/Scrub Wetland	Palustrine		Forested (lowland conifers)	Needle-Leaved Evergreen	19.888	Conflict
	Shrub/Scrub Wetland	Palustrine		Forested (mixed forest)		136.587	Conflict
	Shrub/Scrub Wetland	Palustrine		Forested (other wooded)	Dead	1.830	Conflict
	Shrub/Scrub Wetland	Lacustrine	Limnetic	Open Water/Unknown Bottom		0.646	Conflict
	Shrub/Scrub Wetland	Palustrine		Open Water/Unknown Bottom		1.626	Conflict
	Shrub/Scrub Wetland	Palustrine		Unconsolidated Bottom (open water)		0.137	Conflict
Other	No MIRIS	Palustrine		Forested	Dead	1.278	Other wooded lowland
Wooded	Wooded Wetland	No NWI				28.696	Other wooded lowland
Lowland	Wooded Wetland	Lacustrine	Limnetic	Open Water/Unknown Bottom		0.410	Conflict
	Wooded Wetland	Lacustrine	Littoral	Open Water/Unknown Bottom		0.384	Conflict
	Wooded Wetland	Palustrine		Emergent		0.896	Conflict
	Wooded Wetland	Palustrine		Open Water/Unknown Bottom		0.625	Conflict
Other	No MIRIS	Lacustrine	Littoral	Beach/Bar		0.733	Other wetland
Wetland	No MIRIS	Lacustrine	Littoral	Unconsolidated Shore		36.510	Other wetland
	Flats	No NWI				0.231	Other wetland
	Flats	Palustrine		Emergent		0.241	Conflict
	Flats	Palustrine		Forested (lowland hardwoods)	Broad-Leaved Deciduous	0.166	Conflict

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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