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Natural Resource Program Center

Assessment of Coastal Water Resources and Watershed Conditions

Lake Clark National Park and Preserve

Natural Resource Technical Report NPS/NRPC/WRD/NRTR—2008/144

ON THE COVER
Clockwise from left: Tuxedni Bay in Lake Clark National Park and Preserve (LACL), photo by Penny Knuckles; Sea Otters in Silver Salmon Creek in LACL, NPS Photo; Chinitna Bay in LACL, photo by Amy Miller; LACL Coast in Winter, photo by Dan Young; Chinitna Bay in LACL, NPS Photo.

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Contents

Page

Contents (continued)

Figures

Page

Figures (continued)

Figures (continued)

Figures (continued)

Tables

Page

Tables (continued)

Appendices

Page

Acronyms and Abbreviations

AC- Alaska Current
ACC- Alaska Coastal Current
ADEC – Alaska Department of Environmental Conservation
ADF&G – Alaska Department of Fish and Game
ADNR – Alaska Department of Natural Resources
ALAG- Alagnak Wild River
ANIA – Aniakchak National Monument and Preserve (National Park Service Designation)
ANILCA – Alaska National Interest Land Conservation Act
AVO- Alaska Volcano Observatory
BNWF- Becharof National Wildlife Refuge
CIRI- Cook Inlet Region, Inc.
CWA- Clean Water Act
DOMTAX- Percent Dominant Taxa
EMAP – Environmental Monitoring and Assessment Program (of the U.S. Environmental Protection Agency)
ENSO - El Niño Southern Oscillation
EPA – US Environmental Protection Agency
EPT/TOT: EPT Individuals/Total Individuals
EPTGEN: Number of EPT Genera
EVOS – *Exxon Valdez* Oil Spill
FAA – Federal Aviation Administration
FBI- Family Biotic Index
GEM – Gulf Ecosystem Monitoring (*Exxon Valdez* Oil Spill Trustee Council)
GLBA- Glacier Bay National Park and Preserve
GOA – Gulf of Alaska
GRS- Geographic Response Strategies
HAB – Harmful Algal Bloom
I&M- Inventory and Monitoring Program
KATM – Katmai National Park and Preserve (National Park Service Designation)
KEFJ- Kenai Fjords National Park (National Park Service Designation)
LACL- Lake Clark National Park and Preserve (National Park Service Designation)
LIA – Little Ice Age
NADP – National Atmospheric Deposition Program
NAWQA- National Water Quality Assessment Program (U.S. Geological Survey)
NOAA – National Oceanic and Atmospheric Administration (U.S. Department of Commerce)
NMFS- National Marine Fisheries Service
NPS – National Park Service (U.S. Department of Interior)
NS&T – National Status and Trends (NOAA)
NWI – National Wetlands Inventory (of the US Fish and Wildlife Service)
ORI- Oil Residence Index
PAHs – Polycyclic aromatic hydrocarbons
PCBs – Polychlorinated biphenyls
PDO – Pacific Decadal Oscillation
POPs – Persistent Organic Pollutants

Acronyms and Abbreviations (continued)

PPOR- Potential Places of Refuge
PSP – Paralytic Shellfish Poisoning
SQG- Sediment Quality Guidelines
SWAN – Southwest Alaska Network
UAS – University of Alaska Southeast
USDA – U.S. Department of Agriculture
USFWS – U.S. Fish and Wildlife Service (U.S. Department of Interior)
USGS – U.S. Geological Survey (U.S. Department of Interior)
WACAP- Western Airborne Contaminants Assessment Project

Executive Summary

This assessment of coastal water resources and watershed conditions in Lake Clark National Park and Preserve (LACL) is provided in response to the National Park Service (NPS) Natural Resource Challenge, initially funded by the U.S. Congress in 2003 to assess the environmental conditions of national park units. LACL is part of the Southwest Alaska Network (SWAN), which also includes the Alagnak Wild River (ALAG), Aniakchak National Monument and Preserve (ANIA), Katmai National Monument and Preserve (KATM), and Kenai Fjords National Park (KEFJ). While few studies have specifically addressed the coastal water resources of LACL, the SWAN units are currently implementing a Vital Signs Monitoring Program, (part of the NPS Inventory and Monitoring (I&M) Program), in which baseline inventories and long-term monitoring are being designed and conducted.

Physical, Oceanographic, and Climatic Setting

Lake Clark National Park and Preserve (66°15'00"N 154°15'00") is located within the Gulf of Alaska in southcentral Alaska, along the western boundary of Cook Inlet, and approximately 160 km (100 mi) southwest of Anchorage. The Chigmit Mountains, at the junction of the Alaska and Aleutian Ranges, separate the steep, rugged, and glaciated Cook Inlet coastal region of LACL from the lower-lying foothills, terminal moraines, and tundra plains in the southwestern part of the unit. As part of the Aleutian "Ring of Fire," the Chigmit Mountains include three active volcanoes (Mt. Spurr, Mt. Redoubt, and Mt. Iliamna) that rise to up to 3,374 m (11,070 ft) in elevation. LACL contains over 9600 km (6000 mi) of streams and rivers, some of which are among the most productive spawning and rearing habitat for sockeye salmon in the world.

The coastal study region that is the subject of this report encompasses approximately 309,646 hectares (765,147 acres) and is defined as those watersheds that are contained within the unit and drain into Cook Inlet. LACL's coastline along Cook Inlet is 209 km (130 mi) long, spanning Redoubt Point to the northern boundary of Chinitna Bay. Salt marshes and wide mud flats each comprise 22% of the shoreline length (and 42% and 24% of the total area), followed by wide sand flat (18% of shoreline length) and wide sand beach (15% of shoreline length). Two major islands lie offshore in close proximity to the LACL coast–Chisik Island at the entrance to Tuxedni Bay and Kalgin Island across from Redoubt Bay. The most visible geographic feature of the coastline is Tuxedni Bay, which extends for several tens of kilometers into the coastal region and narrows into the glacial-fed Tuxedni River. North of Tuxedni Bay, the shoreline is indented with numerous small coves and bays, and the land elevation rises gently to 300 m (1000 ft) above sea level for up to 5 km (3 mi) inland, leading to the rugged and glaciated Mount Redoubt. South of Tuxedni Bay, the topography is markedly steeper and more variable, with highly-incised hills leading to glaciers in the heterogeneous and rugged landscape of the Iliamna Volcano area.

The oceanographic and climatic setting of the coastal LACL region is strongly influenced by the Gulf of Alaska and the rugged topography. Cook Inlet, a large, shallow tidal estuary with depths ranging from 20-100 m, averaging 60 m, has tides that are among the largest in the world. Ocean water from the Alaska Coastal Current in the Gulf of Alaska flows into Cook Inlet through Kennedy Entrance, moves north along the east side of the Inlet, and upwells as the bathymetry

becomes shallow. Water from upper Cook Inlet flows out along the western boundary, passing the coast of LACL. Coastal LACL annual precipitation ranges vary from 38-51 cm (15-20 in) in areas of broad coastal lowlands to 102-203 cm (40-80 in) where steeply rising mountains emerge almost directly off the coastline. The average annual temperature of the coastal region is approximately 5.5°C (42°F).

Hydrologic Information

Watersheds in coastal LACL extend from sea level to greater than 3000 m (~10,000 ft) in elevation in the Aleutian Range. The majority of streams are fed by meltwater from glaciers and permanent snowfields, although small, low-elevation watersheds along the coast derive streamflow primarily from rainfall and intermittent snowmelt. The major streams within the Coastal Study Area of LACL include, from north to south, Little Polly Creek, Crescent River, Tuxedni River, Open Creek, Difficult Creek, Hungryman Creek, Bear Creek, Johnson River, Silver Salmon Lakes and Creek, Red River, Shelter Creek, East Glacier Creek, Middle Glacier Creek, and West Glacier Creek. In addition, there are a large number of major coastal streams that have their headwaters within the LACL boundaries, but leave the park before flowing into Cook Inlet. These include the Drift River, the Big River, Cannery Creek, Harvest Creek, and Redoubt Creek, and, in the northeast section of LACL, rivers feeding into Kenibuna Lake (Chiligan River, Igitna River, Another River, and Neacola River).

Although lakes form major geographic features in interior LACL, with 20 major lakes and numerous smaller lakes and ponds, the Coastal Study Area has relatively few lakes. The largest coastal lake in LACL is Crescent Lake, which drains into the Crescent River. The next largest is Hickerson Lake on the southeastern slope of Iliamna Volcano. Hickerson Lake is snow-fed and has no surface outlet. Other, smaller lakes include Silver Salmon Lakes, Saddle Mountain Lake, and Blue Lake.

No groundwater resources in coastal LACL have been identified and described. Yet considering the coastal area's complex juxtaposition of salt water-influenced marshes, fractured and faulted bedrock, and volcanic and glacial deposits, it is likely that groundwater resources are diverse and heterogeneous over short distances.

Glacial ice has been a dominant landform in the Lake Clark region and its glacial history contains multiple piedmont glaciations. Coastal LACL contains major regions of glaciers and snowfields. Within coastal LACL, glaciers currently cover approximately 121,000 ha (296,526 acres) or 39% of the land area. Most of the glaciers in coastal LACL have been retreating since the end of the Little Ice Age (~150 yrs ago) and continue to retreat today.

Biological Resources

The coastal regions of LACL are among the most biologically productive ecosystems in the Gulf of Alaska. The coastal, intertidal, and nearshore marine areas provide particularly important habitat for residential and migratory birds, brown bears, and a variety of marine mammals. Although the LACL coastline was spared direct contamination from the *Exxon Valdez* Oil Spill, it also did not receive as detailed coastal assessments and resource inventories as the other NPS units in the region did in the late 1980s and early 1990s. As a result, a major effort toward describing and assessing coastal resources, both physical and biological, was conducted in 1994-

1995. For nearly the past decade, LACL has been engaged in the NPS Inventory and Monitorin (I&M) program, which is currently the most extensive effort to describe, catalog, and assess the condition of biological resources in LACL.

Several marine mammal species of concern occur in LACL, including Steller sea lions, harbor seals and Cook Inlet beluga whales. The U.S. western stock of Steller sea lions, including the LACL region, is federally-listed as endangered due to declining populations throughout the western Gulf of Alaska and Bering Sea regions. Steller sea lions are not known to haul-out in LACL; however, they have been observed in nearshore waters. Harbor seals are abundant in LACL and have suffered a similar decline to that of Steller sea lions, and this decline has occurred in roughly the same time period. Cook Inlet beluga whales have declined 50% or more in the last decade and were listed under the Endangered Species Act in 2008.

Many marine birds reside in or spend some time along the LACL coast. The intertidal mud flats of Redoubt, Tuxedni, and Chinitna Bays are of great importance to many migrating and resident bird species, including shorebirds, waterfowl, raptors, and seabirds.

A baseline I&M survey identified 25 freshwater and 24 tidepool or estuarine fish species within LACL. All five species of salmon, Dolly Varden, Arctic char, sticklebacks, sculpins, and many other species are present in coastal LACL. The maintenance of healthy salmon stocks and appropriate fish passage within coastal streams and rivers is important not only for fisheries resources, but also because spawning salmonids have significant impacts on biological resources in both terrestrial and freshwater aquatic ecosystems due to their carcasses' contributions of marine-derived nutrients. One species of amphibian, the wood frog, is a resident of the Park and Preserve.

The LACL intertidal is composed primarily of salt marshes and mud/sand environments. Salt marshes dominate and compose 42% of the total area and 22% of the total length of coast. Most of the remainder of the shoreline is composed of mud and sand flats/beaches, with some cliffs between the Johnson River and Bear Creek. Because the majority of the coast of LACL is composed of soft sediment environments, the coastline is dynamic and constantly changing. As a result, the Southwest Alaska Network (SWAN) I&M program is assessing morphological shoreline changes along the LACL coast.

Wetland environments are abundant in coastal LACL, making up approximately 7% of the unit according to mapping by the National Wetlands Inventory (NWI) program. These wetland areas are important because they serve as an interface between terrestrial habitats and aquatic environments such as streams, lakes, and near-shore marine zones. In particular, wetlands provide important hydrological and ecological functions, including controlling floods and regulating streamflow, providing nutrients to aquatic ecosystems, controlling erosion, and filtering impurities from water that passes through them.

Water Quality Assessment

Water, sediment, and biologic quality in marine waters was surveyed in 2002 by the State of Alaska as part of the nationwide Environmental Monitoring and Assessment Program (EMAP), which showed that water and sediment quality conditions in the region were very high. Vital signs monitoring by the SWAN I&M program is a significant part of NPS natural resource management. Resources to be monitored are chosen based on ecological significance and relevance to SWAN resource management issues. Vital signs selected for the SWAN I&M program that are directly related to the marine nearshore include marine water chemistry, kelp and eelgrass, marine intertidal invertebrates, marine birds, and sea otters. Vital signs related to freshwater resources include surface water hydrology, freshwater chemistry, and landscape processes. Results of an I&M water quality review found no 303(d) waters present within LACL and concluded that although water quality collection has been sporadic, conditions appear to be generally good, with low nutrient levels and little evidence of anthropogenic impacts. For future long-term monitoring of water quality, SWAN streams and lakes were categorized into three tiers by using a ranking procedure that considered access, level of use/management issues, and ecological and spatial cover. In the coastal LACL area, no waterbodies were identified as Tier 1, but the Crescent River system was designated as Tier 2 (targeted for sampling every 2-5 years).

For most water bodies in coastal LACL, water quality conditions are unknown. Without documented baseline information, it is not possible to make an assessment of their condition. A few records are provided for water quality samples collected in the Drift River and Chakachatna River basins, which begin within LACL and then leave the park boundary before emptying into Cook Inlet. Water quality studies in the Johnson River, the Crescent River, and Crescent Lake are available and provide important baseline data. The Johnson River was included as part of the USGS National Water Quality Assessment (NAWQA) Program in the Cook Inlet region between 1998 and 2001. Only a few water quality measures (water clarity and copper concentration) were determined to be above reference levels, likely from natural sources (glacier silt and naturally occurring trace elements). Water quality parameters were measured in multiple reaches of the Crescent River, driven by interests in the river's productive sockeye salmon run and in anticipation of future logging activity. Similar results as the Johnson River were found, with only water clarity and copper concentration above reference levels.

Threats to Water Resources

The release of petroleum poses a great environmental threat, whether as catastrophic spills or chronic discharges. In addition to physical impacts of large spills, the toxicity of many of the individual compounds contained in petroleum is significant, and even small releases can kill or damage organisms. The impact of a release of petroleum would depend on the size of the spill, the location of the spill, the type of petroleum product, and the effectiveness of the response to the spill. Potential oil spills could result from transfers, tanker spill, pipeline spill, well blowouts, permitted discharges of produced water at platforms and shore treatment facilities, permitted discharges of drilling muds and work-over fluids during drilling and servicing of wells, permitted discharge of waste water from oil refinery, water discharge from storage tanks and ballast, chronic leakage from storage tanks and pipelines, municipal treatment plants, marine vessels—commercial and sport fishermen and merchant ships—, and natural oil seeps. Potential source areas include transfers and traffic out of the Valdez Marine Terminal (Prince William Sound), Drift River Marine Terminal (Cook Inlet), Nikiski Oil Terminal and Refinery (Cook Inlet), Anchorage International airport jet fuel pipeline, and seventeen gas and seven oil producing fields within Cook Inlet. Several more oil and gas sales are currently proposed for development over the next five years in the Cook Inlet region, and steady or rising demands for these fuels may prompt further long-term development. Discharges from oil production facilities are permitted in Cook Inlet; however, their impacts on coastal LACL resources are unknown. The Drift River oil facility is a danger to the LACL coastline due to potential flooding and debris flows from the Redoubt Volcano, but it also has a history of being investigated for contamination by petroleum-related chemicals. Tuxedni and Chinitna Bay mud flats are particularly critical habitats because they serve as feeding areas for bears and birds, and potential contamination or destruction of these areas by petroleum would have tremendous impact. Geographic Response Strategies (GRS) are developed for coastal areas of LACL and include West Glacier Creek, Crescent River, Tuxedni River, and Polly Creek.

The effects of marine vessels to water quality along coastal LACL are most likely temporary and limited to the immediate area of vessel traffic. Snug Harbor is the only good harbor within the coastal region of LACL, and therefore, vessel traffic is limited. As a result, many boats bring tourists for bear-viewing or sport fishing on a day trip. Cruise ship traffic along the coast is minimal in comparison to the large cruise ships that travel in southeast Alaska and up to the Prince William Sound area. Commercial fishing occurs and currently focuses on salmon and clamming.

Global atmospheric pollutants such as mercury (Hg) and persistent organic pollutants (POPs) may enter LACL via transport and deposition by spawning salmon that accumulate these toxins in the marine environment and by atmospheric deposition. Studies in nearby Bristol Bay watersheds showed that salmon may be major transporters of marine-derived Hg into freshwater environments, and that strong correlations exist between the densities of salmon runs with PCB concentrations in lake sediments. Hg and most POPs are carried to Alaska via long-range atmospheric pathways, mainly from Asia, and upon deposition (wet or dry) can biomagnify as they pass up trophic levels. Mercury and POPs in northern latitudes show significant concentration increases over the last few decades. Several studies in southern coastal Alaska (focusing on sea bird eggs, lake sediments, and streambed sediment) indicate the region is being impacted by these contaminants and deserves further evaluation and monitoring. Contaminant monitoring has begun in the SWAN. As part of the SWAN I&M program, fish were collected for analyses of heavy metals and organics in the drainage of Lake Clark proper (outside but adjacent to the coastal study region) in 2005, and results are pending.

Climate change is an important natural resource issue for national parks in Alaska, and recent research suggests that changes in climate may dramatically impact water resources in Alaskan parks. Alaska's climate has warmed by approximately 2ºC (4ºF) since the 1950s and is projected to rise an additional 3-10ºC (5-18ºF) by 2100. The most obvious effects of climate change on hydrologic resources in Alaska are changes in the extent of permafrost, snow cover, glaciers, and sea and lake ice cover and duration. In coastal LACL, winter temperatures are typically close to the freezing point of water. As a result, climate warming has the potential to alter patterns of snow accumulation within the park and cause a shift toward higher winter streamflows and lower summer streamflows. Glaciers in coastal LACL have been retreating since the end of the Little Ice Age in the late 1700s and climate warming is continuing to affect the dynamics of glaciers within LACL. An important hydrologic effect of increased glacier melt is an increase in the volume of runoff from glaciers. Unlike glacial rivers, the amount of water in lakes, ponds, and wetlands within LACL will likely decrease as climate warms because of increased evapotranspiration and lower water table levels. Within coastal LACL a decline in sockeye productivity was associated at least in part with the effects of accelerated glacier melt on turbidity, which suggests that climate warming and attendant shifts in the timing and quality of streamflow within LACL have the potential to influence the spawning success of salmon within the park.

Natural geologic hazards such as volcanic eruptions, earthquakes, and tsunamis are common agents of disturbance in LACL. Iliamna and Redoubt Volcanoes in LACL are at the northeastern end of the Aleutian volcanic arc, which is one of the world's most active volcanic areas. Future volcanic eruptions releasing ash clouds and lahars and pycroclastic flows in the LACL area and adjacent regions are certain and unavoidable. The types of impacts of volcanic eruptions on water quality varies from the catastrophic lahars of rapidly melting of snow and ice, which may result in mud-choked streams and major changes in streambed morphology, to more subtle and longer-term influences on biological productivity within lakes and streams due to ashfall contributions. While natural geologic events may be destructive in their own right, they may also trigger secondary hazardous conditions by damaging human infrastructure (such as petrochemical industrial infrastructure) that could lead to pollution of park resources.

The complex interplay of tectonic, isostatic, and global eustatic effects in the Gulf of Alaska results in highly spatially variable sea level histories along the southcentral and southwestern Alaska coast. Coastal erosion from wave energy can be strong in exposed areas, while natural accretion may result from storm-driven waves, high tides, nearshore currents, rainfall and runoff, landslides, and earthquakes. Uplift of the land due to tectonic activity is superimposed upon isostatic rebound from deglaciation, a process which raises the land and reshuffles successional processes on a more gradual time scale. Shoreline change is one of the Vital Signs being monitored by the SWAN I&M program.

Visitor Impacts

Visitor use of the LACL coast has been on the rise for the past decade and comes mainly in the form of sport fishing and bear viewing/photographing, mainly at Silver Salmon Creek and Chinitna Bay. Potential impacts from visitor use include wildlife disturbance and displacement, damage to soil and vegetation, and noise disturbance associated with motorized vehicle/airplane use. Wheeled planes land on beaches and bring visitors (many of whom are cruise ship passengers) to the coastal salt marshes and the several lodges located within private inholdings. Accurate data on the number of visitors to the coastal region are unavailable, due to the lack of required permits. Nonetheless, the NPS collects data on commercial permits, and the most recent such information comes from 2007. Sportfishing and bear viewing (1,162 and 1,012 commercial user days, respectively) dominated the use type, followed closely by combined Photography/Bear Viewing (969 commercial user days). By far, the most heavily used area, accounting for just over 50% of the use, was Silver Salmon Creek (2,156 user days). Crescent and Hickerson Lakes saw relatively light visitor use in 2007, with 69 and 11 user days, respectively, for Photography/Bear Viewing.

Other Threats

The presence and scale of exotic species in LACL coastal watersheds is not known or documented. However, the continued northward migration of escaped farmed Atlantic salmon and other non-native migrating species pose threats to indigenous salmon and trout and their stream communities. The increase in visitor use along the coast may result in the import of exotic species to the area in the near future. Concerns also include spruce beetle infestations and potential arrival of the avian influenza (H5N1) virus in Alaska. More information is needed in order to evaluate if harmful algal blooms (HABs) are an issue of concern to LACL's rich shellfish beds. Chytridiomycosis, a waterborne infectious disease contributing to amphibian declines globally, has been detected in southcentral and southeast Alaska and is likely an emerging threat to LACL wood frog populations, although chytrid prevalence in LACL is currently unknown. Although coastal debris and garbage is regarded as a serious issue in other SWAN units, it is of small concern in LACL.

Future developments that may impact LACL coastal water resources include logging within inholdings that may affect park watersheds, mining in the Johnson River watershed, development of the Beluga (Chuitna) Coal Fields east of LACL, and development of the Pebble mine. The Chuitna Coal Project is proposed to last 25-years (minimum) and would target the mining of up to 1 billion metric tons of subbituminous coal. Although the area of proposed development is outside NPS boundaries, LACL likely would be affected by coal dust air pollution and the increased shipping traffic (by coal transport vessels) off the LACL coast. The proposed Pebble Mine is located approximately 36 km (20 mi) southwest of the LACL border. Development details are unclear, and the Pebble Partnership is in only the initial phases of conducting environmental impact studies. Therefore, it is difficult to assess at this point in time how natural resources in coastal LACL may be affected. (The magnitude of environmental impact on the inland portion of LACL would likely be extensive with a mine of the proposed scale; however such discussion is beyond the scope of this report). What is certain is that the mine's immense size would require tremendous power generation, which would probably need to be met through hydroelectric sources or gas or coal combustion, as locally developed power sources are nonexistent. Early versions of the mine's development proposal stated that one potential means of providing power to the mine would be through transmission lines that would cut through LACL boundaries.

Specific recommendations for management and monitoring of both freshwater and marine water resources in LACL are provided in Table 1 and detailed in the *Condition Overview and Recommendations* section.

Table 1. Water resources-related indicators and current/potential stressors of aquatic resources in Lake Clark National Park and Preserve.

Indicator	Freshwater	Intertidal, Bays, Estuaries & Salt Marshes	Coastal waters
Water Quality			
Nutrients/ Eutrophication	OK	OK	OK
Contaminants	PP	PP	EP
Hypoxia	OK	OK	OK
Turbidity	OK	OK	OK
Pathogens	OK	OK	OK
Habitat Disruption			
Coastal development	PP	PP	OK
Water quantity/ withdrawals	OK	OK	OK
Shoreline modification by humans	OK	PP	OK
Natural geologic hazards	IP	IP	IP
Natural coastal uplift and erosion	OK	EP	OK
Mining impacts	PP	PP	PP
Logging in private inholdings	PP	OK	OK
Power development, coal and hydro	PP	PP	OK
Recreational usage			
Tourism (Fishing and bear viewing)	PP	PP	OK
ORV usage	PP	PP	OK
Other Indicators			
Oil spills	NA	PP	PP
Harmful algal blooms	NA	PP	PP
Aquatic & marine invasive species	PP	PP	PP
Climate change	EP	EP	EP
Coastal trash	NA	PP	NA

Definitions: EP= existing problem, IP= Intermittent Problem, PP = potential problem, OK= no detectable problem, shaded =limited data, NA= not applicable.

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Purpose and Scope

This assessment of coastal water resources and watershed conditions in Lake Clark National Park and Preserve (LACL) in southwest Alaska (Figure 1) is provided in response to the NPS Natural Resource Challenge, initially funded by the U.S. Congress in 2003 to assess the environmental conditions of national park units. Of particular interest are the threats posed by point source and non-point source pollutants, nutrient enrichment, coastal development and tourism, resource extractive uses, and the spread of exotic species. The Watershed Assessment Program has been tasked with synthesizing existing data, formulating recommendations, and guiding management actions to reduce factors which currently stress, or threaten to stress, the health of NPS watershed resources.

This report is an assessment of coastal and watershed resources in LACL and provides a synopsis of existing knowledge about its coastal watersheds. Specifically, the ca. 309,646 hectares (765,147 acres) of lands within the "LACL Coastal Study Area," the focus of this report, are defined as those watersheds that are contained within the unit and drain into Cook Inlet (Figure 2). These watersheds, from north to south, include Little Polly Creek, and the streams in the Tuxedni Bay area, south into and including West Glacier Creek. Although not technically in the coastal study area, numerous other streams originate in LACL and flow into Cook Inlet through non-NPS lands, and these are also given attention in this assessment report.

LACL is part of the Southwest Alaska Network (SWAN), which also includes the Alagnak Wild River (ALAG), Aniakchak National Monument and Preserve (ANIA), Katmai National Park and Preserve (KATM), and Kenai Fjords National Park (KEFJ) (Figure 1). These park units are currently implementing their Vital Signs Monitoring Plan, in which baseline inventories and long-term monitoring protocols and plans are being developed for climatic, biological, geophysical, hydrochemical, and other parameters that are considered to be "vital signs," key indicators of ecological and physical conditions within the park units. The list of vital signs selected for the network is presented in Appendix A of this report. Many products of the ongoing SWAN I&M Program are relevant to this Watershed Assessment effort. Information, bibliographies, and other resources regarding the SWAN I&M Program are found at http://science.nature.nps.gov/im/units/swan/.

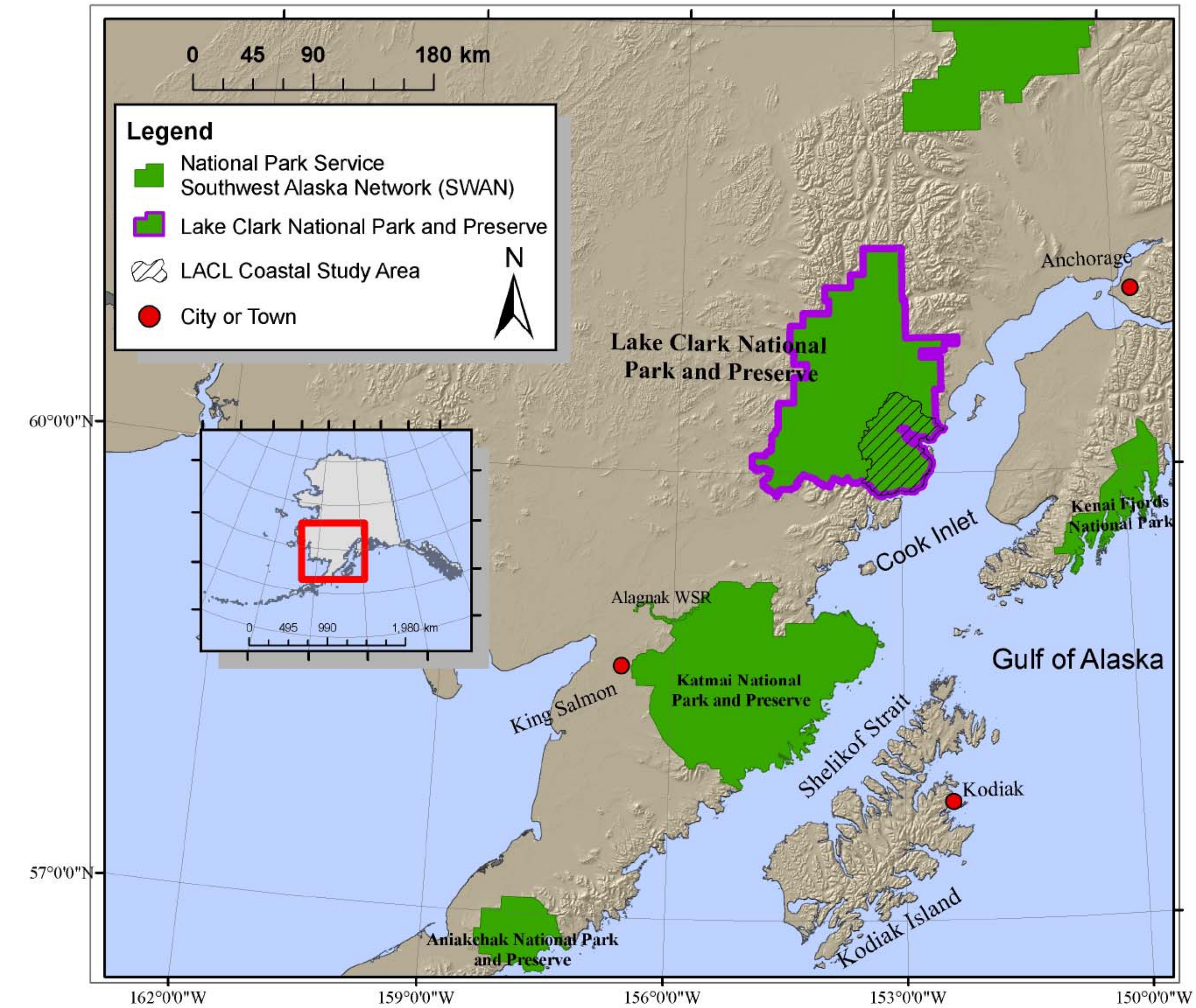


Figure 1. Location of Lake Clark National Park and Preserve and other SWAN NPS units in Alaska. The coastal study area in Lake Clark National Park and Preserve is hatch-marked.

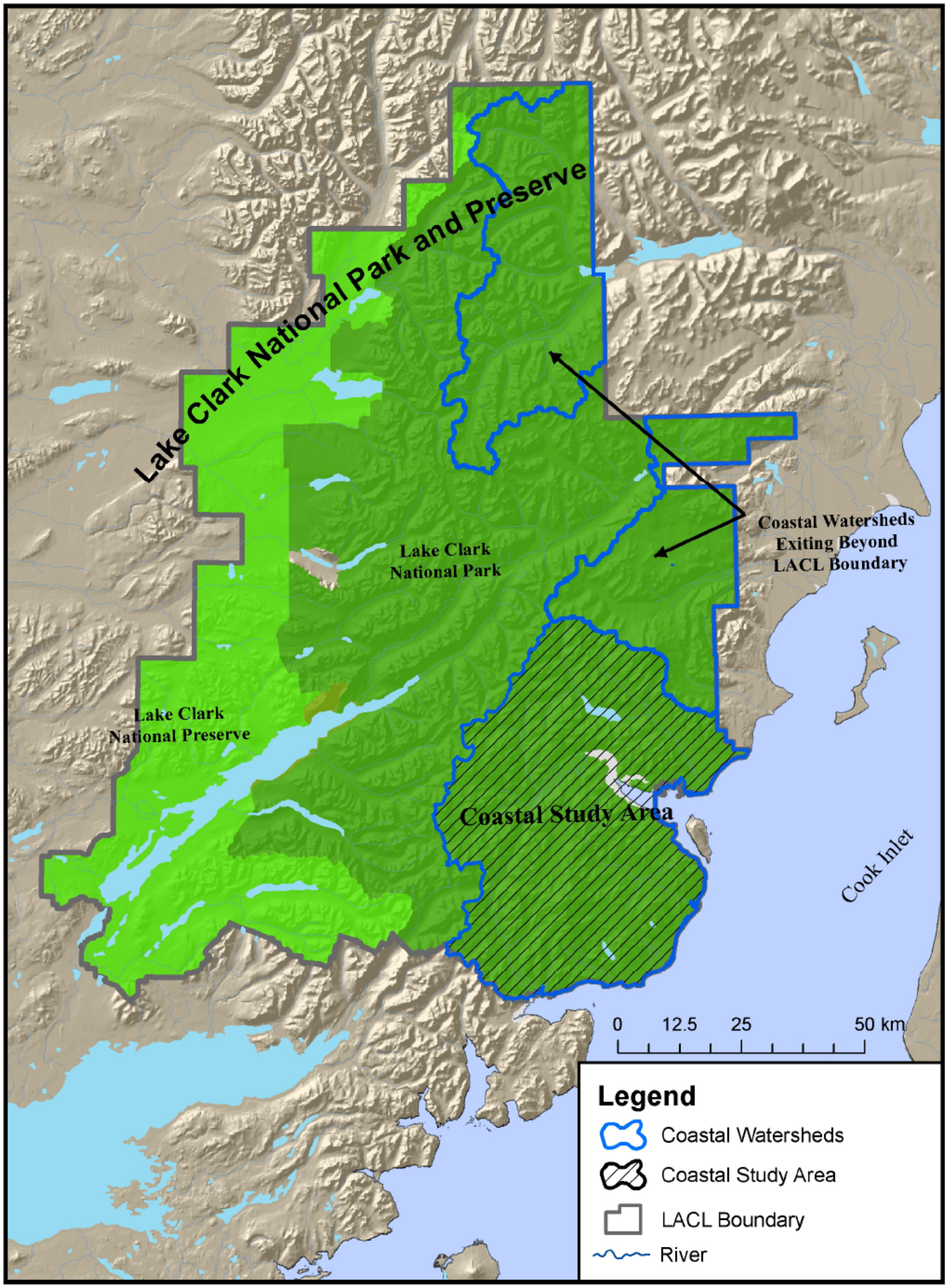


Figure 2. Location of the Coastal Watershed Study Area and administrative boundaries in Lake Clark National Park and Preserve.

Park Description and History

Setting

Geographic setting

Lake Clark National Park and Preserve (66°15’00”N 154°15’00”) is located in southcentral Alaska across Cook Inlet from the Kenai Peninsula and approximately 160 km (100 mi) southwest of Anchorage. The Chigmit Mountains, at the junction of the Alaska and Aleutian Ranges, separate the steep, rugged, and glaciated Cook Inlet coastal region of LACL from the lower-lying foothills, terminal moraines, and tundra plains in the southwestern part of the unit. As part of the Aleutian “Ring of Fire,” the Chigmit Mountains include three active volcanoes (Mt. Spurr, Mt. Redoubt, and Mt. Iliamna) that rise up to 3,374 m (11,070 ft) in elevation. LACL contains over 9600 km (6000 mi) of streams and rivers, some of which are among the world’s most productive spawning and rearing habitat for sockeye salmon.

The coastal study region that is the subject of this report encompasses approximately 309,646 hectares (765,147 acres). LACL’s coastline along Cook Inlet is 209 km (130 mi) long, spanning Redoubt Point to the northern boundary of Chinitna Bay. The coastal region includes numerous glaciers, volcanically-disturbed streams, forested watersheds, as well as lakes, ponds, low-lying coastal wetlands, wide beaches and shallow bays, and estuarine salt marshes with tremendous ecological importance. Salt marshes and wide mud flats each comprise 22% of the shoreline length (and 42% and 24% of the total area), followed by wide sand flat (18% of shoreline length) and wide sand beach (15% of shoreline length) (Bennett, 1996). Two major islands lie offshore in close proximity to the LACL coast—Chisik Island at the entrance to Tuxedni Bay and Kalgin Island across from Redoubt Bay. The most visible geographic feature of the coastline is Tuxedni Bay, which extends for several tens of kilometers into the coastal region and narrows into the glacial-fed Tuxedni River. North of Tuxedni Bay, the shoreline is indented with numerous small coves and bays, and the land elevation rises gently to 300 m (1000 ft) above sea level for up to 5 km (3 mi) inland. South of Tuxedni Bay, the topography is markedly steeper and more variable, with highly-incised hills leading to glaciers in the heterogeneous and rugged landscape of the Iliamna Volcano area.

The LACL landscape has been shaped not only by volcanic events but also by major glaciations in the recent geologic past. At the time of the last glacial maximum (ca. 23,000 years ago) most of southcentral Alaska, including all of LACL, was covered by the Cordilleran ice sheet (Reger et al., 2007). Air masses from the north Pacific Ocean delivered abundant snowfall to the Alaska Range and built thick glaciers that flowed eastward into Cook Inlet (Reger et al., 2007). The glaciers’ numerous advances carved out the U-shaped valleys, jaggedly sculpted peaks, and thick moraine deposits of the Chigmit Mountains, while their retreat left behind the numerous lakes pockmarking the landscape of much of the Alaskan Peninsula.

There are no major towns in or immediately adjacent to LACL, although there are five resident zone communities—Port Alsworth, Nondalton, Iliamna, Pedro Bay, and Lime Village. From Port Alsworth visitors may also access the only designated trail available in the entire park unit—a 2.5 mile trail to Tanalian Falls. The closest major towns to the LACL coast are approximately 60 km across Cook Inlet on the Kenai Peninsula and include Kenai, Soldotna, and

Homer. Access to LACL is limited to boats and small aircraft travel, and it is estimated to be the second least visited national park unit in Alaska, after ANIA.

Park history and land ownership

On December 2, 1980, the Alaska National Interest Lands Conservation Act (ANILCA) established Lake Clark National Park and Preserve, two years after President Carter's designation of Lake Clark National Monument. ANILCA states that the purpose of the park and preserve is: "To protect the watershed necessary for perpetuation of the red salmon fishery in Bristol Bay; to maintain unimpaired the scenic beauty and quality of portions of the Alaska Range and the Aleutian Range, including active volcanoes, glaciers, wild rivers, lakes, waterfalls, and alpine meadows in their natural state; and to protect habitat for and populations of fish and wildlife including but not limited to caribou, Dall sheep, brown/grizzly bears, bald eagles, and peregrine falcons."

The National Park portion of the unit contains 1.07 million hectares (2.64 million acres), in which the coastal study area is included, and the National Preserve encompasses another 567,000 hectares (1.4 million acres). Part of ANILCA (Section 701(b)) also established a nearly 1 million hectare (2.3 million acres) Lake Clark Wilderness, located almost entirely within the National Park portion. The NPS boundary is generally defined as following the mean high tide line. However, in Tuxedni Bay (as well as in the Silver Salmon Creek area), the boundaries, established by ANILCA, are drawn across the bay near the outlet.

Land ownership issues in LACL have been complicated and legally contentious. Until recently, the Federal government has had title to approximately 83% of LACL land, whereas about 205,000 hectares (507,000 acres) were under application under the Alaska Native Claims Settlement Act and the Alaska Statehood Act. Of the land claims made by private corporations, approximately 12,000 hectares (29,000 acres) were located between Tuxedni Bay and Chinitna Bay (Lee Fink, NPS-Port Alsworth, personal communication, 2005). Recently, after thirty years of dispute, the Ninth District Court sided with the Bureau of Land Management (BLM) and NPS that the claims are not valid and that the lands are part of LACL (Page Spencer, NPS-Port Alsworth, personal communication, 2007). Another 75,000 hectares (185,000 acres) of LACL land are non-Federally owned (NPS [National Park Service], 2004d). The non-Federal lands are split between the state of Alaska's 38,445 hectares (95,000 acres), Cook Inlet Regional Corporation, Nondalton Village Corporation, Iliamna Village Corporation, Pedro Bay Village Corporation, and Tanalian Inc. Native Group (NPS, 2004d). An additional 4,000 hectares (10,000 acres) of small tract holdings include Native Allotments, homesites and a farm, nine patented mining claims, and ten cemetery and historical sites.

Human utilization

Little archaeological information is available for LACL and particularly for its coastal Cook Inlet region. Based on the limited evidence, the area has been used by Native peoples from as early as 8000 B.C., and the occupants of LACL were the Dena'ina (also known as Tenaina), a branch of the much larger Athabaskan people with probable origins in northeast Asia and Siberia (NPS, 2004d). These peoples inhabited mostly the inland plateaus west of the Alaska range; however, according to linguistic and oral historic evidence, the Dena'ina were expanding their territory into the coastal Cook Inlet region at about the time of European contact (NPS, 2004d). Cultural remains have been excavated in the Kijik Village site, on the northwest shore of Lake Clark and along the Kijik River (also in interior LACL), where an estimated 150-175 people lived between 1875-1890 (Van Stone and Townsend, 1970). Toward the end of the 18th century, European settlers in Bristol Bay and in the Kenai Peninsula brought both disease epidemics and the lure of trade and income from new canneries and fur trading posts, and the Kijik village was abandoned by 1909 (NPS, 2007a). Currently, the only Native villages within LACL are Nondalton and Port Alsworth, although Native peoples continue to make seasonal use of the unit's land and resources (NPS, 1973).

Hydrologic information

Oceanographic setting

LACL is located in the northern Gulf of Alaska (GOA). The GOA is bordered by the Alaska Peninsula to the northwest and the Canadian mainland at Queen Charlotte Sound to the southeast (Figure 3). The oceanography of the GOA is composed of gyres, surface currents, predominant downwellings, and punctuated localized upwellings. Offshore circulation is dominated by a cyclonic subarctic gyre. The sluggish, easterly-flowing North Pacific Current bifurcates near 52° N and becomes the Alaska Current (AC) northward and the California Current southward. The Alaska Coastal Current (ACC), inshore of the AC, is a low-salinity, cyclonic (counter-clockwise), fast-moving (13 – 133 cm/s, 5-52 in/s) current driven by winds and density gradients established through freshwater input (Hood and Zimmerman, 1986).

Precipitation within the GOA ranges from 2-6 m (7-20 ft) per annum (Weingartner, 2005). The region is affected by intense winter storms that frequently become trapped or stalled by the surrounding rugged coastal topography (Royer, 1998; Wilson and Overland, 1986). Winter storms, characterized by low sea-level pressures, can routinely produce >15 m (49 ft) waves and gale strength winds (Wilson and Overland, 1986). Persistent cyclonic winds, coupled with onshore surface Ekman transport, promote downwelling favorable conditions for much of the GOA; however, episodic and local upwelling may be generated by eddies or other local geography. Despite predominant downwelling, the Gulf of Alaska is a productive ecosystem. Nutrients are supplied from small-scale upwelling, eddies, shear, Ekman transport, resuspension of shelf sediments, and river discharge (Stabeno et al., 2004).

The Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO) are global-scale atmospheric and oceanic conditions that influence climate, weather events, circulation, and, ultimately, the biology of the GOA. The PDO is characterized by descriptive weather indices that track anomalies of sea surface temperature, wind stress, and sea level atmospheric pressure (Hare et al., 1999). Wintertime location of the Aleutian Low creates a proxy which characterizes the regime of the PDO. A negative PDO occurs when the Aleutian Low is centered in the southwestern GOA, over the Aleutians and suthern Bering Sea. A positive PDO occurs when the Aleutian Low has a northeastern GOA locus, and the climate of the GOA is characterized by warmer sea surface temperatures, higher precipitation, and windier conditions (Hare et al., 1999). Opposite patterns for the Gulf are observed during negative phases of the PDO. Winters with

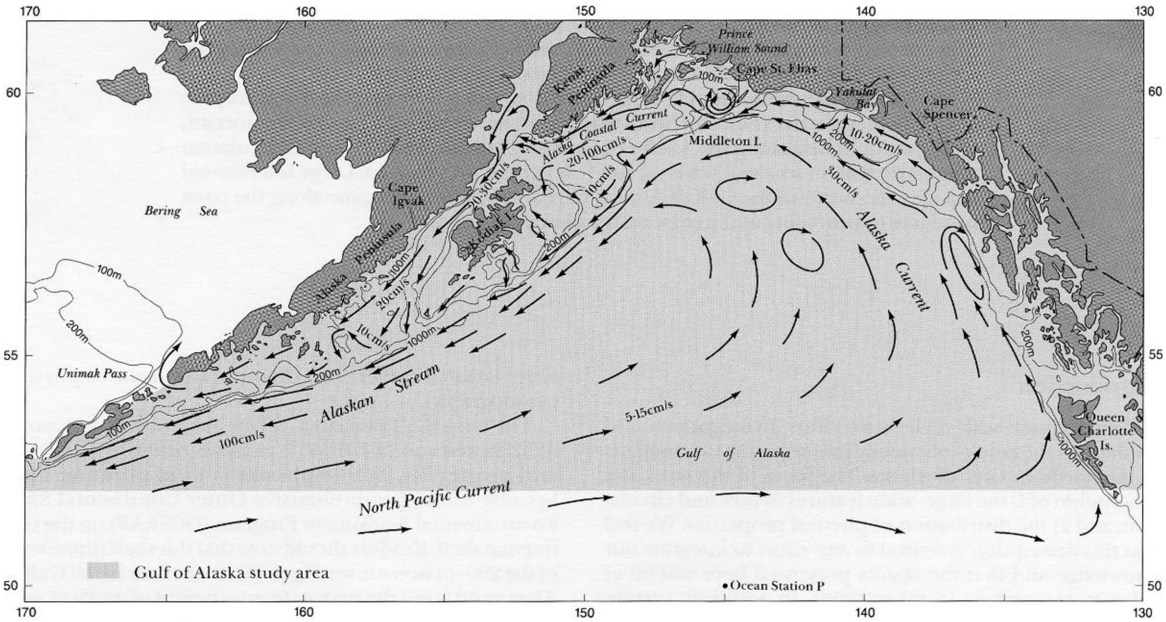


Figure 3. Predominant currents in the GOA (Reed and Schumacher, 1986).

strong Aleutian Lows tend to be associated with ENSO warming events (Niebauer, 1988). During a warming event (El Niño), sea levels rise, upwelling shuts off, and water temperatures in equatorial Pacific near Peru may rise as much as 5.4°C (9.7°F). During a cool phase (La Niña), cooler surface waters (< 20°C, 68°F) extend offshore of Peru and intensify upwelling currents in that region. Warming in the equatorial Pacific is not always associated with intensification of the Aleutian Low and vice-versa.

Cook Inlet is a large, shallow tidal estuary with depths ranging from 20-100m, averaging 60 m. The oceanography within Cook Inlet is influenced by the GOA and tidal mixing; tides in Cook Inlet are among the largest in the world. Ocean water from the Alaska Coastal Current flows into Cook Inlet through Kennedy Entrance, moves north along the east side of the Inlet, and upwells as the bathymetry becomes shallow. Water movement in Cook Inlet is predominantly counterclockwise, and relatively sediment-laden and fresher water moves out of the Inlet along the western side and exits at Cape Douglas. Along the east side of Cook Inlet, the water is relatively well mixed, as evidenced by salinity profiles (Figure 4) and strong vertical shear in the top 100m of the water column at Kennedy Entrance that results from tidal mixing (Figure 5; Stabeno et al., 2004). In the summer, temperature increases and salinity decreases along a gradient from lower to upper Cook Inlet (Figures 6 and 7). Mixing continually supplies nutrients to the surface and sustains high production (Larrance et al., 1977), making lower Cook Inlet one of the most productive high-latitude shelf regions in the world (Sambrotto and Lorenzen, 1987). Water along the west side of Cook Inlet is stratified due to freshwater input (Figure 4); however, this freshwater input varies seasonally, reaching a peak in July and August, and is lowest in winter. This freshwater contains high concentrations of suspended sediment that enters Cook Inlet and does not settle out. Sediment concentrations, primarily from glacial sources, are very high, averaging 200 mg/L and ranging up to 2,000 mg/L (Sharma and Burrell, 1970; Feely and Massoth, 1982). Within LACL, the heads of Tuxedni Bay and Chinitna Bay are strongly

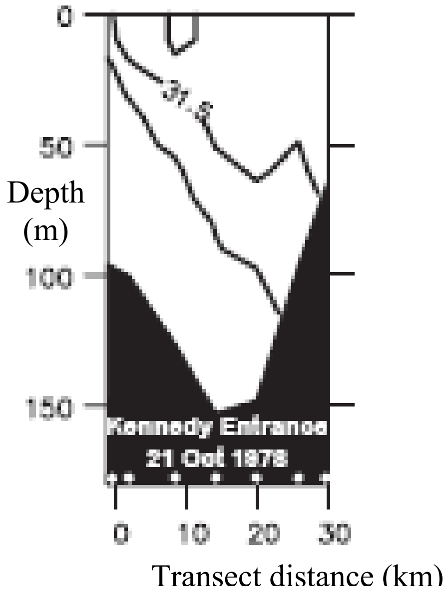


Figure 4. Cross-shelf transect at Kennedy Entrance Demonstrating shelf structure of salinity (psu) during October 1978. Contours are in 0.5 unit increments (Stabeno et al., 2004).

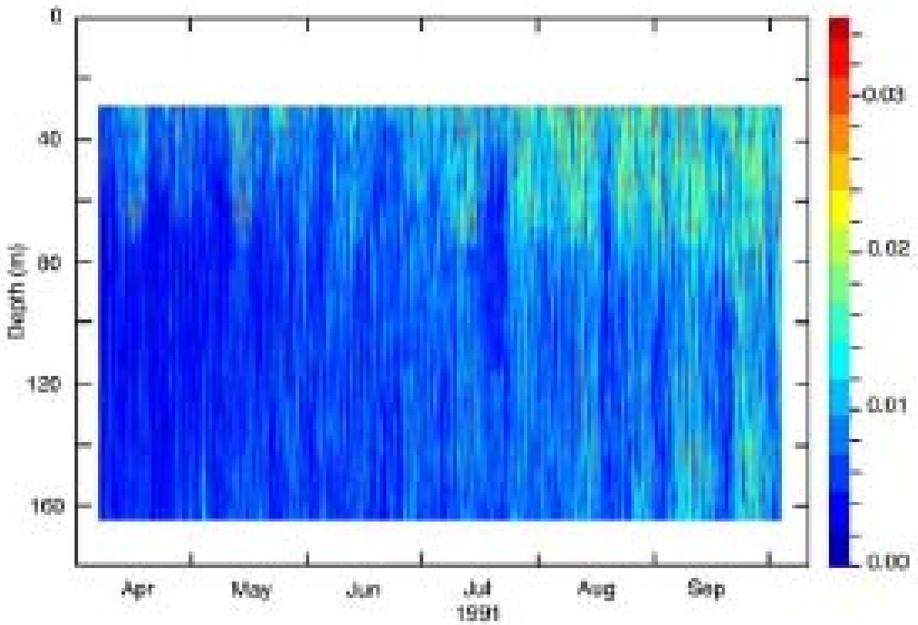


Figure 5. Vertical shear (s^{-1}), which is a reflection of current speed, at Kennedy Entrance from Acoustic Dopler Current Profiler. Blue indicates low shear and warmer colors indicate higher shear. Note that the highest shears are observed in the top 80 m of the water column and that shear is higher in the fall compared to the spring and summer (Stabeno et al., 2004).

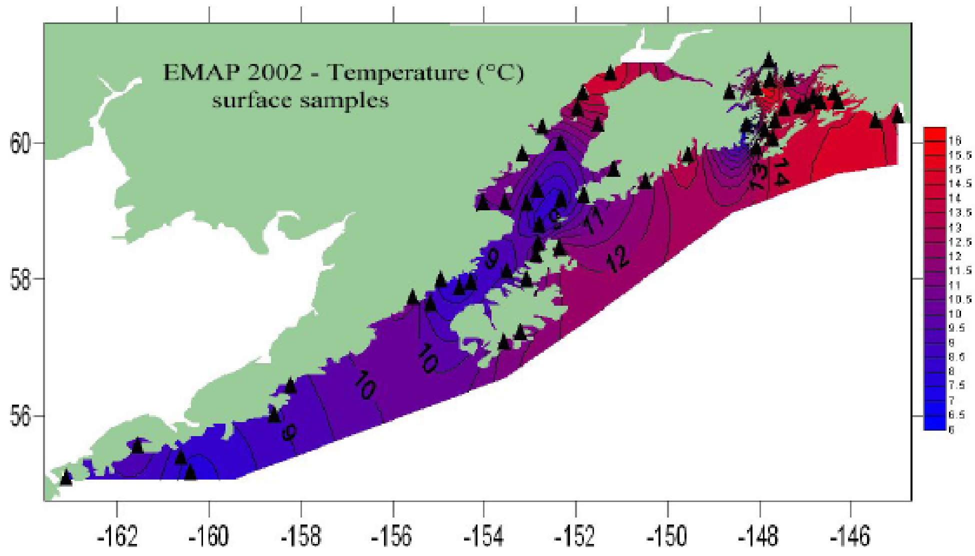


Figure 6. Surface temperature contours estimated from the 54 stations (triangles) sampled as part of the EMAP program (see section IV.A.1.a). Sampling occurred between June-August 2002 (Saupe et al., 2005).

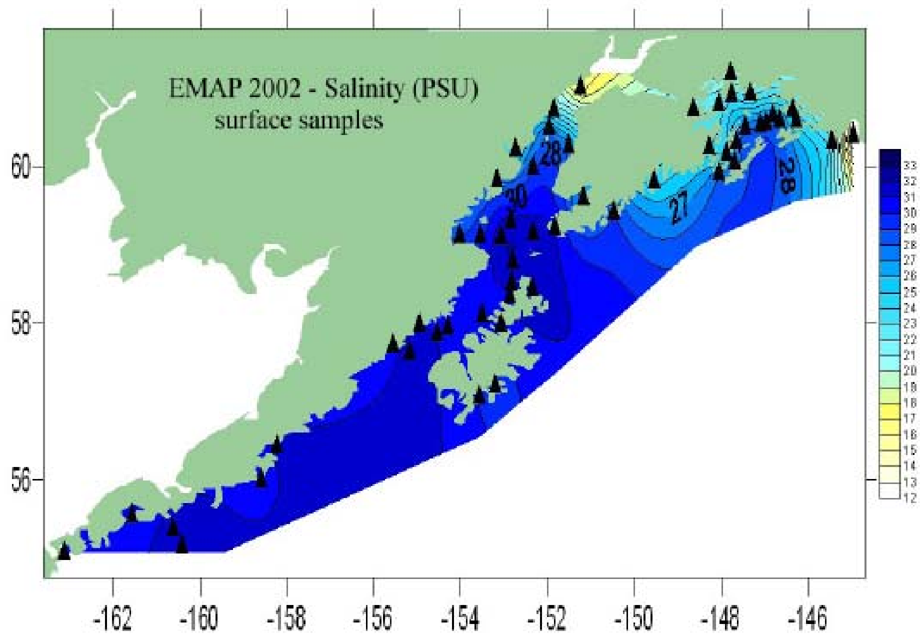


Figure 7. Surface salinity contours estimated from the 54 sampled stations (triangles), showing the lowest salinities occur relative to the major inputs of the principal rivers (Saupe et al., 2005).

influenced by large volumes of freshwater input. The Kenai and Drift Rivers are major contributors to freshwater input to Cook Inlet.

Climatic setting

Brabets et al. (1999) categorize the Cook Inlet region into three main climatic regions—continental, transitional, and maritime (Figure 8). The Chigmit Mountains form a major climatic divide in the LACL region, dividing the maritime coastal region from the continental interior (Weeks, 2001b). Coastal LACL annual precipitation ranges vary from 38-51 cm (15-20 in) in areas of broad coastal lowlands to 102-203 cm (40-80 in) where steeply rising mountains emerge almost directly off the coastline (e.g. the coast south of Tuxedni Bay) (Weeks, 2001b). The average annual temperature of the coastal region is approximately 5.5°C (42°F) (Brabets et al., 1999). The high humidity, low temperatures, and short summer season limit the amount of moisture returned to the atmosphere via evaporation and transpiration (Brabets et al., 1999).

The SWAN I&M program now has remote automated weather stations (RAWS) at two sites within coastal LACL. The Chigmit Mountains site is located in the coast mountains at 1372 m (4500 ft) elevation in the coast range (http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?akACHG), and the Hickerson Lake site is located closer to the coast at 305 m (1000 ft) elevation (http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?akAHIC). Other RAWS sites around coastal LACL include Pfaff Mine, Port Alsworth, and Snipe Lake (http://www.wrcc.dri.edu/wraws/akF.html).

The nearest National Weather Service weather stations in current or recent operation are at Big River Lakes and at the Drift River Terminal, both located between the NPS boundary line and Cook Inlet (Figure 9). The Big River Lake station began operation in November, 2003 and continues to the present (data for the site accessible from the Western Regional Climate Center at http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?akpalv). The station monitors wind speed and direction, air temperature, and relative humidity, but not precipitation. The Drift River Terminal meteorological station is the closest station to the coastal LACL study region. Data are available for the period August 1999 - June 2006 (http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?akadrf/). Meteorological parameters for this period include wind speed and direction and air temperature, but not relative humidity or precipitation. Monthly mean air temperature at the Drift River station ranges from 13°C (55° F) in August to -5°C (23°F) in January (Figure 10). A comparison of temperatures at Drift River to those at Port Alsworth, which is representative of interior LACL, indicates that the coastal region of LACL is up to 5°C warmer than the interior in the winter months and slightly cooler in the summer months.

The Federal Aviation Administration (FAA) operates live weather cameras in Merrill Pass, Lake Clark Pass, near Big River Lakes (Lake Clark Pass East), and at the upper end of Lake Clark (Lake Clark West). Images from both west- and east- facing cameras at the passes are normally updated every 10 minutes and are available from the FAA weather camera webpages, listed at http://akweathercams.faa.gov/sitelist.php. No quantitative climate data are available at the sites.

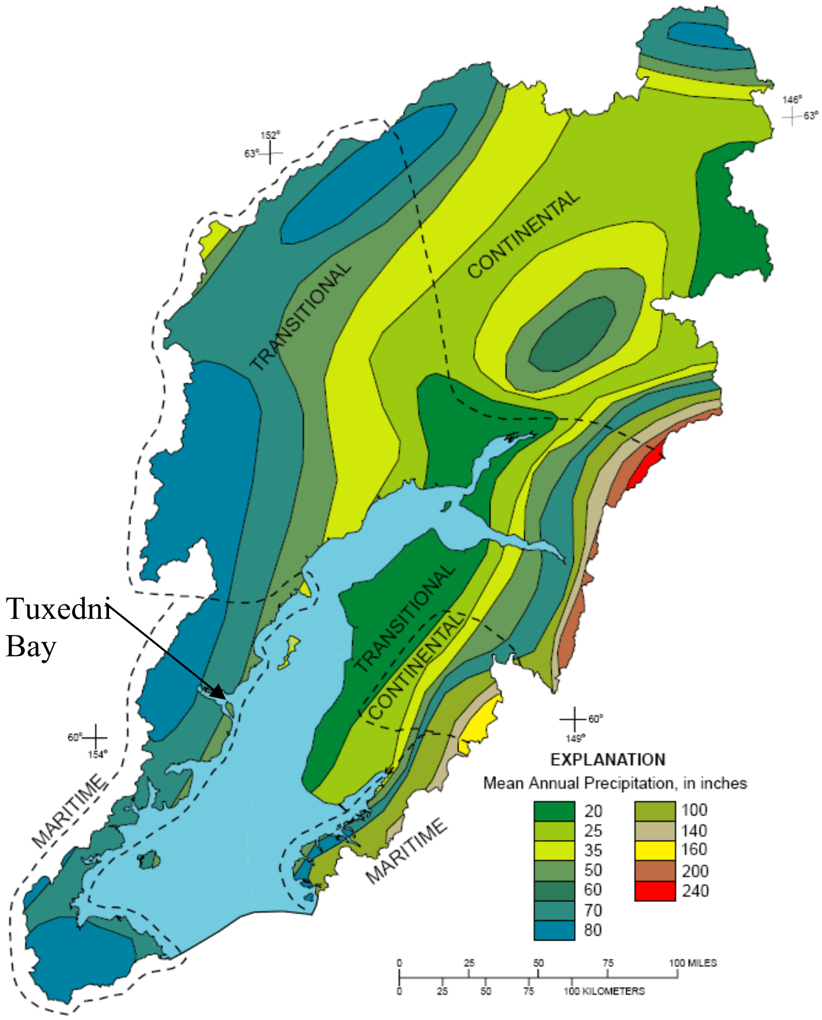


Figure 8. Climate and precipitation zones of the Cook Inlet Basin (Brabets et al., 1999; Jones and Fahl, 1994). LACL is in the lower left region, with Tuxedni Bay label added for orientation.

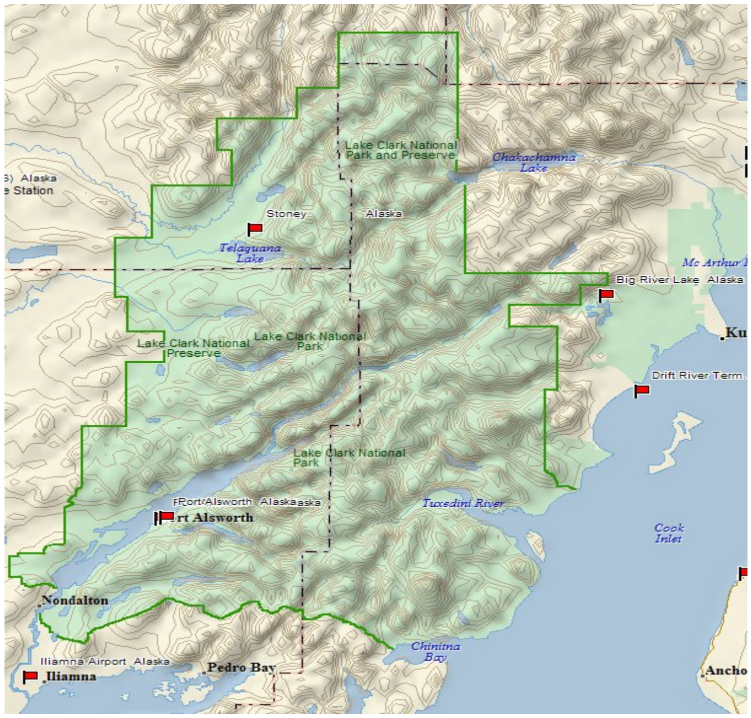


Figure 9. Map of weather stations in the immediate LACL region. Map downloaded from http://www.wrcc.dri.edu/lakeclark/. Recently added SWAN I&M RAWS sites at Hickerson Lake and the Chigmit Mountains are not shown.

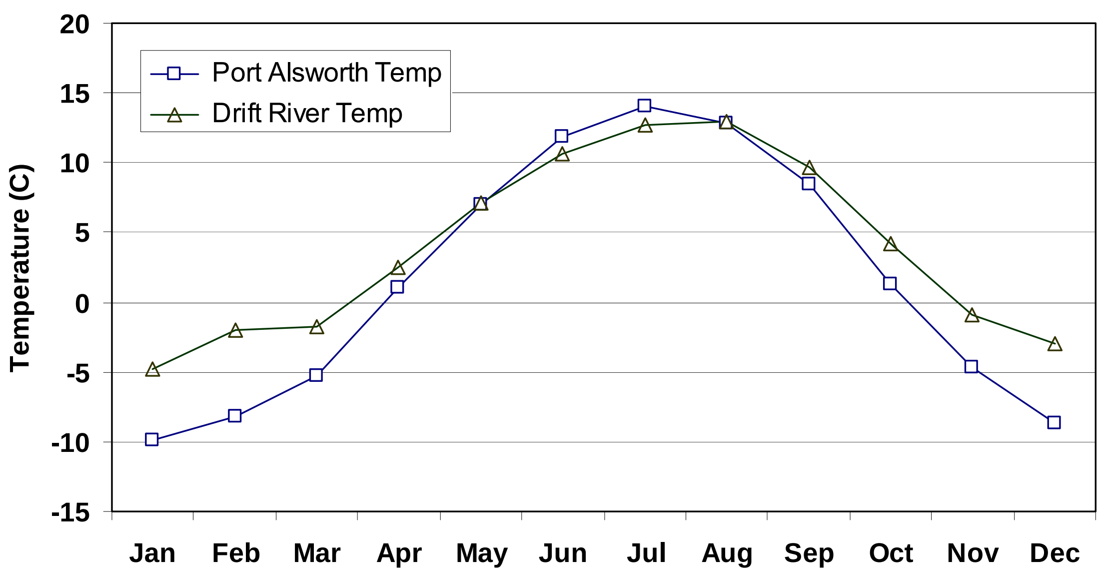


Figure 10. Mean daily air temperature for Port Alsworth (representative of interior LACL) and the Drift River Terminal (representative of coastal LACL). Port Alsworth data from http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ak7570 and Drift River data from http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?akadrf/ .

Streams and streamflow

Descriptions and lists of streams: Watersheds in coastal LACL extend from sea level to greater than 3000 m (~10,000 ft) in elevation in the Aleutian Range. The majority of streams are fed by meltwater from glaciers and snowfields, although there are a number of small, low-elevation watersheds along the coast where streamflow is derived primarily from rainfall and intermittent snowmelt. The major streams within the Coastal Study Area of LACL include, from north to south, Polly Creek, Crescent River, Tuxedni River, Open Creek, Difficult Creek, Hungryman Creek, Bear Creek, Johnson River, Silver Salmon Lakes and Creek, Red River, Shelter Creek, East Glacier Creek, Middle Glacier Creek, and West Glacier Creek (Figure 11). In addition, there are a large number of major coastal streams that have their headwaters within the LACL boundaries, but leave the park before flowing into Cook Inlet. These include the Drift River, the Big River, Cannery Creek, Harvest Creek, Redoubt Creek, and, in the northeast section of LACL, rivers feeding into Kenibuna Lake (Chilligan River, Igitna River, Another River, and Neacola River) and making up the headwaters of the Chakachatna River.

Many of the watersheds to the north of Tuxedni Bay drain gently rolling hills skirting the steep, glaciated Chigmits and are characterized by silty, glacial outwash- and volcanic ash- laden braided streams (e.g. the Crescent River, Figure 12). In their lower reaches, these streams develop broad, shallow mud flats that characterize this area of the LACL coastline. South of Tuxedni Bay, the topography steepens markedly, and the landscape is sharply carved by glacial valleys that empty into deeper coastal waters. Streams draining active volcanoes include the Drift River, Redoubt Creek, and the Crescent River (all draining Redoubt Volcano), and all streams from the Tuxedni River to West Glacier Creek that drain portions of the Iliamna Volcano and its foothills. The lower portions of the Tuxedni River, Johnson River, and West Glacier Creek are tidally influenced for several miles (Cusick and Bennett, 2005).

Streamflow and physical habitat information: There are currently no operational USGS stream gages within LACL, although there are six operational gages located within about 52 km (32 mi) of the southern boundary of LACL (Figure 13, Table 2). All of these stream gages are located at interior locations and thus are probably not directly representative of the hydrologic regime of streams in the LACL coastal region. Recent streamflow data from the USGS are available for two of the streams within coastal LACL, the Johnson River and the Crescent River. The USGS maintained the gage on the Johnson River from July 1995 through September 2004, when it was discontinued. However, during the period of operation, the gage did not record streamflow between the months of November and April, with the exception of during the winters of 2002 and 2003. The gage on the Crescent River was operational from June 2005 through September 2006; however, data were not collected during the winter (November-April) (http://waterdata.usgs.gov/ak/nwis/sw).

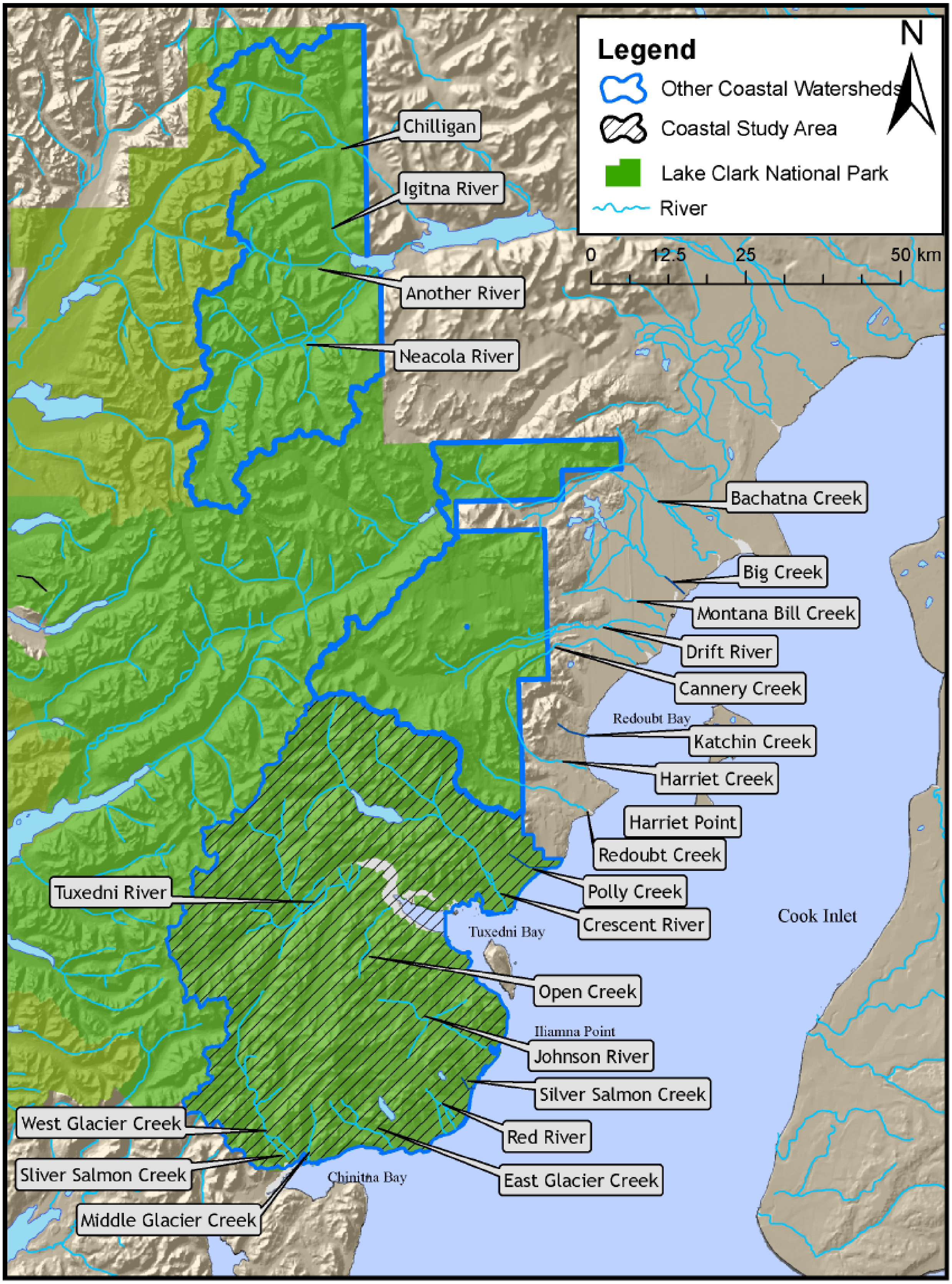


Figure 11. Major streams within the LACL coastal study area.

Figure 12. The headwaters area of the Crescent River (Photo by T.P. Brabets, USGS; in Glass et al., 2001).

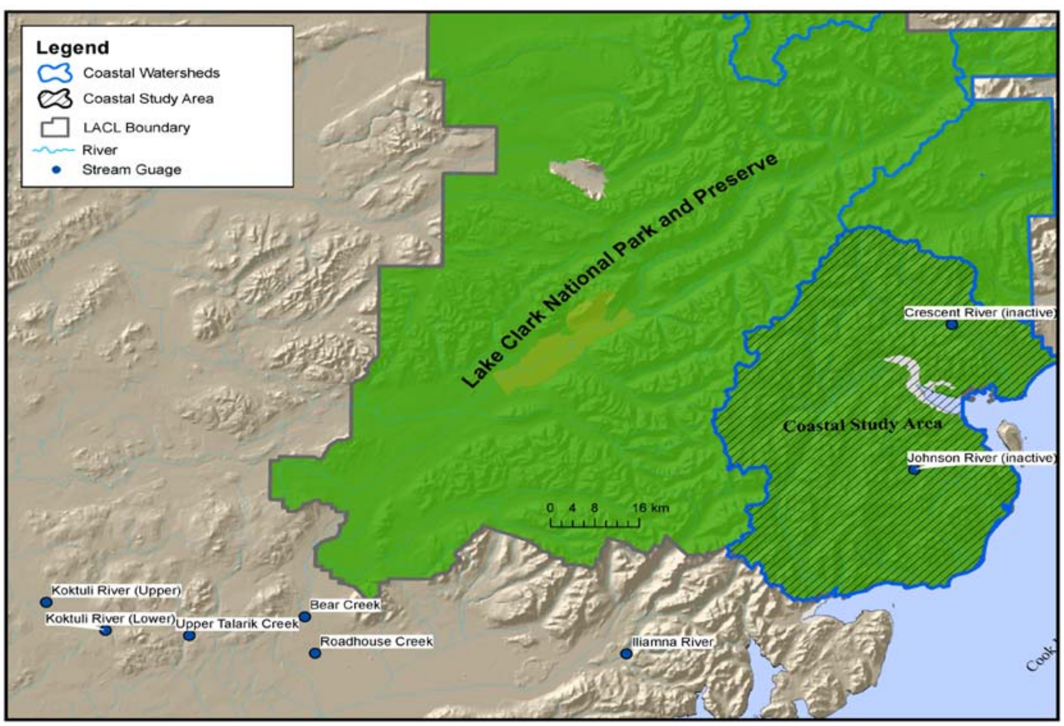


Figure 13. Stream gages within and around LACL.

Table 2. USGS streamflow gages near LACL. Coordinates are in NAD83. Data from USGS streamflow database for Alaska (http://waterdata.usgs.gov/ak/nwis/sw).

Station Name	Gauge #	Lat.	Long.	Dist. From LACL (km)	Period of Record
Iliamna R	15300300	59.758	-153.847	19	1996-present
Koktuli Upper R	15302200	59.793	-155.525	52	2004-present
Koktuli Lower R	15302250	59.843	-155.719	42	2004-present
Roadhouse Ck	15300200	59.757	-154.849	15	2005-present
Upper Talarik Ck	15300250	59.786	-155.255	29	2004-present
Bear Creek	15300100	59.824	-154.884	9	2006-present
Johnson R	15294700	60.095	-152.911	-	1995-2004
Crescent R	15294640	60.358	-152.819	-	2005-2006

Based on the limited information available, the hydrologic regime of the coastal LACL watersheds appears to be dominated by runoff from snow and glaciers. The Johnson River (Figure 14) is typical of a stream where glacial melt is the dominant hydrologic event on an annual basis. Precipitation events, particularly in late summer and fall, can result in transient increases in discharge; however, the monthly hydrograph for the Johnson River shows a broad peak during the period June-September when glacial melt is at a maximum (Figure 15). Inputs from the Lateral, Johnson, and Double Glaciers can result in an increase in the streamflow of the Johnson River of more than two orders of magnitude between the winter low flow and summer high flow periods. The limited discharge data from the Crescent River also show an ice and snowmelt dominated hydrograph with peaks in mid-summer (Figure 16). Although other coastal LACL streams have not been gaged, they likely follow the same general streamflow pattern in cases where glaciers make up a significant portion of the watershed area. For the smaller, non-glacial coastal streams, runoff patterns are likely more erratic and flashy in response to precipitation and snowmelt events. In terms of water quality, glacial streams also have higher water and sediment yields, and a lower water temperature and ionic strength compared to non-glacial streams (Brabets et al., 1999).

Figure 14. Hydrologist taking a discharge measurement in the Johnson River (Photo by S.A. Frenzel, USGS). From Glass et al, 2004.

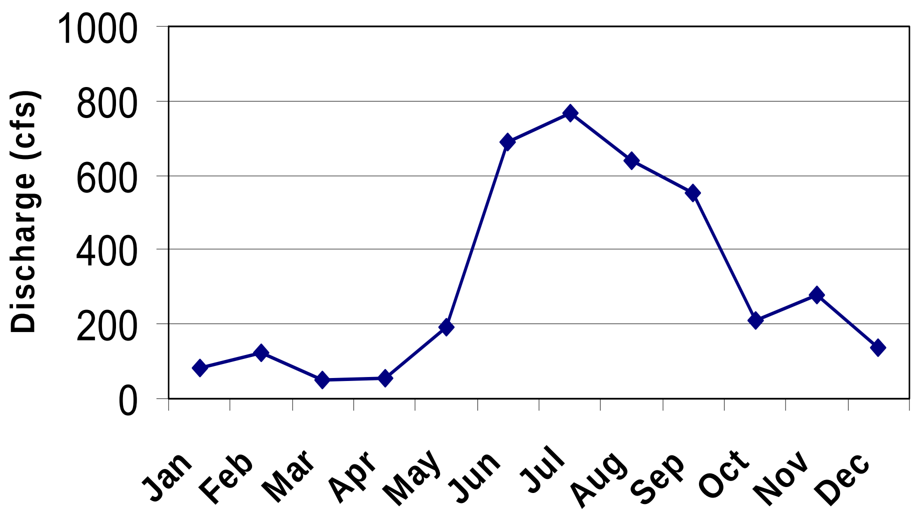


Figure 15. Mean monthly streamflow during the period of record available (1995-2004) for the Johnson River USGS stream gage. Note that data for Nov-Apr are only available for one year (2002-3) during the period of record. Data retrieved from USGS streamflow database for Alaska (http://waterdata.usgs.gov/ak/nwis/sw).

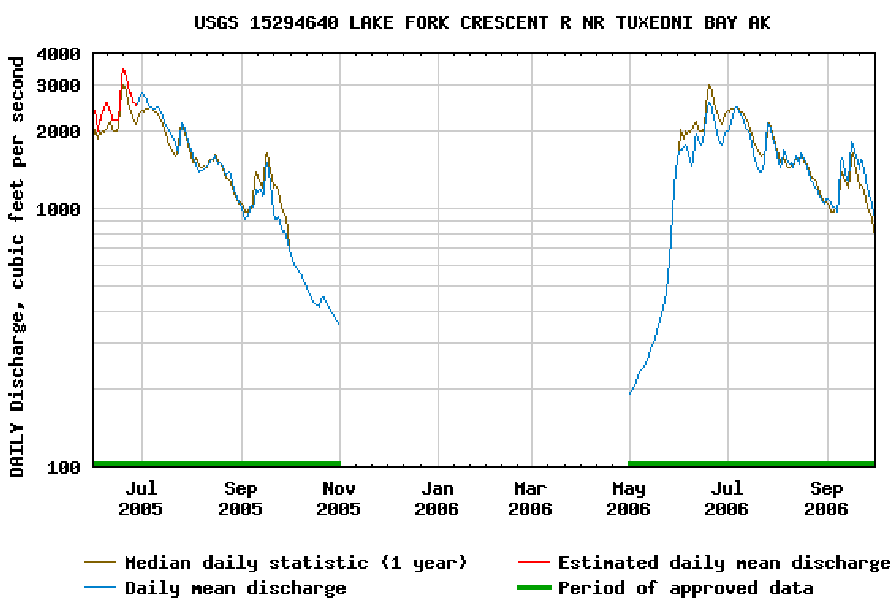


Figure 16. Discharge on the Lake Fork of the Crescent River (USGS gage site number 15294640) from June 2005 - September 2006. Source: USGS Alaska Science Center.

Although not in the coastal region, one useful source of streamflow and water quality information comes from a detailed USGS study conducted during the 2001 and 2002 water years on the Tlikakila River, which drains into Lake Clark (Brabets et al., 2004). The study identified the runoff components (11% from glacial ice melt, 75% from snowmelt, 14% from rainfall, and 1% from groundwater) in the Tlikakila River, demonstrating the dominant role that glacial and snowmelt plays in generating and sustaining streamflows in watersheds that span the coastal mountains. While streams on the coastal side of the Chigmit Mountains that drain into Cook Inlet likely have higher rainfall and groundwater contributions, it is probable that they are similarly dominated by glacier and snowmelt runoff, as shown in the limited data from the Johnson River gage data.

Several other reports provide information on discharge in coastal LACL streams. A reconnaissance study on the Crescent River by Deschu (2003) included estimates of discharge in the mainstem and two tributaries on a single day (September 1) in 1997. Tributaries "Lake Fork" and "North Fork" had estimated discharges of 487 and 432 cfs, respectively, with a combined discharge below their confluence of 919 cfs (Deschu, 2003). A more recent study of the Crescent River watershed included stage recordings and occasional measurements of discharge on the Crescent River and two of its tributaries in May-October, 2003-2004 (Brabets and Ourso, 2006). Stage readings were measured continuously on the Lake Fork of Crescent River, and stage-discharge relationships were considered good during this period. (Stage records at the North Fork and mainstem sites were considered poor due to constantly shifting channels). Direct measurements of discharge on the Lake Fork Crescent River ranged from 462 to 2,680 cfs, on the North Fork Crescent River from 89 to 721 cfs, and on the mainstem from 742-5,250 cfs (Brabets and Ourso, 2006). In the Drift River, reports on the massive debris flows and floods resulting from the Redoubt Volcano eruptions in 1966-68 and 1989-90 provide estimates on the magnitude of flow; flows were estimated to have peaked at 20,500 m3/s (720,000 cfs) in 1966 and at 30,000 m^3/s (106,000 cfs) in 1989 (Major and Janda, 1990; Trabant and Brabets, 1990; Trabant and Meyer, 1992b).

Lakes and ponds

Although lakes form major geographic features in interior LACL, with 20 major lakes and numerous smaller lakes and ponds, the Coastal Study Area has relatively few lakes (Figure 17). The largest coastal lake in LACL is Crescent Lake (area=13.6 km^2; mean depth = 23 m; max depth= 32 m; volume= $313*10^6$ m^3), which drains into the Crescent River (Edmundson and Mazumder, 2001). The next largest is Hickerson Lake (3.7 km [2.3 mi] long; width unsurveyed; and max depth of 41m [135 feet]), on the southeastern slope of Iliamna Volcano (Russell, 1980). Hickerson Lake is snow-fed and has no surface outlet (Russell, 1980). Other, smaller lakes include Silver Salmon Lakes, Saddle Mountain Lake, and Blue Lake.

Physical information on Crescent Lake is available from Edmundson and Edmundson (2002), who conducted a study on the lake's sockeye salmon population, and from a basin-scale water quality investigation by Brabets and Ourso (2006). Both reports provide physical descriptions of the lake's dimensions and note that the semi-glacial lake is fed by two major inlet streams—one mid lateral and one at the upper end (Figure 18). Brabets and Ourso (2006) add that the lake is oligotrophic, ice-free from about June through October, and dimictic—circulating twice per year. Brabets and Ourso (2006) estimate that Crescent Lake's annual water-residence time is 0.7 to 0.8 years, with most of the inflow being derived from overland runoff and snowmelt. Water quality results from the studies are discussed in the section *Specific lakes.*

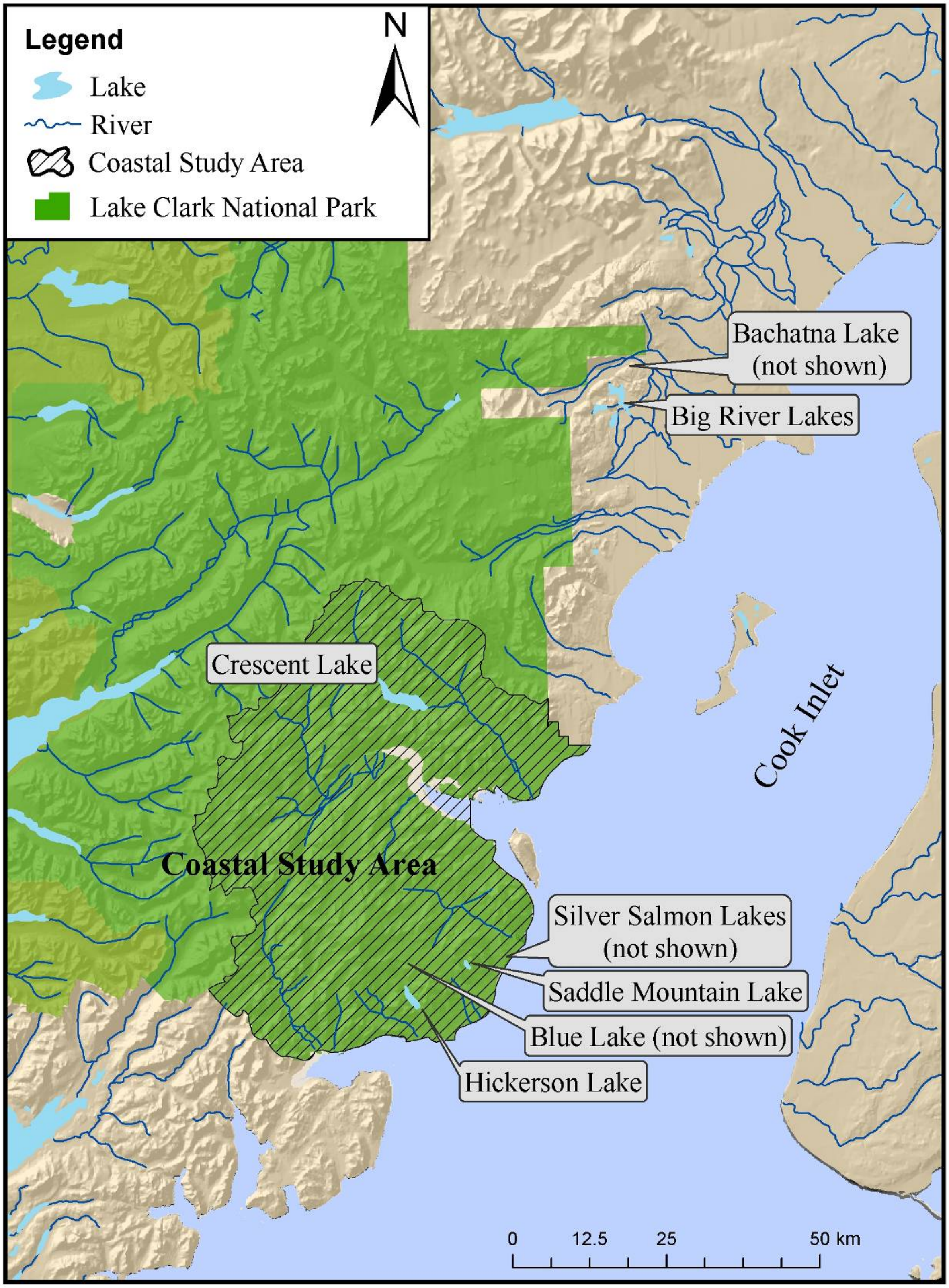


Figure 17. Lakes within and adjacent to the coastal LACL region.

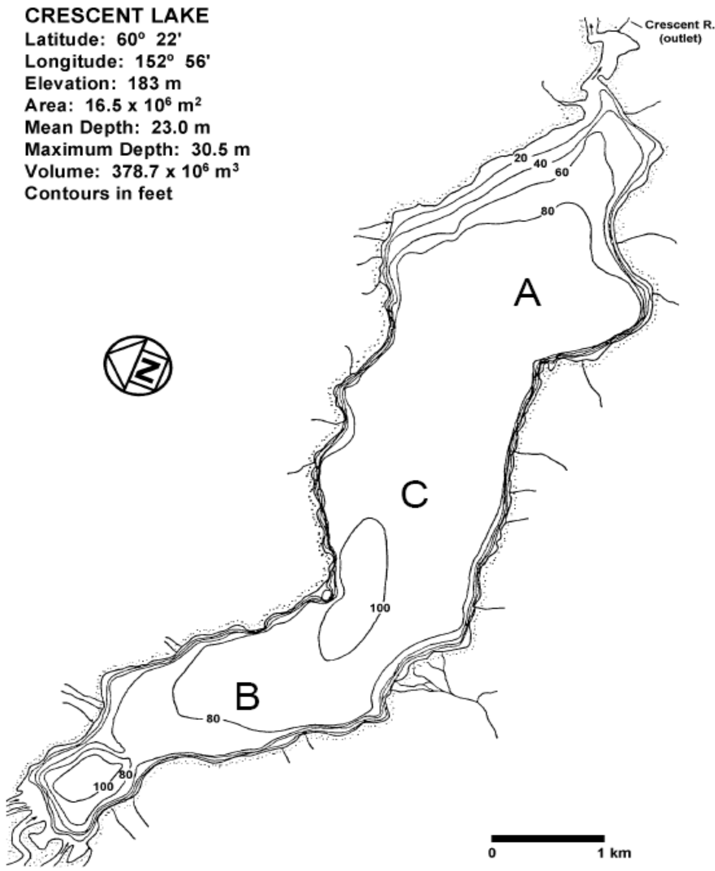


Figure 18. Bathymetric map of Crescent Lake from Edmundson and Edmundson (2002). A, B, and C refer to sampling locations where physical, chemical, and biological samples were taken.

Groundwater

No groundwater resources in coastal LACL have been inventoried or described. Yet, considering the coastal area's complex juxtaposition of salt water-influenced marshes, fractured and faulted bedrock, and volcanic and glacial deposits, it is likely that groundwater resources are diverse and heterogeneous over short distances (Weeks, 2001b).

Snow, ice, and glaciers

There are numerous permanent snowfields within LACL; however, there are no known studies on the aerial dimensions and/or chemical attributes of these water resources. Coastal LACL contains abundant glaciers (Figure 19); however, none of these glaciers have ongoing programs to measure mass balance. The closest glaciers to LACL that have long-term records of mass balance are the Wolverine Glacier on the Kenai Peninsula and the Gulkana Glacier in the Alaska Range, both of which are U.S. Geological Survey Benchmark Glaciers (http://ak.water.usgs.gov/glaciology/). In addition, data on changes in glacial aerial extent between the 1980s and 2000 are available for glaciers in KATM and KEFJ through the SWAN I&M program (http://science.nature.nps.gov/im/units/swan/index.cfm?theme=glacial_extent).

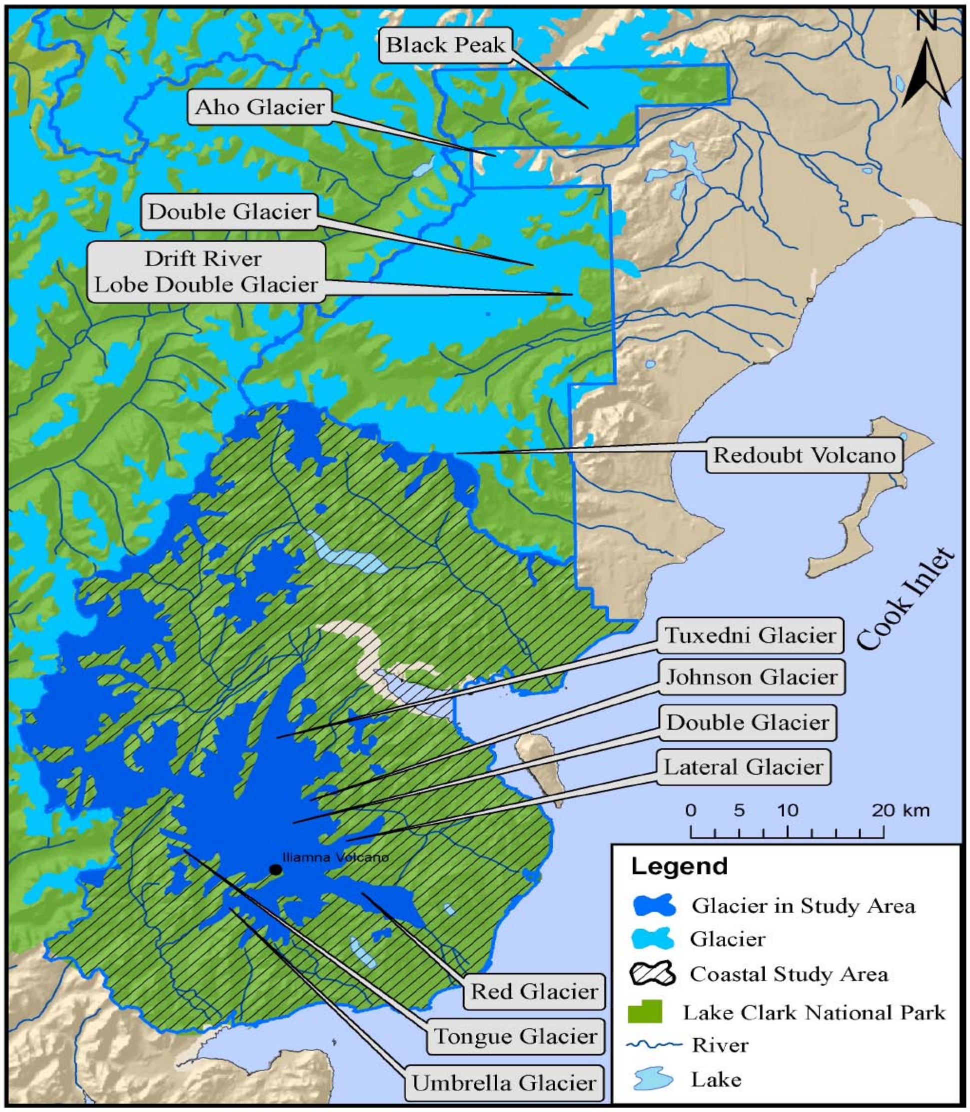


Figure 19. Glaciers in and adjacent to the LACL coastal study area

Glacial ice has been a dominant landform in the Lake Clark region and its glacial history contains multiple piedmont glaciations. Coastal LACL contains major regions of glaciers and snowfields, most of which are associated with the Redoubt and Iliamna volcanoes. Within coastal LACL, glaciers currently cover approximately 121,000 ha (296,526 acres) or 39% of the land area (Figure 19). Thus, glacier coverage is slightly higher in the coastal region of LACL as compared to the park as a whole, where glacier coverage has been estimated at 30% (Weeks, 2001a). Most of the glaciers in coastal LACL have been retreating since the end of the Little Ice Age (~250 yrs ago) and continue to retreat today. The effects of climate change on glaciers in LACL are discussed in the *Climate Change* section. The majority of glaciers in coastal LACL have grounded termini; there are no tidewater glaciers of the type found in Glacier Bay and Kenai Fjords National Parks. The largest glaciers in coastal LACL are located on the Iliamna Volcano and include the Tuxedni, Red and Lateral Glaciers (Figure 19). The Redoubt Volcano also has a high concentration of glaciers, and the Double Glacier on Double Peak immediately to the north of the coastal study area is a large glacier with lobes contributing streamflow to both the Big River and the Drift River (Figure 19). The longest of these glaciers exceed 25 km (15.5 miles) in length. Despite the widespread occurrence of glacial ice, the coastal region of LACL is relatively free of permafrost because of the mild, maritime climate.

Glaciers within coastal LACL have profound effects on the landscape, including erosion and deposition that produce moraines, pro-glacial lakes, and eskers. Additionally, meltwater flowing from glaciers creates broad outwash zones and braided stream channels, such as those seen in the Tuxedni and Drift Rivers. In addition, glacial runoff has a dramatic influence on the annual sediment yield and hydrograph of glacial rivers and streams (Lawson, 1993). The hydrologic system of a glacier determines the rate at which the glacier transmits and discharges freshwater. In addition, glacial hydrology can control the occurrence of outburst floods and rates of glacier sliding and surging, both of which are enhanced by the presence of meltwater at the glacier base. The hydrology of glaciers is relatively complex and not well understood. Meltwater channels can develop on the glacier surface (supraglacial), beneath the glacier (subglacial), as well as within the glacier (englacial). Recent research suggests that the hydrologic system of temperate glaciers like those found in LACL is dominated by networks of fractures within the glacier ice that convey water at relatively slow speeds (Fountain et al., 2005). These fractures are regenerated seasonally and are the primary conduit through which water moves from the surface of a glacier to the glacier bed.

There has been substantial research on glaciers in LACL. A group from the Geophysical Institute at the University of Alaska Fairbanks began studying the Drift Glacier on the north side of Mt. Redoubt in 1977. They documented that snow accumulation at the summit was more than 5 m of water equivalent and measured ice flow on the lower portions of the glacier which exceeded approximately 500 m per year (Sturm et al., 1983; Sturm et al., 1986). A later study by the same group examined the effects of the 1966-1968 eruptions of Mt. Redoubt on the flow of the Drift Glacier. It was determined that the two year eruptive cycle removed 6×10^7 m^3 of glacier ice from the upper region of the glacier and that the upper and lower portions of the glacier became decoupled during this period (Sturm et al., 1983; Sturm et al., 1986). The eruptions also triggered a sequence of jokulhaups or glacier lake outburst floods which caused a series of floods on the Drift River. One of these floods, in January 1966, flooded the site of the oil tanker terminal on Cook Inlet at the mouth of the Drift River. These flood events also deposited a heavy mantle of sand and ash (up to ~5 m thick) on the piedmont lobe of the glacier. These deposits reduced ice ablation on the lower lobe of the glacier by insulting the glacier ice (Sturm et al., 1983; Sturm et al., 1986). The upper portion of the Drift Glacier was regenerated in 1976, eight years after the eruptions, by normal snow accumulation combined with intense avalanching; the regenerated glacier then connected the lower portion of the glacier and caused greatly accelerated surface velocities (Sturm et al., 1983; Sturm et al., 1986).

The glaciological effects of the 1989-1990 eruption of Redoubt Volcano on the Summit ice mass and Drift Glacier were also studied by several researchers. Trabant and Brabets (1990) estimated that eruptions during this period removed approximately 15% of the total volume of the Drift Glacier and approximately 50% of the perennial ice mass in the summit crater (8×10^7 m^3 total of snow and ice removed). They further estimated peak discharges of 20,000-30,000 m^3/s approximately 22 km from the volcano vent associated with these eruptions. These flows were the largest in the Drift River in the 20th century and were two orders of magnitude greater than the estimated 100 year flood from this river (Trabant and Meyer, 1992a). Trabant and Brabets (1990) also noted that, as of 1990, an advance of several 100 meters by the Drift Glacier could dam the Drift River and produce a second flood source. Waitt et al. (1990b) examined the effects of the 1989-1990 eruption on the morphology of the Drift Glacier and found that the hot pyroclastic flows from the volcano interacted with snow and glacier ice to form large debris floods (known as lahars) down the Drift River Valley. As with earlier eruptions, the lower lobe of the glacier was covered with a several meters thick layer of ice conglomerate and pyroclastic debris that shielded the piedmont lobe from further erosion (Waitt et al., 1990b). Overall, Trabant and Meyer (1992a) estimated that the flow of the Drift Glacier would be altered for longer than the two decade perturbation associated with the 1966-1968 eruption and also commented that ash deposits on many glaciers within several 10s of km from the Redoubt Volcano would affect their mass balances, runoffs, and ice-flow regimes for several decades after the 1989-1990 eruption.

In the late 1990s, the perennial volumes of snow and ice on Iliamna Volcano were estimated using volume modeling constrained by field measurements using an ice-penetrating radar (Trabant, 1999). The estimated volumes of perennial snow and ice on the four largest glaciers on the volcano (the Tuxedni, Lateral, Red, and Umbrella Glaciers) were 8.6, 0.85, 4.7, and 0.60 cubic kilometers, respectively, with errors of no more than ±25%. The volume of ice on Iliamna equates to three times the ice stored on Mt Rainier and 82 times the pre-eruption ice on Mt. St. Helens (Trabant, 1999). Both Mt. Ranier and Mt. St. Helens have well documented geohydraulic hazards, in large part because volcanoes mantled by substantial deposits of snow and ice can produce catastrophic lahars and floods. Although Iliamna volcano has not had a well documented eruption in the last 200 years, it is considered to be dormant rather than extinct. As a result, flooding and lahars would threaten all of the drainage basins with their headwaters on the Iliamna Volcano (Trabant, 1999).

More recently, Brabets et al. (2004) studied the glacier changes and runoff characteristics of the Tlikakila River basin. Although this is outside of the coastal region of LACL, their findings are relevant to glaciers in coastal LACL. Brabets et al.(2004) studied 64 glaciers in the Tlikakila Basin and mapped changes in their terminus positions during the periods 1957-78 and 1978-99. They found that in the 1957-1978 period, 33% of glaciers advanced, 12% were stable, and 55% retreated. In the later period (1978-1999) 11% of glaciers advanced, 5% were stable, and 84% retreated. The average retreat rate for the glacier termini increased from 4 m per year in 1957-78 to 14 m per year in 1978-99. This study also used airborne laser profiling to estimate volume changes in the Tanaina, Glacier Fork, and North Fork Tlikakila glaciers during the period 1957-2001. They estimated a total ice loss of 1.03×10^{10} m^3, which represents thinning rates for these glaciers of between 0.5 and 0.9 m/yr. The study also examined the mass balance of these three glaciers during the 2001 water year and found that all had negative water equivalent mass balances ranging from a high of -1.15 m on the North Fork Glacier to a low of -0.05 m on the Glacier Fork Glacier.

The SWAN I&M program has identified glacier extent as an important vital sign to monitor and is using satellite imagery (primarily LANDSAT) to monitor changes in glacial coverage in SWAN parks. Changes in glacial extent between 1986 and 2000 have been estimated for both

KEFJ and KATM and mapping is in progress for LACL (Michael Shephard, NPS-Anchorage, written communication, 2008). During this period, the areal extent of the Harding Icefield in KEFJ has decreased by 2.3% (~42 km^2) and the primary glacier complexes with KATM have decreased in area by 7.7% (~76 km^2) (Giffen et al., 2008, in review). The SWAN I&M program is currently working with Dr. Compton Tucker (NASA-Goddard Space Flight Center) to map glacier extent in LACL for the years 1974, 1987, 2000, and 2007. However, there are several issues that complicate efforts to map glaciers in LACL, including substantial areas of ice that are covered with moraine and/or volcanic ash, seasonal snowfall, and terrain shadows. This mapping effort will be particularly useful for evaluating ecosystem changes in LACL because unlike the large icefield complex in KEFJ, LACL contains numerous small glaciers, many of which have disappeared in the last 40 years (Alan Bennett, NPS-Anchorage, personal communication, 2005).

In addition to mapping efforts, the SWAN I&M program is cataloging repeat photographs that document changes in glacier extent within LACL. There are currently repeat photographs containing glaciers available for several locations in LACL, including Kenibuna Lake, Johnson Glacier, Another River, and Lake Clark Pass (http://science.nature.nps.gov/im/units/swan/index.cfm?theme=glacial_extent). Dr Matthew Sturm from the Cold Regions Research and Engineering Lab (CRREL) in Fairbanks has also taken aerial photos of glaciers in LACL that will be repeated in the future (Alan Bennett, NPS-Anchorage, personal communication, 2005).

Biological Resources

The coastal regions of LACL are among the most biologically productive ecosystems in the Gulf of Alaska (Bennett, 1996). The coastal, intertidal, and nearshore marine areas provide particularly important habitat for residential and migratory birds, brown bears, and a variety of marine mammals (Bennett, 1996). Although the LACL coastline was spared direct contamination from the *Exxon Valdez* Oil Spill (EVOS), it did not receive as detailed coastal assessments and resource inventories as the other SWAN units did in the late 1980s and early 1990s. As a result, a major effort toward describing and assessing coastal resources, both physical and biological, was conducted in 1994-1995 (Bennett, 1996). The results of this inventory (Bennett, 1996) are referenced throughout this report.

For nearly the past decade, LACL has been engaged in the NPS I&M program, which is currently the most extensive effort to describe, catalog, and assess the condition of biological resources in LACL. Information on the SWAN I&M program can be found at http://science.nature.nps.gov/im/units/swan/index.cfm/. As part of the NPS I&M program, species lists have been compiled for vascular plants, fish, birds, and mammals within each of the SWAN units (Lenz et al., 2002). The inventory completed in 2001 listed 1358 vascular plant species (576 confirmed as present), 55 fish species (43 confirmed as present), 189 bird species (160 confirmed as present), and 45 mammal species (37 confirmed as present) as occurring in LACL (the entire unit, not only the coastal region) (Lenz et al., 2002). A bibliography of the sources of information used to develop these lists is available through the I&M program (Lenz et al., 2001). The full species lists are provided by the NPS (NPS, 2004a, b, c).

Marine biological resources

Marine mammals

Harbor seals: The National Marine Fisheries Service (NMFS) has joined efforts with ADFG, the Alaska Sealife Center and the Alaska Native Harbor Seal Commission to produce a joint research plan (National Marine Fisheries Service et al., 2003) in which harbor seals (*Phoca vitulina*) in different regions of Alaska are surveyed every five years. Harbor seals in the Gulf of Alaska were most recently surveyed by NMFS in 2006. However, stock status reports by NMFS have not been updated since December, 1998, because the geographic boundaries of Alaskan stocks are under consideration (Angliss and Outlaw, 2005).

Along the LACL coast, harbor seals utilize three haul-outs: Upper Tuxedni Bay, Upper Chinitna Bay/Clearwater Creek, and the Johnson River delta (Bennett, 1996). Abundances at haul-outs vary seasonally, with highest use during summer and no use during winter. During surveys in 1994-1995, abundance of harbor seals peaked in July at all haul-outs, when up to 280 animals were counted (Bennett, 1996).

Beluga whales: Cook Inlet beluga whales (*Balaena mysticetus*) are a distinct population segment and considered as a species by the Endangered Species Act (Hobbs et al., 2006). The population of Cook Inlet beluga whales declined by over 50% from 1994 to 1998 from an estimate of 653 to 347 whales (Hobbs et al., 2006). In 1999, the subsistence hunt was curtailed; however, the population continued to decline. The most recent estimate (2007) is 302 whales (National Marine Fisheries Service, 2007). In LACL, beluga whales had been observed seasonally off glacial river mouths in Tuxedni and Chinitna Bays and in 1994-1995 were most numerous in September (160-200 individuals) (Bennett, 1996). However, their range has contracted and they are now most common in the upper Inlet and less common near LACL. They were listed as endangered under the Endangered Species Act in October 2008 (National Marine Fisheries Service, 2008).

Steller sea lions: The U.S. western stock of Steller sea lions (*Eumetopias jubatus*) located westward of Cape Suckling, 144º W, and including the LACL region, is federally-listed as endangered due to declining populations throughout the western Gulf of Alaska and Bering Sea regions (Sease and Loughlin, 1997). Critical habitat for Steller sea lions has not been identified or designated within Cook Inlet (50 CFR 226.202 available at http://www.fakr.noaa.gov/protectedresources/stellers/habitat.htm). NPS is not aware of any Steller sea lion haul-outs in LACL (Colleen Matt, NPS-Port Alsworth, personal communication, 2005). Steller sea lions were observed to move northward along the LACL coastline passing through Tuxedni Channel but did not haul-out during Bennett's (1996) surveys.

Other marine mammals: Other marine mammal species of concern that have been sighted in or near LACL include harbor porpoise (*Phocoena phocoena*), Northern sea otters (*Enhydris lutris kenyoni*), which are a vital sign in SWAN"s nearshore monitoring program, killer whales *(Orcinus orca)*, and minke whales *(Balaenoptera acutorostrata)* (Bennett, 1996).

Marine Fishes: Anadromous and freshwater fish species are addressed in the *Freshwater Fishes* section. Many species of marine fish likely occur in marine waters off the LACL coast, although a complete survey has not been conducted. The NPSpecies list (NPS 2004a) includes 22 species of marine fishes (Table 3).

Table 3. Marine fishes on the NPSpecies list for LACL (NPS 2004a).

Family	Species Name	Common Name
Agonidae	*Asterotheca alascana*	Gray starsnout
Agonidae	*Pallasina barbata*	Tubenose poacher
Agonidae	*Agonus acipenserinus*	Sturgeon poacher
Ammodytidae	*Ammodytes hexapterus*	Pacific sand lance
Clupeidae	*Clupea pallasii pallasii*	Pacific herring
Cottidae	*Cottus aleuticus*	Coastrange sculpin
Cottidae	*Cottus cognatus*	Slimy sculpin
Cottidae	*Gymnocanthus galeatus*	Armorhead sculpin
Cottidae	*Icelinus borealis*	Northern sculpin
Cottidae	*Leptocottus armatus*	Pacific staghorn sculpin
Cyclopteridae	*Liparis gibbus*	Variegated snailfish
Gadidae	*Gadus macrocephalus*	Pacific cod
Gadidae	*Microgadus proximus*	Pacific tomcod
Gadidae	*Theragra chalcogramma*	Walleye Pollock
Hexagrammidae	*Hexagrammos octogrammus*	Masked greenling
Pleuronectidae	*Platichthys stellatus*	Starry flounder
Pleuronectidae	*Atheresthes stomias*	Arrowtooth flounder
Pleuronectidae	*Limanda aspera*	Yellowfin sole
Pleuronectidae	*Pleuronectes isolepis*	Butter sole
Stichaeidae	*Leptoclinus maculates*	Daubed shanny
Stichaeidae	*Lumpenus sagitta*	Snake prickleback
Trichodontidae	*Trichodon trichodon*	Pacific sandfish

Marine fisheries: Fishing of anadromous species is discussed in section the *Freshwater resources, Fishes* section. Documenting the marine commercial fisheries that occur within the vicinity of LACL is a large task that is well beyond the scope of this report (and the boundaries of LACL). A brief description and history can be found below in the *Sport and commercial fisheries and clamming* section.

Birds: The intertidal mud flats of Redoubt, Tuxedni, and Chinitna Bays are of great importance to many migrating and resident bird species, including shorebirds, waterfowl, raptors, and seabirds (Figure 20; Bennett, 1996). An estimated 86,000 to 122,000 shorebirds use intertidal mud flats in Tuxedni and Chinitna Bay during the spring migration (Bennett, 1996). During spring migration, the number of shorebirds rose from <1000 to 62,600 counts per day, with the majority (63%) of the shorebirds being composed of western sandpipers *(Calidris mauri*), followed by dunlins (*C. alpine*) at 28%, and least sandpipers (*C. minutilla*) at 4%. LACL had the

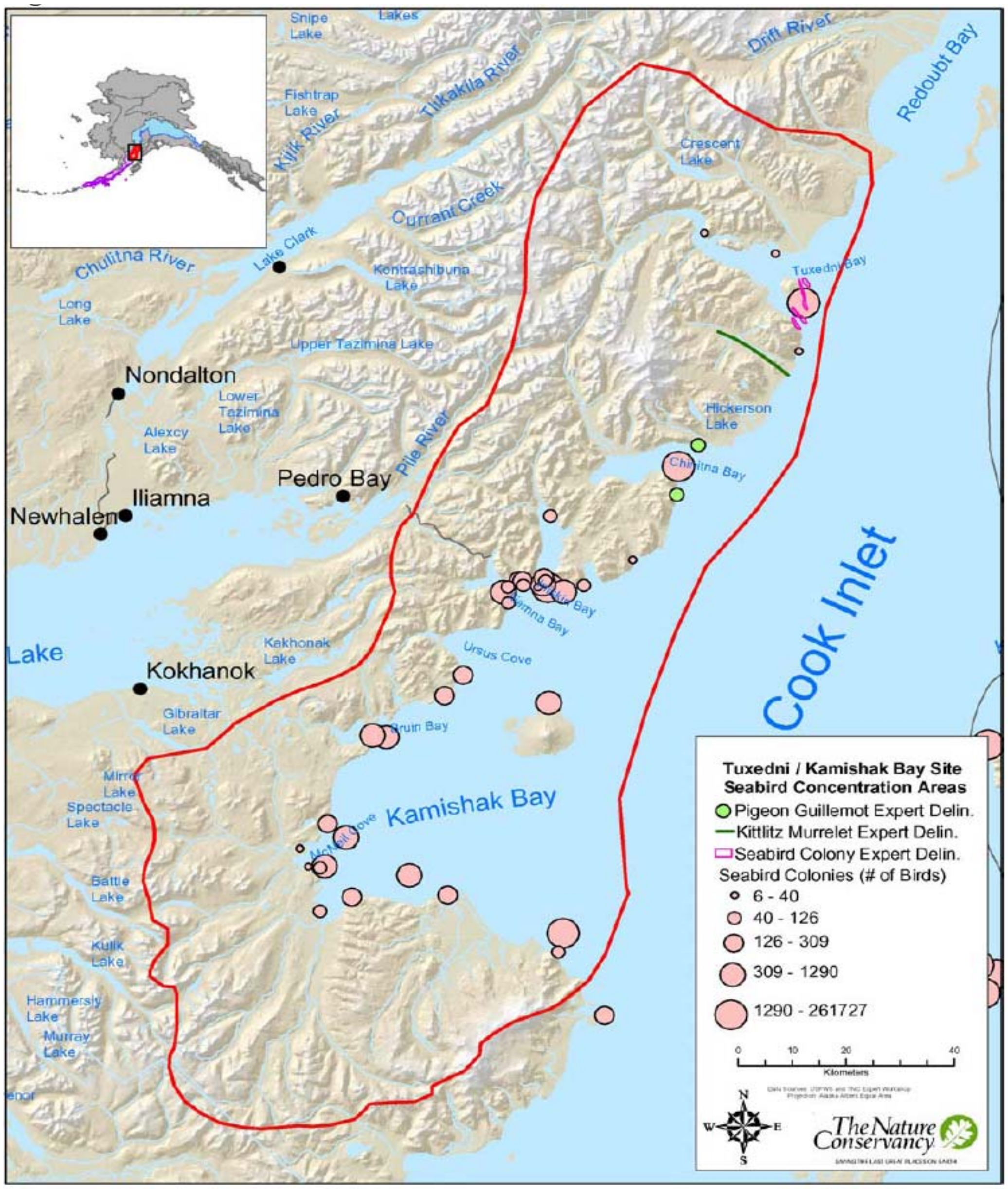


Figure 20. Seabird concentration areas in LACL are primarily in Tuxedni Bay and Chinitna Bay (Witten, 2003).

second highest density of birds in Cook Inlet (332 birds/km^2) (Arneson, 1980). As for waterfowl, the Bennett (1996) survey found that sea ducks, primarily surf and white-winged scoters, were the most abundant marine birds during all months except May. Dabbling ducks—mainly mallards *(Anas platyrhynchos*), but also Northern pintail *(A. acuta)* and others—also used the LACL coastline extensively during spring and, in some cases, fall migrations. Seven seabird colonies were identified, the largest was in Tuxedni Channel with 2,700 black-legged kittiwakes. Bald eagles' nests were mapped and surveyed for productivity, which exceeded levels necessary for stable populations. Peregrine falcon distribution was also described by Bennett (1996), who observed that most breeding sites were directly adjacent to sea bird colonies. Please refer to the Bennett (1996) report for more detailed information on bird distributions, migration timing, and abundance. The report, along with an earlier report by the same author (Bennett, 1992), emphasizes the high risk that birds using the LACL coast face from potential acute and chronic oil spills due to their strong dependence on the forage provided by the mud flats of this coastal region.

Another extensive bird survey of the Cook Inlet Region, in 1999, echoed many of the observations and conclusions made earlier by Bennett (1996) in regards to the importance of the region in supporting a diverse array of both common and rare birds (Gill and Tibbitts, 1999). Gill and Tibbitts (1999) state that "it should be of major concern to conservation planners" that shorebird use of this magnitude and importance occurs on one of the most active gas and oil exploration and development areas of the continent.

Several earlier surveys of birds along the LACL coast include, but are not limited to, a swan (trumpter and whistling) survey in the Chinitna Bay area in 1984 (Twitchell, 1984), a waterfowl survey in May 1989 (Faro et al., 1989), a shorebird survey conducted in April and May 1992 (Bennett, 1992), double-crested cormorant and raptor surveys in 1996 (Kralovec et al., 1996a, b), and a bald eagle survey in 1999 (Putera, 1999).

A bird species of concern is the Steller's eider (*Polystica stelleri*), a state species of concern and a federally listed threatened species, which is a winter visitor to coastal LACL. No specific studies for LACL on the species are currently available.

Marine intertidal resources: It is important to note that the estuarine and marine wetlands in LACL are primarily under the jurisdiction of the State of Alaska, and only those regions above the high tide zone are managed by the NPS.

Intertidal mapping: ShoreZone is a coastal mapping project that provides a comprehensive and recent source of information on the LACL nearshore environments, descriptive overviews of coastal habitat, and classifications of physical and biological attributes. This project aerially surveyed intertidal and shallow subtidal areas of Cook Inlet during extremely low tides in the summer for the purpose of identifying shoreline morphology, substrate, wave exposure, and biota of intertidal and nearshore habitats. This multi-agency funded mapping effort is accessible online through a database with interactive GIS layers, digital maps, aerial images and video of the LACL coastline. At the Gulf of Alaska Imagery website (http://mapping.fakr.noaa.gov/Website/ShoreZone/viewer.htm), one can generate maps of habitat and substrate types (Figure 21), as well as those of many other coastal ecological and geological features (e.g. wave exposure – Figure 22) by turning on various layers available through the internet browser. Additional information on the ShoreZone mapping program for coastal Alaska is available at www.coastalaska.net.

The LACL intertidal is primarily composed of salt marshes and mud/sand environments. Salt marshes dominate and compose 42% of the total coastal study area and 22% of the total length of coast (Table 4; Weeks, 2001). The remainder of the shoreline is composed of mud and sand flats/beaches, with a few cliffs north of the Johnson River and around Tuxedni Channel. Because the majority of the coast of LACL is composed of soft sedimentary environments, the coastline is dynamic and constantly changing. As a result, the SWAN I&M program is assessing

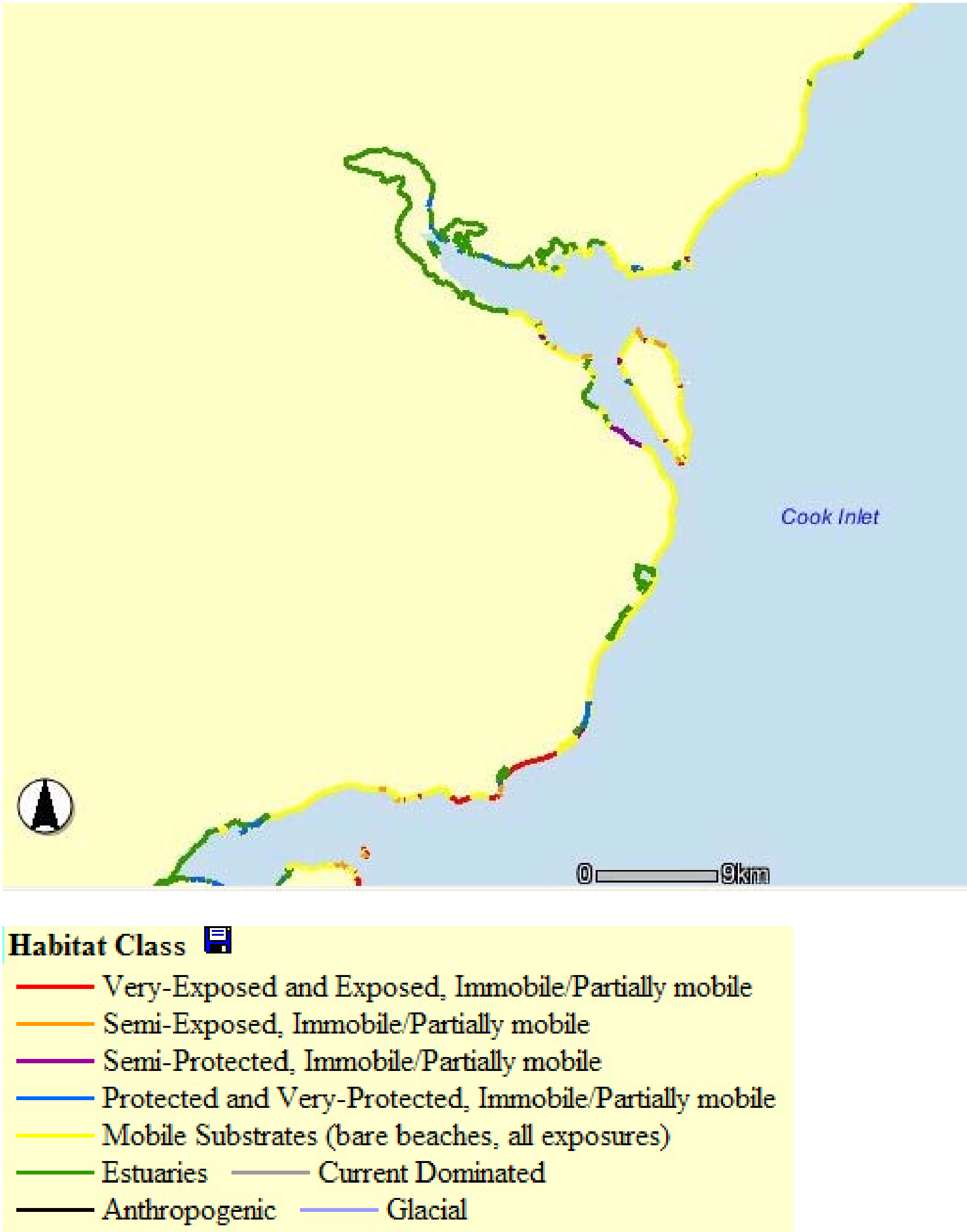


Figure 21. Habitat along the LACL is predominantly bare beaches and estuaries. Source: ShoreZone Interactive Mapping website.

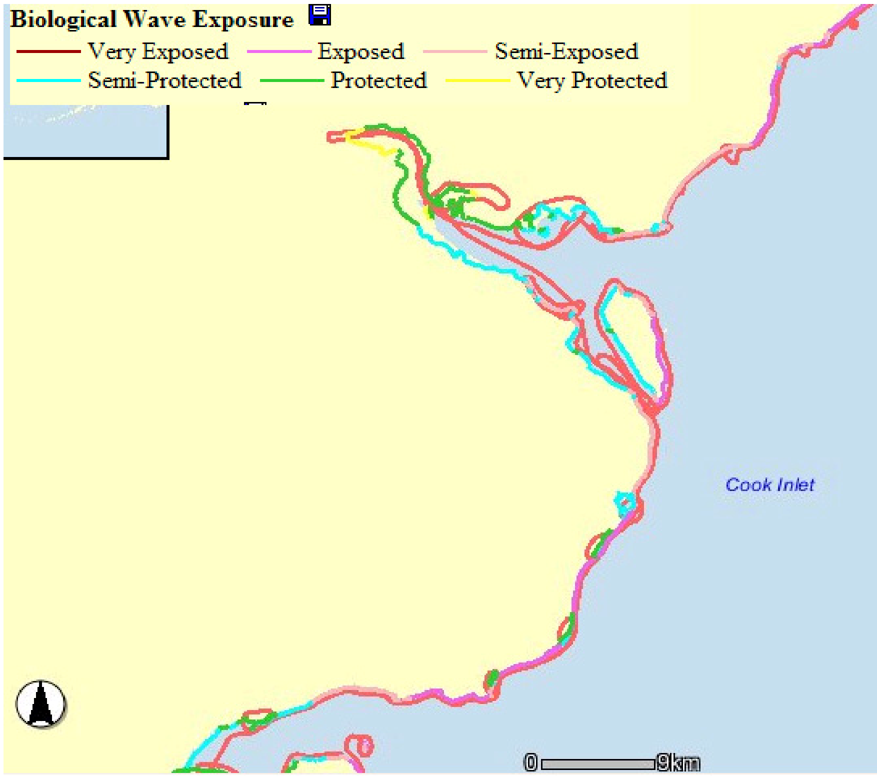


Figure 22. Wave exposure levels along the LACL coast. Source: ShoreZone Interactive Mapping website http://mapping.fakr.noaa.gov/Website/ShoreZone/viewer.htm

Table 4. Approximate length and area of shoreline types along the coast of LACL (Bennett, 1996; modified by Weeks, 2001).

Segment Type	Length (ft) [mi]	% Total Length	Area (acre^2)	% Total Area
salt marsh	101,957 [19.3]	22	1314	42
wide mud flat	98,637 [18.7]	22	736	24
wide sand flat	79,321 [15.0]	18	387	12
wide sand beach	68,087 [12.9]	15	97	3
wide sand and gravel flat	31,140 [5.9]	7	307	10
Cliffs w/ narrow sand & gravel	27,058 [5.1]	6	16	1
Narrow sand & gravel flat	12,117 [2.3]	3	21	1
Gravel alluvial fan	11,999 [2.3]	3	46	1
Cliffs w/ narrow gravel beach	9,193 [1.7]	2	7	<1
Cliffs w/ narrow sand beach	4,462 [0.8]	1	20	1
Ramp w/ narrow sand beach	6,585 [1.2]	1	3	<1
river channel			159	5
Total	**450,556 [85.3]**		**3113**	

morphological shoreline changes along the LACL coast (Cusick and Bennett, 2005). Seven beach profiles were surveyed in 1992 and resurveyed in 2004 to determine rates of erosion and accretion. Five profiles were determined to be eroding at rates of 0.18 to 0.5 m/yr, and two were determined to be accreting at rates of 0.55 to 3.13 m/yr. Another intensive effort is collecting and analyzing changes in high resolution imagery over time and has identified three sets of imagery from 1993, 1978, and 1954-1957 to compare with recent IKONOS satellite imagery from the 2000s (Manley et al., 2008). As of 2008, this analysis is ongoing and will produce vector and raster geospatial datasets (GIS layers such as the coastline shapefiles and derived layers) with metadata. The Manley et al. (2008) draft report included a pilot study of orthorectified imagery for LACL. Once completed, this study will provide important information on coastline changes in LACL.

An extensive survey of the LACL coastline by Bennett (1996) characterized the distribution and abundance of the salt marshes and wetland environments which provide critical habitat for bears, birds, and many other vertebrates and invertebrates. Bennett (1996) delineated and mapped 32 km^2 of salt marshes and, during these surveys, classified physiographic location, site moisture, vegetation type, growth form and landscape features. In addition, Tande and Bennett (1996) developed vegetation cover map classifications for coastal LACL. This effort included identifying vegetation types from aerial photographs, doing field studies to ground-truth the extent and identification of vegetation, and describing the species composition and physical site characteristics of the vegetation types in coastal LACL. Salt marshes along LACL are most abundant in Tuxedni and Chinitna Bays, Bear Creek, Silver Salmon Creek, Shelter Creek, and Clearwater Creek (Figure 23). These wetland areas are important because they serve as an interface between terrestrial habitats and aquatic environments such as streams, lakes, and near-shore marine zones. Within coastal LACL, wetlands have been mapped at 1:63,000 scale by the U.S. Fish and Wildlife Service National Wetlands Inventory mapping program (http://wetlandsfws.er.usgs.gov/; Table 5). These wetland ecosystems include estuarine, palustrine, lacustrine, and riverine wetlands, the majority of which are located along the coast and in valley bottoms.

Salt marsh vegetation: The salt marsh vegetation is dominated by sedges with some variation in species composition among different salt marshes (Table 6). A vascular plant species list generated from a mapping and classification effort of coastal LACL is provided in Appendix B in Tande and Bennett (1996). This salt marsh vegetation provides important forage and habitat for brown bears, waterfowl, and shorebirds (Bennett, 1996). Salt marshes were identified as the source of organic material that is responsible for the high productivity of benthic invertebrates in adjacent mud flats and tidal sloughs and, by association, of all other coastal habitats (Bennett, 1996; Warwick and Price, 1975). Salt marsh vegetation species, which cover a significant stretch of LACL coast (Figure 24), are sensitive to changes in marsh hydrology, whether natural (e.g. glacial melt, sea-level rise, uplift) or anthropogenic (coastal logging and road construction, and other process that may disrupt depositional processes), and climate change (Bennett, 1996). Concerns about the effects of salt marsh loss (likely due to uplift and isostatic rebound) is addressed in the *Uplift and Erosion* section.

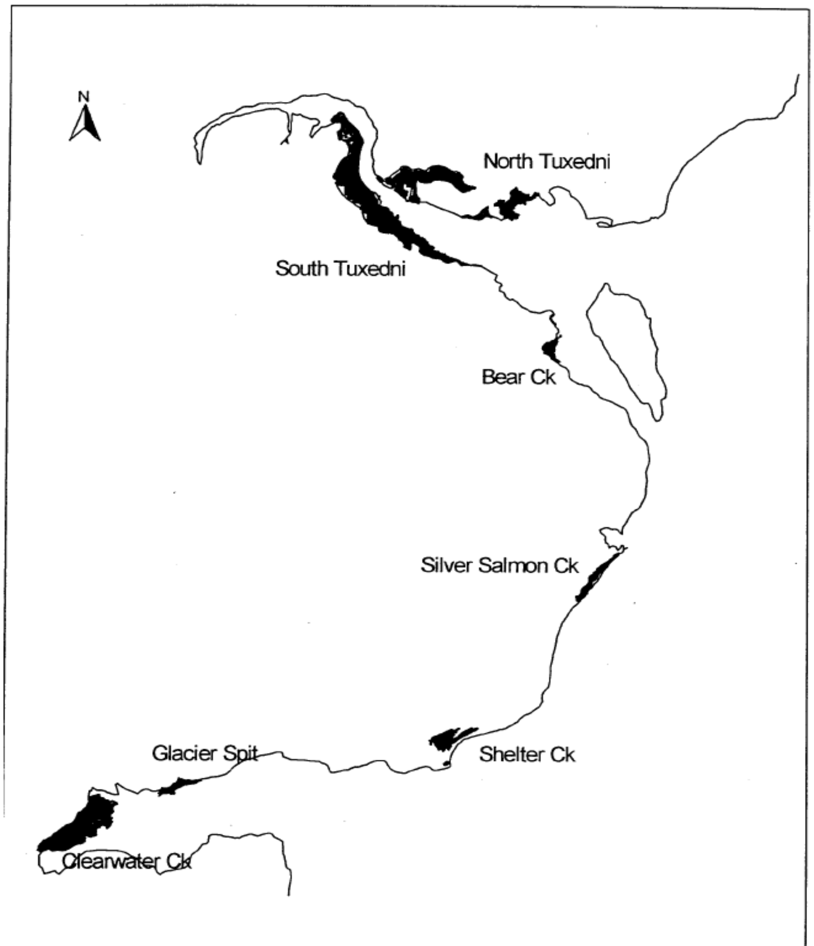


Figure 23. Major salt marshes along the LACL shoreline (Bennett, 1996).

Table 5. Acreages of different wetland types in coastal LACL mapped by the U.S. Fish and Wildlife Service National Wetlands Inventory mapping program.

Wetland System	Hectares	% of Coastal Study Area (310,000 hectares)
Estuarine	5613	1.80%
Lacustrine	3258	1.10%
Palustrine	9667	3.10%
Riverine	3985	1.30%

Table 6. Characteristics of salt marsh vegetation in coastal LACL (Witten, 2003, compiled with information from Bennett, 1996).

Salt Marshes	**Characteristics**
Tuxedni Bay Marshes: • Horsefly Bay • Squarehead Cove • South Tuxedni Bay • Bear Creek	Monotypic stands of *Carex ramenskii* comprise 41 % of the dominant sedge communities; the remainder is complex of *C. ramenskii*, forbs, and grasses (*Hordeum brachyantherum-Calamagrostis deschampsioides-Poa eminens/Argentia egedii*). Further inland are expansive sedge meadows on silty soils bisected by shallow, narrow drainages. The inland meadows are only infrequently flooded by tides. *Triglochin maritimum-Puccinellia phrayganodes/Plantago* maritime graminoid community is an important mid-marsh cover type in all the Tuxedni Bay marshes except Bear Creek, and is dominant at Squarehead Cove. A *Triglochin palustre*-dominant community occurs only in the South Tuxedni marsh east of Open Creek. This cover type is grazed heavily by brown bears and white-fronted geese, and their distribution conforms to the occurrence of the type.
Silver Salmon Creek	*Triglochin maritimum-Puccinellia phrayganodes/Plantago* maritime graminoid community is dominant on the south half of this marsh. These marshes contain numerous lakes and ponds containing various floating and rooted shallow-water aquatic species, including *Sparganium* spp., *Potamogeton* spp., *Utricularia* spp., and *Myriophyllum* spp..
Shelter Creek	*Triglochin maritimum-Puccinellia phrayganodes/Plantago* maritime graminoid community is common.
Glacier Creek	*Triglochin maritimum-Puccinellia phrayganodes/Plantago* maritime graminoid community is common. These marshes contain numerous lakes and ponds containing various floating and rooted shallow-water aquatic species, including *Sparganium* spp., *Potamogeton* spp., *Utricularia* spp., and *Myriophyllum* spp..
Clearwater Creek	Vast meadows of almost pure *Carex lyngbyei* occur over a flat, shallow gradient between grass/forb levees, extending inland from grass/forb communities on mudflats and pannes. Pure communities of *C. lyngbyei* also occur on ice-heaved margins of large brackish lakes at Clearwater Creek. The western two-thirds of these marshes are predominantly pure *C. ramenskii*. These marshes contain numerous lakes and ponds containing various floating and rooted shallow-water aquatic species, including *Sparganium* spp., *Potamogeton* spp., *Utricularia* spp., and *Myriophyllum* spp..

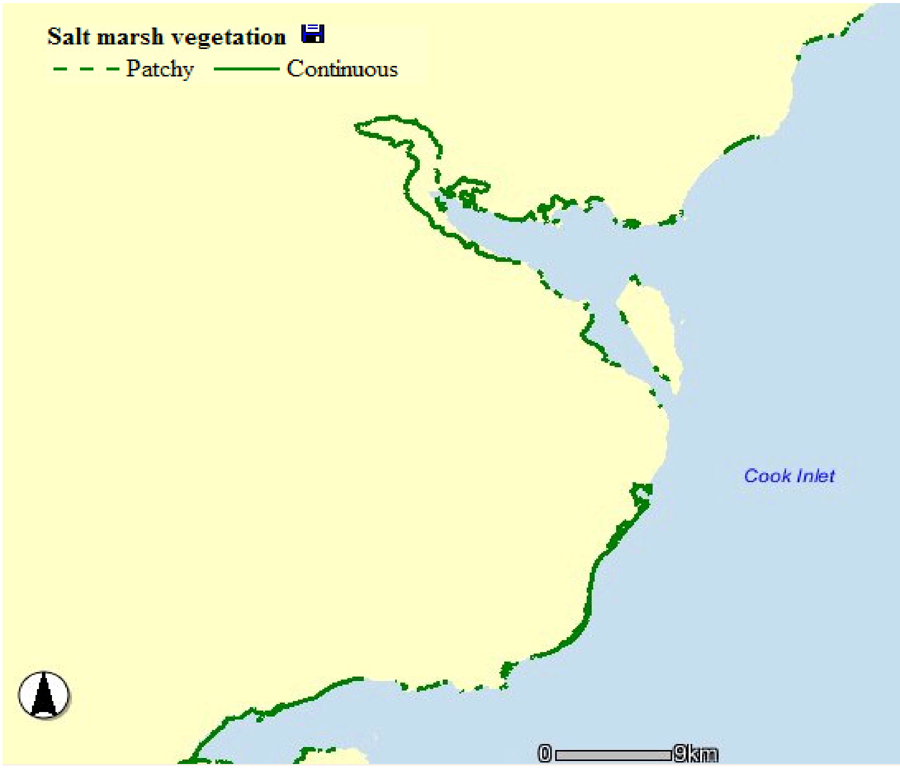


Figure 24. Salt marsh vegetation along the LACL coast. Source: ShoreZone Interactive Mapping website http://mapping.fakr.noaa.gov/Website/ShoreZone/viewer.htm

Marine invertebrates: Intertidal marine invertebrates in LACL are an important food source for migratory waterfowl and sea birds in the Gulf of Alaska. In Chinitna and Tuxedni Bays, the dominant species are *Macoma balthica*, the polychaete *Nephtys,* and the echiuran *Echiurus* (Bennett, 1996). Lees and Driskell (2006) conducted a reconnaissance survey of marine/estuarine bivalves in soft sediments in 2004 in LACL (Figure 25). Bivalves were surveyed using 0.25-m^2 (2.7 ft^2) and macrobivalve excavations and 0.0625-m^2 (0.67 ft^2) microinfaunal core samples. The soft sediment habitats in LACL were composed of sand (56%), silty sand (11%), sandy silt (22%), and clayey silt (11%) (Lees and Driskell, 2006).

A variety of bivalve species were observed (Table 7) and examined to determine which species might serve as sentinel species in a network-wide monitoring program. Habitats and biological features are markedly less diverse at LACL, presumably because the beaches in LACL appear to be exposed to rigorous physical processes (Lees and Driskell, 2006). Bivalve diversity was lower at LACL than at KEFJ or KATM, and only four of the major bivalve species were observed (Table 8). These four species could serve as potential sentinel species, and include Pacific razor clams (*Silqua patula*), softshell clams (*Mya arenaria*), Arctic surf clams (*Mactromeris polynyma*), and Baltic macomas (*Macoma balthica*) (Table 7; Lees and Driskell, 2006).

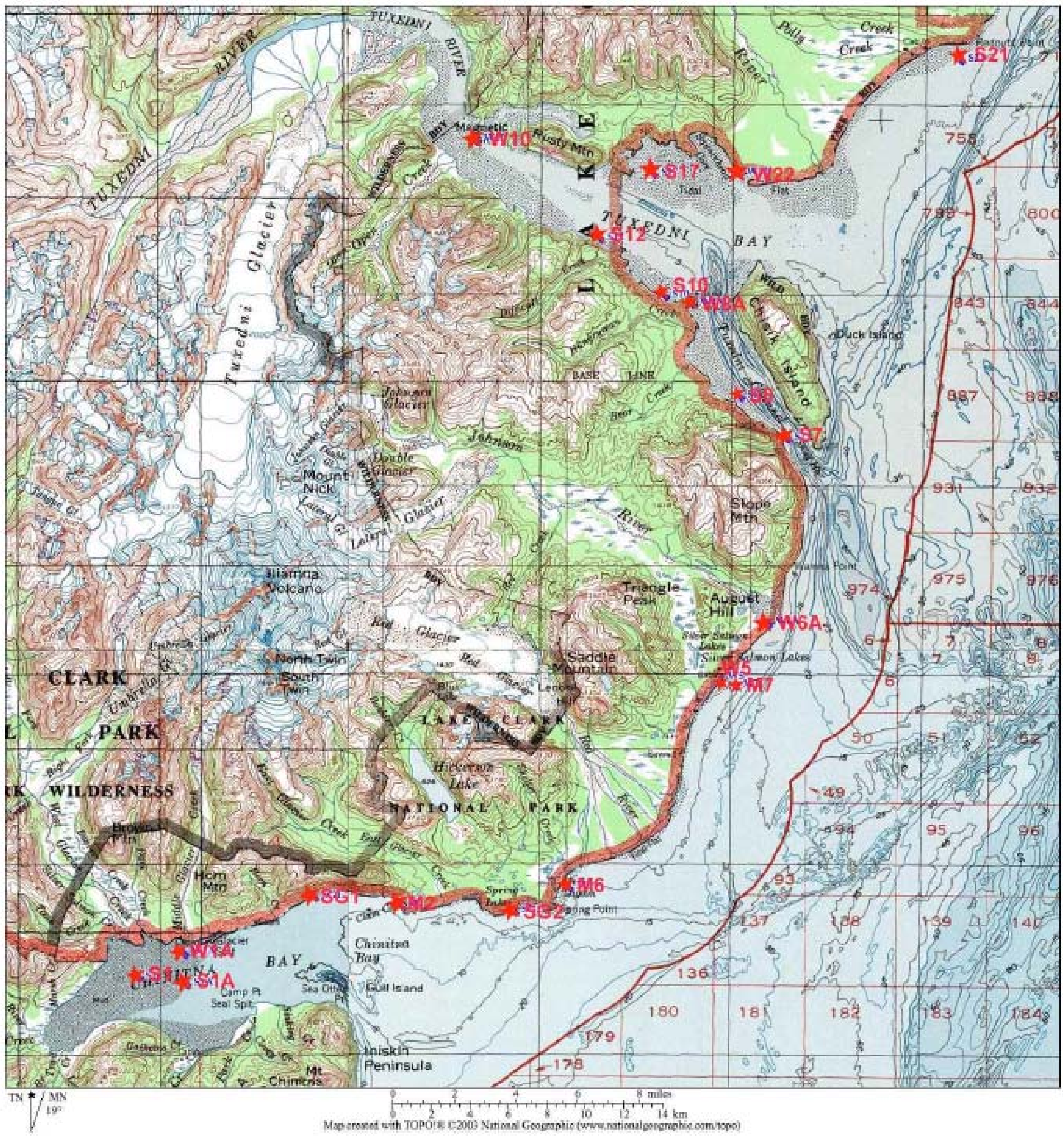


Figure 25. Sites visited by the soft-sediment intertidal reconnaissance survey in LACL in 2005 (Figure 4 in Lees and Driskell, 2006).

Table 7. Common and scientific names of bivalves observed in soft-sediment intertidal reconnaissance surveys in KATM, KEFJ and LACL (Table 1 in Lees and Driskell, 2006).

Common Name	Scientific Name	Common Name	Scientific Name
Northern horsemussel	*Modiolus modiolus*	Foolish mussel	*Mytilus trossulus*
Silky axinopsid**	*Axinopsida serricata*	Rough diplodon	*Diplodonta impolita*
Suborbicular kellyclam*	*Kellia suborbicularis*	Compressed montacutid*	*Neaeromya ?compressa*
Robust mysella**	*Rochefortia tumida*	Basket cockle	*Clinocardium nuttallii*
Broad smoothcockle*	*Serripes ?laperousii*	Kennerley venus*	*Humilaria kennerleyi*
Butter clam	*Saxidomus giganteus*	Littleneck clam	*Protothaca staminea*
Lord dwarf-venus**	*Nutricola ?lordi*	Minute turton**	*Turtonia minuta*
Alaska great-tellin*	*Tellina lutea*	Salmon tellin	*Tellilna nuculoides*
Baltic macoma	*Macoma balthica*	Thick macoma*	*Macoma ?crassula*
Expanded macoma	*Macoma expansa*	Oval macoma	*Macoma golikovi*
?Pointed macoma	*Macoma ?inquinata*	Bent-nose macoma	*Macoma nasuta*
Alaska razor clam*	*Siliqua alta*	Pacific razor clam	*Siliqua patula*
Arctic surf clam	*Mactromeris polynyma*	Gaper clam*	*Tresus* sp.
Softshell clam	*Mya arenaria*	False softshell clam	*Mya pseudoarenaria*
Truncate softshell	*Mya truncata*	Arctic hiatella	*Hiatella arctica*

* Species observed only in excavation samples or extralimitally.
** Small species observed only in core samples.

Table 8. Major bivalve species, as a function of substrate, observed at soft-sediment intertidal reconnaissance sites in KATM, KEFJ and LACL (Table 11 in Lees and Driskell, 2006).

Sediment Type	Grav-el	Mud			Sand			Mixed-soft		
Species / Park	Foolish Mussel	Baltic Macoma	Softshell Clam	False Softshell Clam	Arctic Surf Clam	Alaska Razor Clam	Pacific Razor Clam	Oval Macoma	Butter Clam	Littleneck Clam
KATM – No. of Sites	7	14	10	4	8	6	1	8	6	1
% of Sites	26	52	37	15	30	14	4	30	22	4
KEFJ– No. of Sites	24	21	2	4	0	0	0	11	10	13
% of Sites	71	62	6	12	0	0	0	32	30	38
LACL– No. of Sites	0	5	4	0	1	0	4	0	0	0
% of Sites	0	56	44	0	11	0	44	0	0	0
Feeding Mode	SF*	FSDF	SF	SF	SF	SF	SF	FSDF	SF	SF

* SF – Suspension feeder; FSDF – Facultative suspension/deposit feeder

Freshwater biological resources

Freshwater fishes: Information on presence and types of anadromous fishes in the coastal area is contained in *The Catalog of Waters Important for Spawning, Rearing, or Migration of Anadromous Fishes* (Johnson and Weiss, 2006), which is regularly updated by the Alaska Department of Fish and Game and provides information on the presence and types of anadromous fishes in streams in the whole state. Fish species that occur in the main coastal LACL streams, according to this catalog, are summarized in Table 9.

Information on species presence in numerous other streams in LACL is available through this catalog. Many other streams are unnamed, but are identified by way of a cataloged numbering system and by geographic location (latitude and longitude, USGS quad map name). Figures 26 through 30 map the distribution of spawning and rearing habitats and presence for the five species of salmon that are present in coastal LACL (Witten, 2003).

Another source of information on fishes in LACL comes from the SWAN I&M program, which used data collected by Russell (1980) in a larger report describing baseline inventories of

Table 9. Anadromous fish species present in coastal LACL streams according to Johnson and Weiss (2006).

Stream	Chinook salmon	Sockeye salmon	Coho salmon	Pink salmon	Chum Salmon	Arctic char	Dolly Varden
Little Polly Creek			X		X		X
Crescent River	X	X	X	X	X		X
Tuxedni River		X	X				X
Open Creek					X		
Difficult Creek					X		
Hungryman Creek					X		
Bear Creek			X		X		
Johnson River	X			X	X		X
Silver Salmon Lakes			X		X		X
Red Creek			X				
Silver Salmon Creek			X		X	X	
East Glacier Creek			X				
West Glacier Creek			X			X	

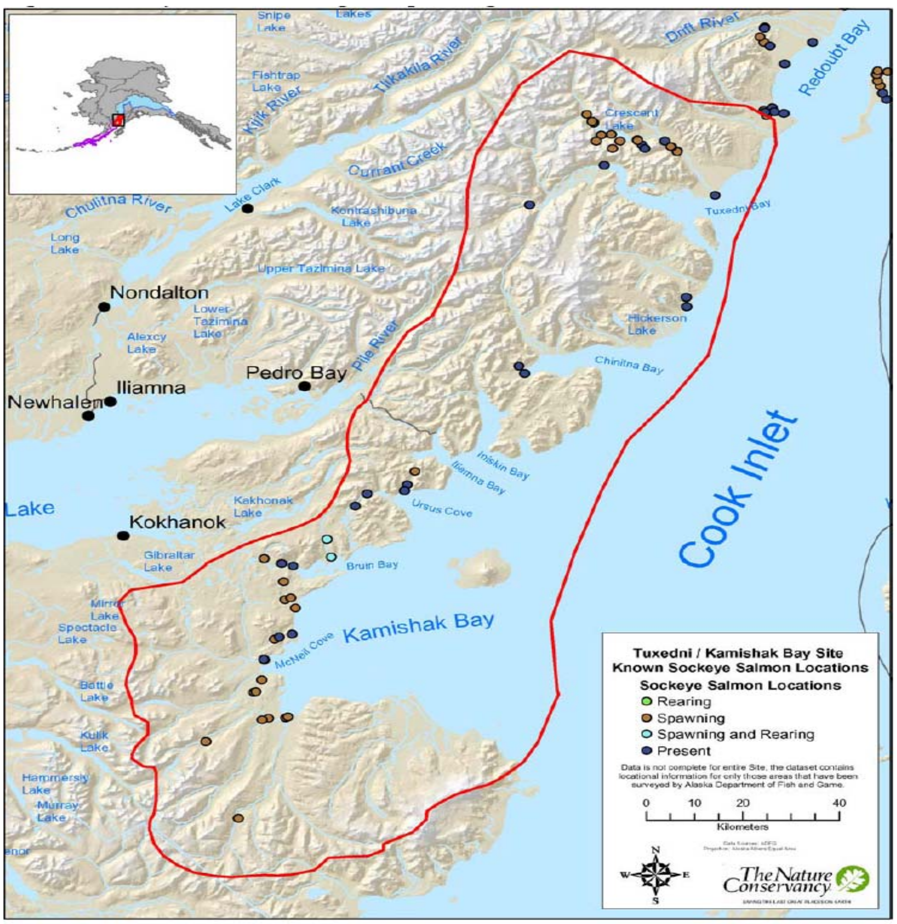


Figure 26. Sockeye salmon rearing and spawning habitats and presence (Witten, 2003).

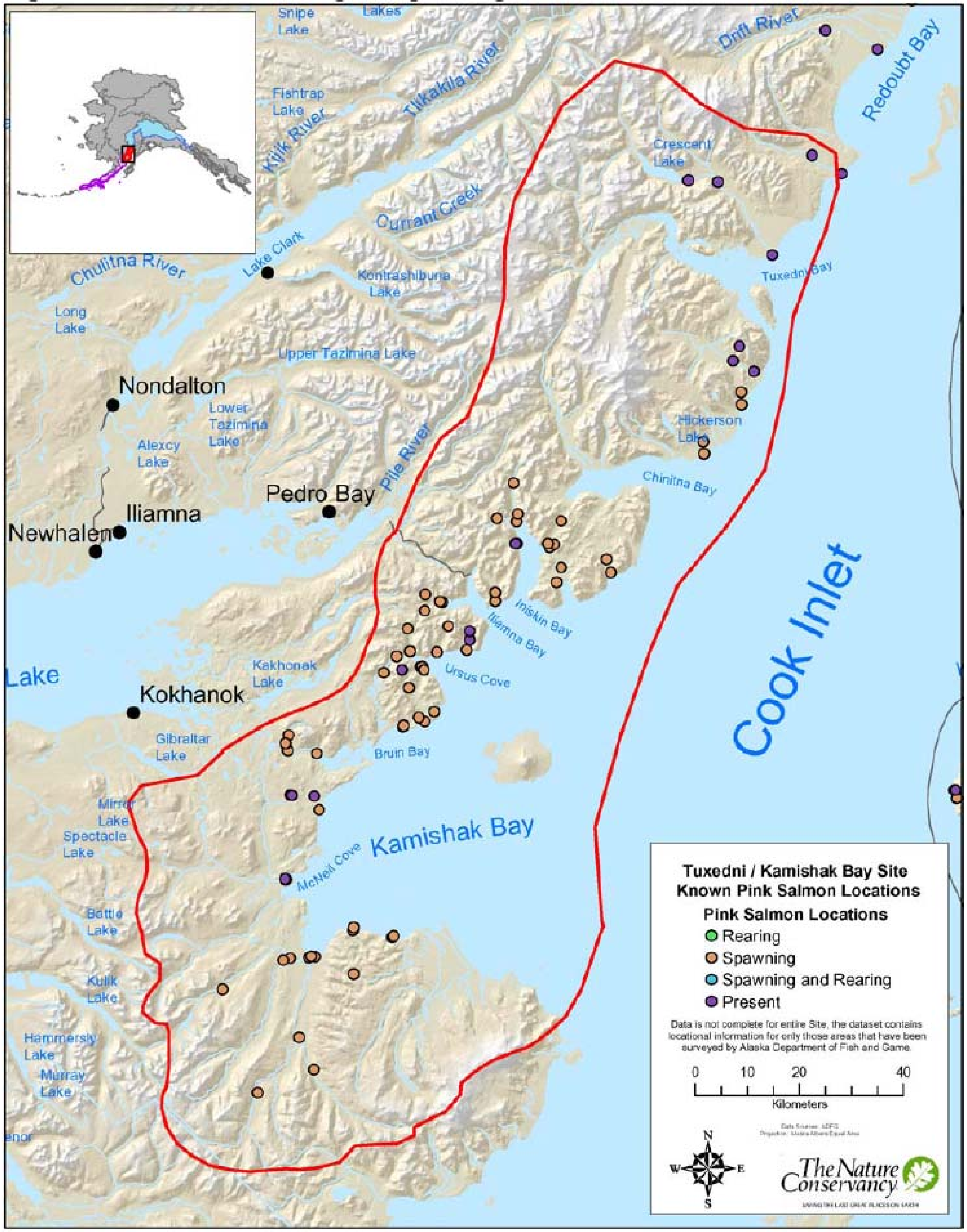


Figure 27. Pink salmon rearing and spawning habitats and presence (Witten, 2003).

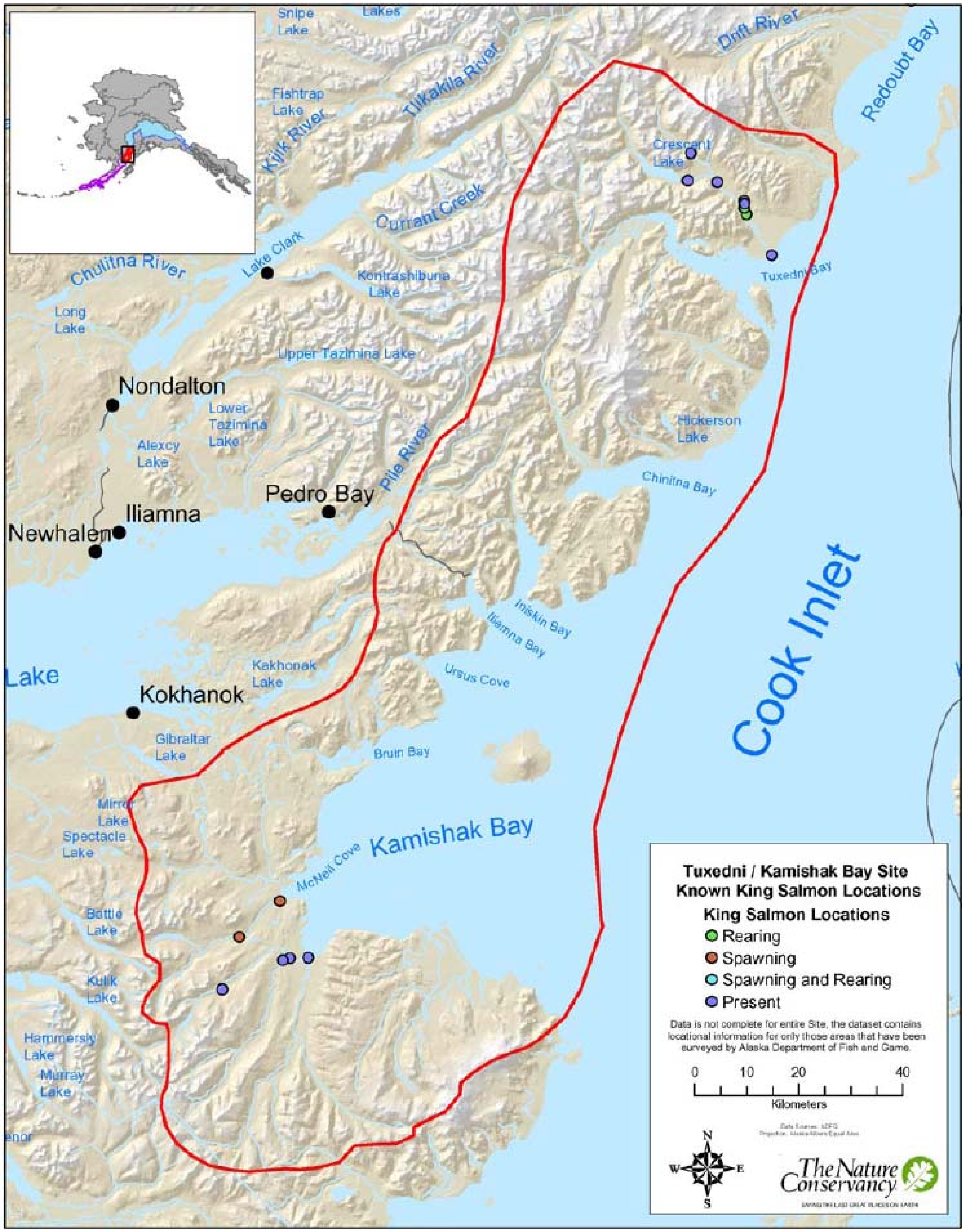


Figure 28. King salmon rearing and spawning habitats and presence (Witten, 2003).

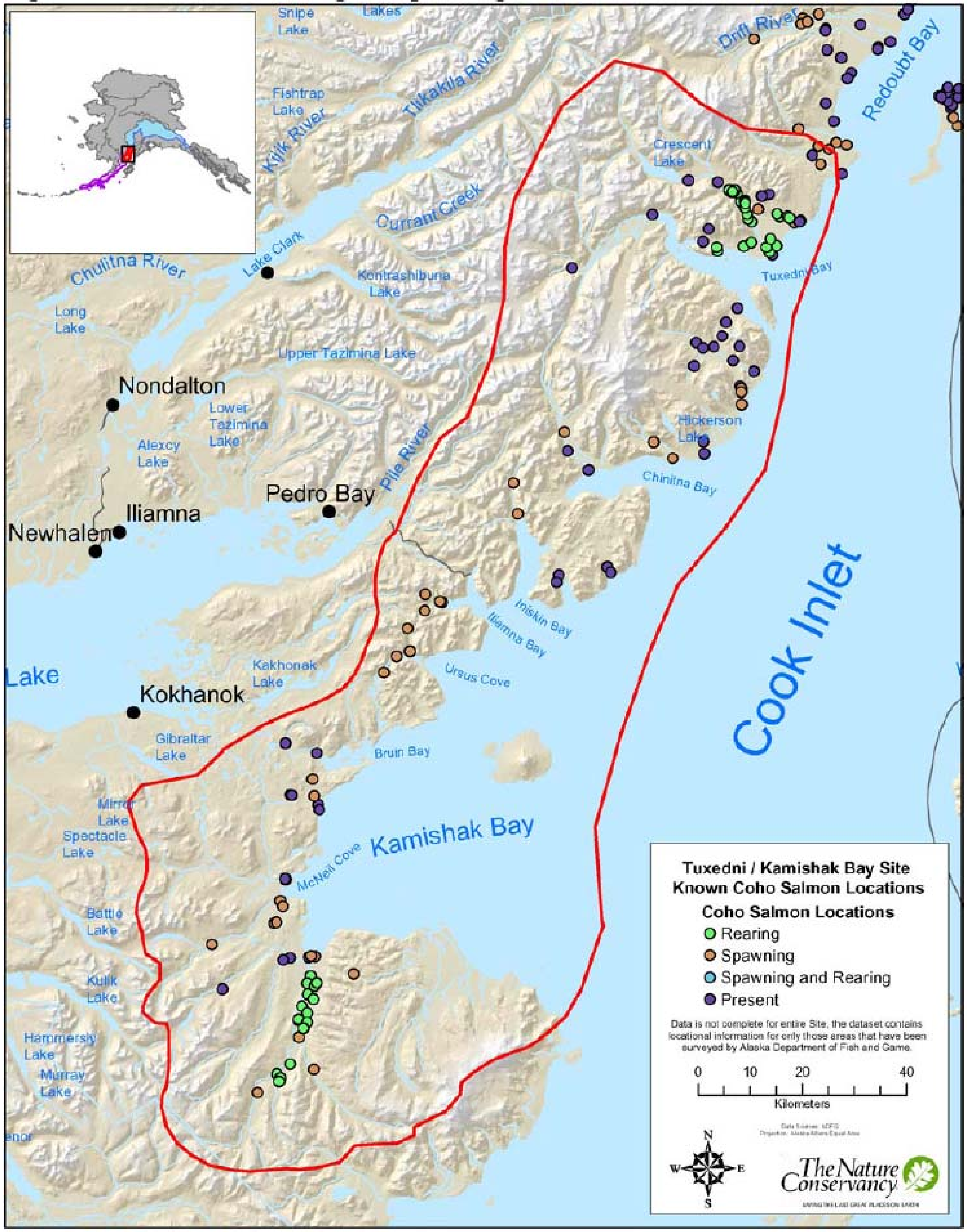


Figure 29. Coho Salmon rearing and spawning habitats and presence (Witten, 2003).

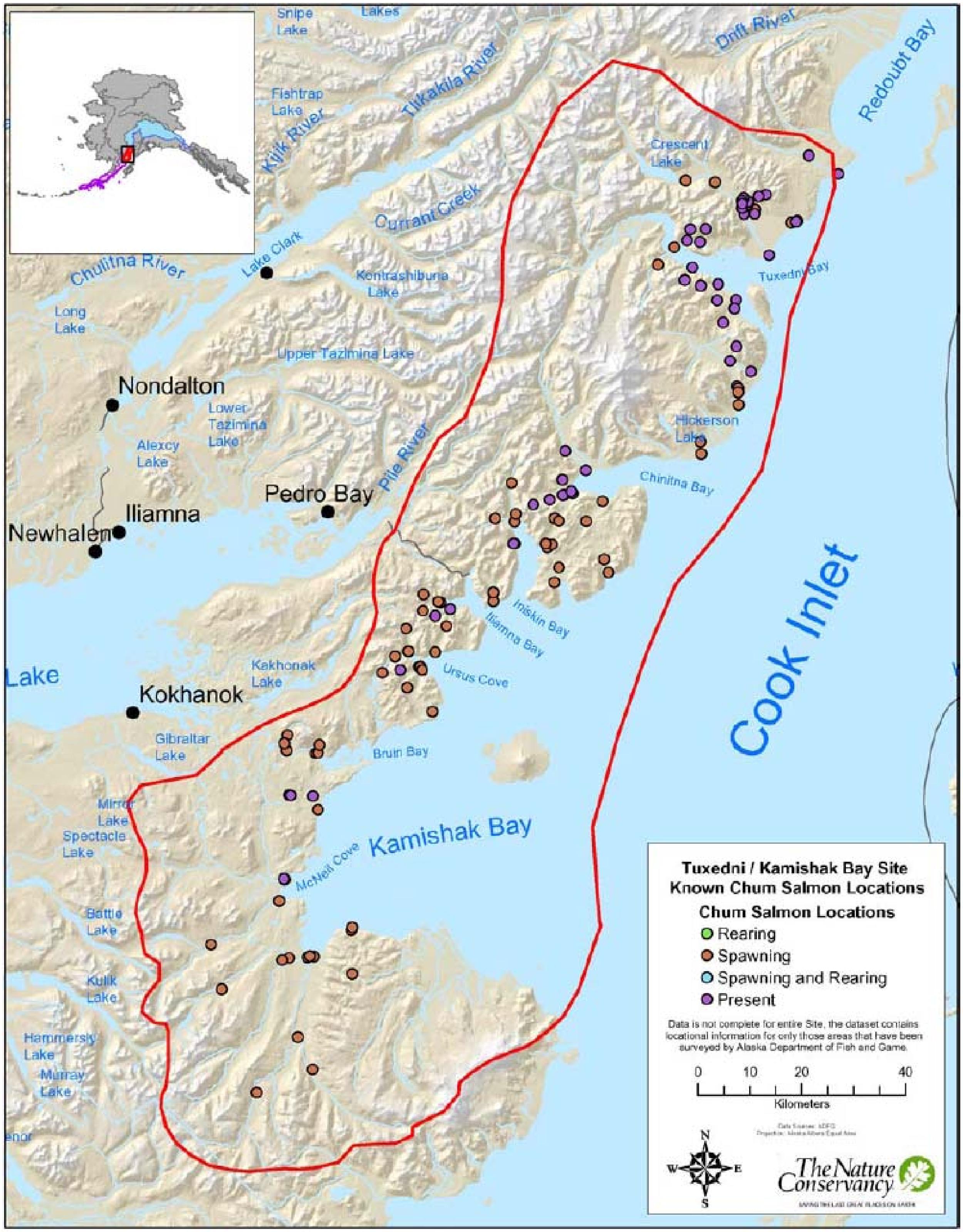


Figure 30. Chum salmon rearing and spawning habitats and presence (Witten, 2003).

freshwater fish in all the SWAN units (without specific results for the coastal study areas) (Jones et al., 2005). This survey found that 25 freshwater fish species occurred within LACL (entire unit) and that another 24 species were considered tidepool or estuarine (Jones et al., 2005). As an added note, the SWAN-wide inventory also stresses that the paucity of water quality and streamflow data make ecological assessments of fish habitats and distribution difficult or impossible (Jones et al., 2005).

In terms of fish presence in coastal LACL lakes, the main documentation is that by Russell (1980) and further described and mapped by Witten (2003) (Figures 26-30). The Russell (1980) report documents the following fishes in LACL lakes that drain into Cook Inlet:

- Lake Chakachamna: sockeye salmon (adults), lake trout, round whitefish, Dolly Varden, and slimy sculpin.
- Crescent Lake: lake trout, Dolly Varden, chinook salmon, sockeye salmon, threespine stickleback, and coastrange sculpin.
- Hickerson Lake: Dolly Varden.

A more detailed study of Crescent Lake sockeye salmon is provided by Edmundson and Mazumder (2001). Their work points to the combined effects of limited food resources, cold rearing temperatures—both of which may be related to increased glacial melt from upstream sources—and high fry densities as possible factors leading to declines in salmon productivity in the lake (Edmundson and Edmundson, 2002).

Spawning salmon are an important resource for both terrestrial and aquatic ecosystems within LACL. When salmon return to their natal streams to spawn, they transport marine nutrients and energy across ecosystem boundaries and their carcasses release large quantities of “marine-derived nutrients” to freshwater and terrestrial ecosystems (Cederholm et al., 1999; Johnston et al., 2004; Willson et al., 1998). Salmon directly affect the ecology of consumers at many trophic levels, and thus their annual return has widespread effects on the food webs of coastal watersheds (Cederholm et al., 1999; Gende et al., 2002). The organic and inorganic nutrients (carbon, nitrogen, and phosphorus) released by spawning salmon are important to the overall health of these watersheds (Bryant and Everest, 1998) and can also strongly affect productivity in coastal streams (Chaloner and Wipfli, 2002; Wipfli et al., 1998). In particular, the seasonal pulse of salmon carcasses can dramatically elevate streamwater levels of limiting nutrients such as nitrogen and phosphorus during spawning (Mitchell and Lamberti, 2005) and thereby increase primary and secondary productivity in receiving streams. Outside of the spawning season, it is likely that alder are a primary source of inorganic N to streams in LACL (Compton et al., 2003). In addition, carcasses that end up in the riparian zone as a result of changes in stream discharge or bear activity provide a substantial input of nutrients such as nitrogen and phosphorus to riparian soils (Gende et al., 2002). These nutrients can be assimilated rapidly by microbial communities and vegetation in the riparian environment (Bilby et al., 1996) and have been hypothesized to increase the growth rate of trees in the riparian forest (Helfield and Naiman, 2002).

Amphibians: No formal surveys of amphibians have been conducted in LACL, and there are no published records of amphibian occurrences specifically within the coastal watershed study area. However, a single species, the wood frog (*Rana sylvatica*), is known to be a resident of the Park and Preserve (Anderson, 2004). Park records include three verified observations of wood frogs in

LACL along the northwestern shore of Lake Clark and in the Two Lakes area (Figure 31). This freeze tolerant species, which is observed throughout the Alaska Peninsula and occurs as far north as Brooks Range, inhabits a wide variety of forest, muskeg, and tundra habitats, sometimes far from water (Hodge, 1976). Although wood frog populations are not known to be declining like a majority of other amphibian species globally, the occurrence of chytrid fungus, the putative cause of these declines, has not been investigated in LACL.

There is also a remote possibility that the boreal toad (*Bufo boreas*), which has probably declined throughout most of their historic range in Alaska (Pyare, unpublished data), occurs in LACL. The northernmost observations of boreal toads occur approximately 250km east in the Prince William Sound area; however, the northern extent of this species' range has not been established.

Aquatic invertebrates, chlorophyll, phytoplankton, and zooplankton: Four studies, two each from the Johnson and Crescent River watersheds, provide some information on aquatic invertebrates, chlorophyll, phytoplankton, and/or zooplankton in the LACL coastal region.

Johnson River watershed: In 1995-1997, Milner (1998) conducted a water quality and macroinvertebrate survey in the Johnson River watershed in order to provide a baseline to which changes from possible future mining could be compared. The study, based on collections from 11 mainstem and tributary sites, concluded that bioassessment metrics would not be informative for purposes of macroinvertebrate monitoring in the mainstem due to the overwhelming influence of glacial runoff that greatly reduces taxa diversity. Only one species, *Plumiperla,* found in several lower watershed sites, showed potential as an indicator species in the mainstem. However, several tributaries proved to be useful for biomonitoring: Kona Creek, the "waterfall" tributary, Rocky Creek, Bear Creek, and Ore Body Creek (maps not provided in the report, and tributary names are likely unofficial, but qualitative descriptions of the sties are given) (Milner, 1998). Densities were sufficiently large enough for bioassessment matrix calculations only in Rock Creek. Bioassessment matrices calculated consisted of Ephemeroptera + Plecoptera + Trichoptera (EPT) Individuals/Total Individuals (EPT/TOT), Family Biotic Index (FBI) and Number of EPT Genera (EPTGEN), and Percent Dominant Taxa (DOMTAX) (please see Milner (1998) for explanation of these matrices). Milner (1998) found that all sites supported EPT taxa with typical indicators of clean water. However, there were enough annual variability and unpredicted bioassessment results in the dynamic watershed to warrant more detailed site assessments in order to track potential impairments from possible future road building or mining pollution.

The second study on the Johnson River provides information from only one site (Frenzel and Dorava, 1999). The study site was within close proximity of the Lateral Glacier and the USGS gaging station, approximately 32 km (20 miles) upstream of the mouth. Thirteen taxa of benthic macroinvertebrates were collected from Richest Targeted Habitat (RTH) samples in the Johnson River (Frenzel and Dorava, 1999). Ninety-five percent of individuals in the RTH sample were composed of Diptera; specifically, Diamesa comprised 49% of the sample. The dominance of these taxa is typical for glacier-dominated streams. A second type of sample, the Qualitative Multi-Habitat (QMH) sample, revealed an additional six taxa, although in small numbers, such as Ephemeroptera and Trichoptera (Frenzel and Dorava, 1999).

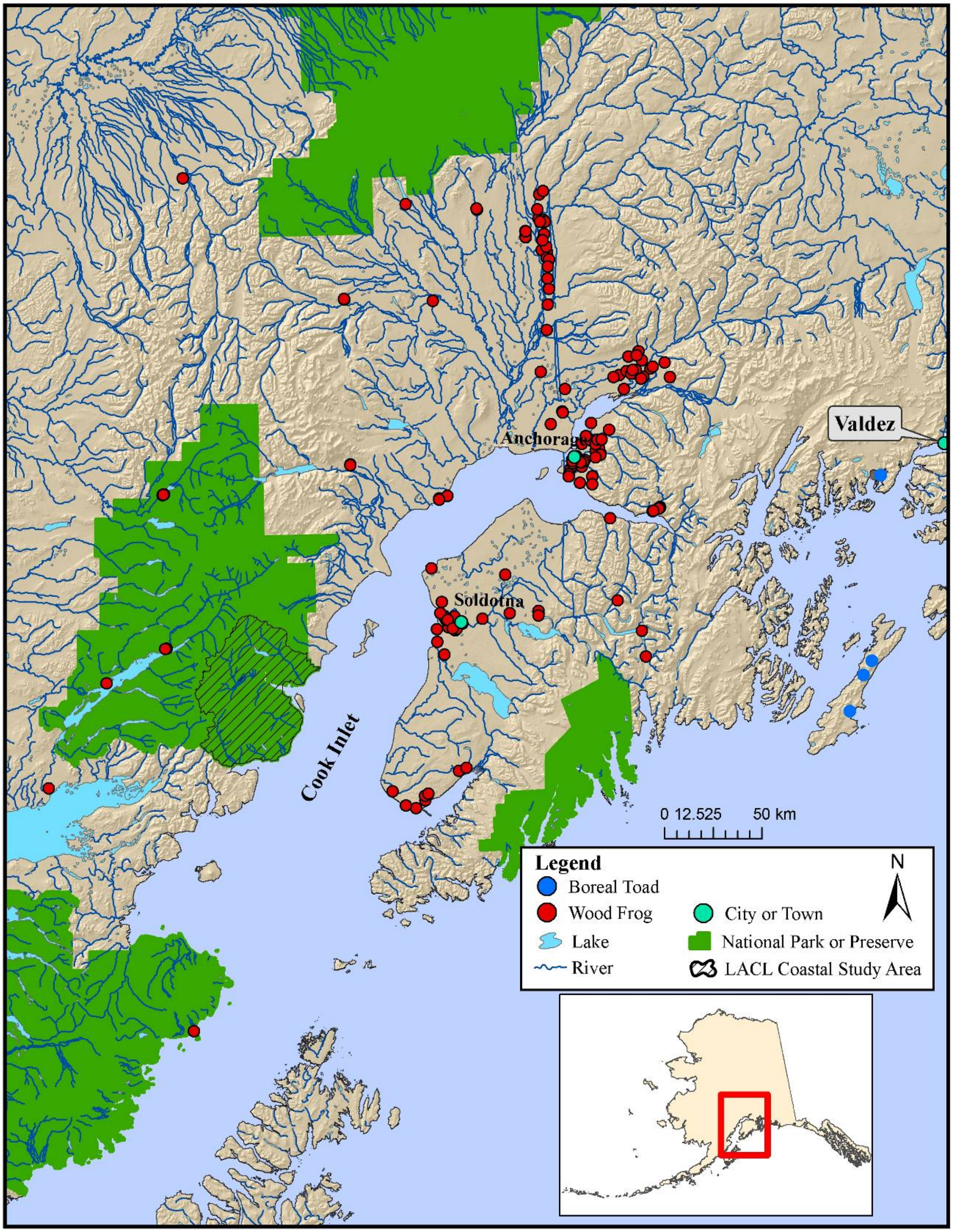


Figure 31. Location of amphibian reports in Southcentral Alaska. (Source: Alaska Natural Heritage Program).

Crescent River watershed: Edmundson and Edmundson (2002) evaluated biomass densities over time in an overall effort to evaluate sockeye salmon productivity and habitat in Crescent Lake in 1979-1982 as compared to 1996-2000. They report that the sole representative of the limnetic macrozooplankton community of Crescent Lake, the copepod species *Cyclops scutifer*, showed a precipitous decline in density and biomass, 5- and 4- fold reductions, respectively, during the 1996-2000 as compared to 1979-1982 (Edmundson and Edmundson, 2002). These results corroborate other findings from the same study that pointed to increasing turbidity levels in the lake, possibly due to increased glacial melting from regional climate warming and/or to ash contributions from Redoubt eruptions. The authors noted that silty, glacial lakes tend to have lower zooplankton production (abundance, biomass, and diversity) on average than clear lakes. The report also found a spatial difference in chlorophyll-a concentrations between sites A and B (Figure), with higher concentrations at site A, further from the glacial input. Although changes in chlorophyll-a over time were not found, concentrations were so close to the analytical detection limit that those inferences were difficult to make (Edmundson and Edmundson, 2002).

A recent USGS study characterizing the Crescent River watershed included zooplankton samples from *three* sites in Crescent Lake and benthic algae samples from the Crescent River (Brabets and Ourso, 2006). Lake zooplankton samples were collected in June, July, August, and September of 2004. The only genus identified was *Cyclop*, a major food source for rearing sockeye salmon juveniles. Both the North Fork of the Crescent River and the River mouth were sampled for algae, and 59 taxa from 4 phyla (Rhodophyta [Red algae], Cyanophyta [Blue-green algae], Chlorophyta [Green algae], and Chrysophyta [Diatoms]) were identified. Twice as many taxa were found in the river mouth site compared with the North Fork site. Brabets and Ourso provide a detailed discussion of the specific species types of these biota in relation to their location, nutrient levels in the water, and other biogeochemical conditions that may influence their occurrence and abundance.

Water Resources Assessment

Water quality

Intertidal and marine

EMAP in southcentral Alaska: Water, sediment, and biologic quality in marine waters were surveyed in 2002 by the Environmental Monitoring and Assessment Program (EMAP, information available at http://www.dec.state.ak.us/water/wqamp/emap.htm). Under this program, administered by the Alaska Department of Environmental Conservation (ADEC), samples were collected at 55 sites (at 3-352 m (10-1150 ft) depth) located throughout southcentral and southwest Alaska. Sites were located in Prince William Sound, Cook Inlet, Shelikof Strait, and along the Alaska Peninsula (Figure 32). They sampled dissolved oxygen concentration, salinity, water depth, pH, temperature, total suspended solids, fluorescence, chlorophyll-a concentration, transmittance, secchi depth, and nutrient concentrations (nitrates, nitrites, ammonia, and phosphate) in the water; organic and inorganic contaminants, total organic carbon, grain size, and toxicity in the sediment; and infaunal and fish species composition, infaunal and fish abundance, infaunal and fish species richness and diversity, fish tissue contaminants, histopathy specimens, and external pathological anomalies in fish on the benthos. Results from this sampling effort comprise the most comprehensive dataset available on the physical and biological conditions in the marine waters adjacent to LACL and are presented in Saupe et al. (2005). Overall, water quality conditions in the region were very good. For example, 100% of the study area met Alaska water quality standards for dissolved oxygen for all marine water uses. Water clarity (measured by Secchi depth and total suspended solids) indicated high light transmittance except for in areas near inputs of glacial rivers, which contribute massive volumes of glacial flour. Surface and bottom chlorophyll-a concentrations indicated that waters in the study region were not eutrophic and were less than the NOAA value of 5 µg/L for low-eutrophication (Bricker et al., 1999) at 100% of the sampled sites. Although measured only once at each station, dissolved nitrogen (nitrate-N, nitrite-N, and ammonium), which may vary significantly over short time scales, was below the NOAA threshold value (Bricker et al., 1999) of 1.0 mg/L for nitrate-N and nitrite-N (no State of Alaska or national EPA standards exist for coastal waters for nitrate-N and nitrite-N), and far below both the acute and chronic Alaska water quality standards for ammonium at all sample sites. Except for one outlier, identified as likely due to contamination, all phosphate-P concentrations fell below the NOAA threshold value of 0.1 mg/Ll (Bricker et al., 1999). Ninety five percent of the study area had sediment total organic carbon concentrations that were between 0.5 and 3%; concentrations lower and higher than this range have been linked with adverse effects on benthic communities (Hyland et al., 2005).

In terms of contaminants, the EMAP project found few indications of levels of concern (Saupe et al., 2005). The EMAP project tested for 25 polycyclic aromatic hydrocarbons (PAHs), 21 polychlorinated biphenyls (PCBs), DDTs and 13 other chlorinated pesticides, and 15 metals in fish tissues and sediments. Sediment data were compared to sediment quality guidelines (SQGs) developed by NOAA's National Status and Trends (NS&T) Program (Long et al., 1995) and to Washington State Sediment Quality Standards (Washington State Legislature, 1995). The

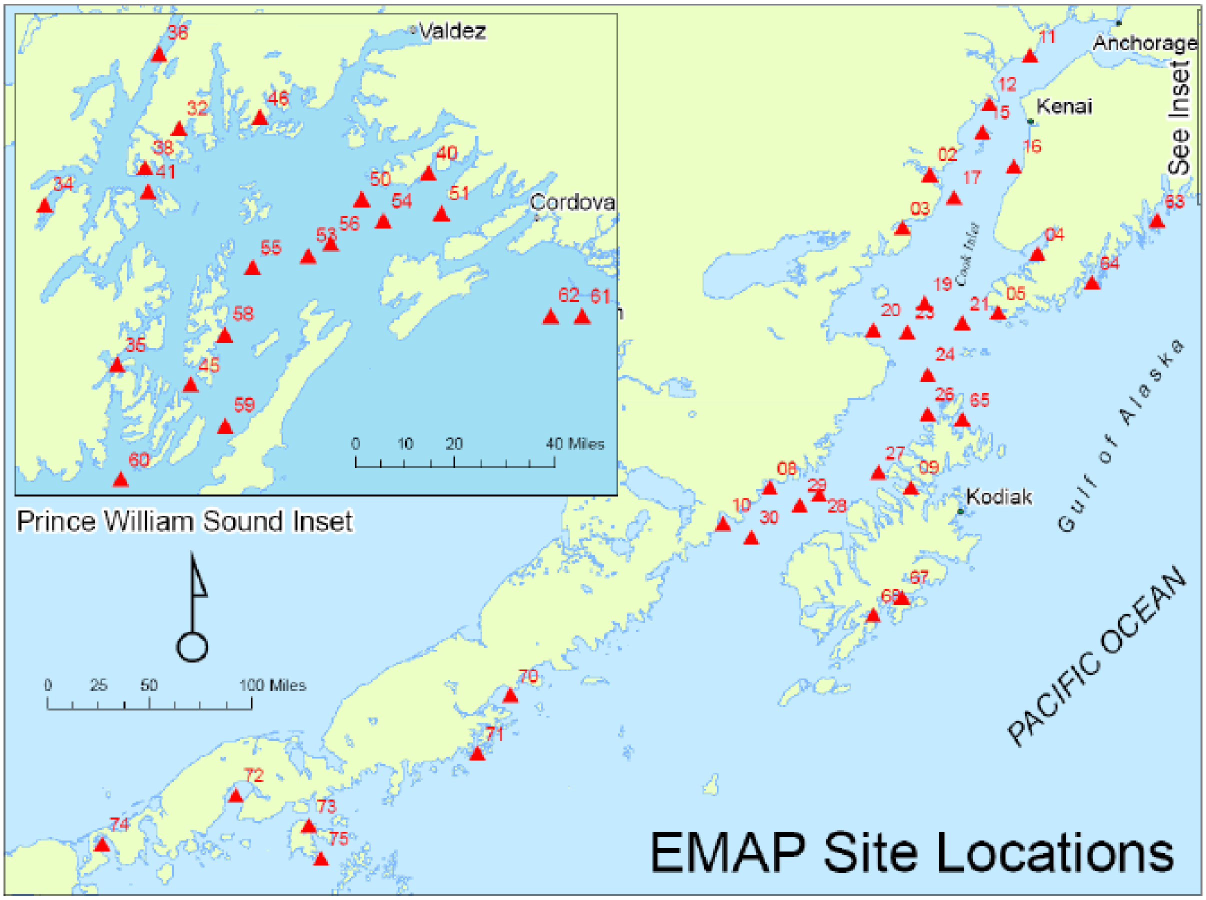


Figure 32. Sites sampled by EMAP in southcentral Alaska in the summer of 2002 (Saupe et al., 2005). The two-digit numbers reflect the last two numbers of each station. Prince William Sound is inset. Stations closest to LACL are, from north to south, 15, 2, 17, and 3.

concentrations of metals (Ag, Al, Cd, Cr, Cu, Hg, Fe, Pb, Mn, Ni, Se, Sb, Sn, Zn) and arsenic in the sediments collected off the LACL coast were all of acceptable quality (with the one exception of Ni, which was elevated at many sites in Cook Inlet in relation to the sediment quality guidelines developed by Long et al. (1995), likely due to a combination of high source rock concentrations and mineral mining in localized areas), and almost all samples from the EMAP southcentral region were as well. Saupe et al. (2005) provide detailed graphical and tabular presentations of the metal concentrations in the samples distributed across the sampling area.

Sediment hydrocarbon concentrations were generally low and within acceptable levels based on existing but limited standards (Figure 33; Saupe et al., 2005). High concentrations may be indicative of natural sources (e.g. oil seeps, eroded source petroleum sedimentary rock, coal, terrestrial and marine plants and animals, peat, and forest fire deposits) and/or anthropogenic sources (e.g. petroleum industry discharges, municipal wastewater treatment discharges, non-point source runoff from urban zones, small spills from marine vessels, and large-scale spills such as the 1989 *Exxon Valdez* Oil Spill). Total polynuclear aromatic hydrocarbons (PAH) concentrations were below, with 90% one order of magnitude below, the Effects Range Low

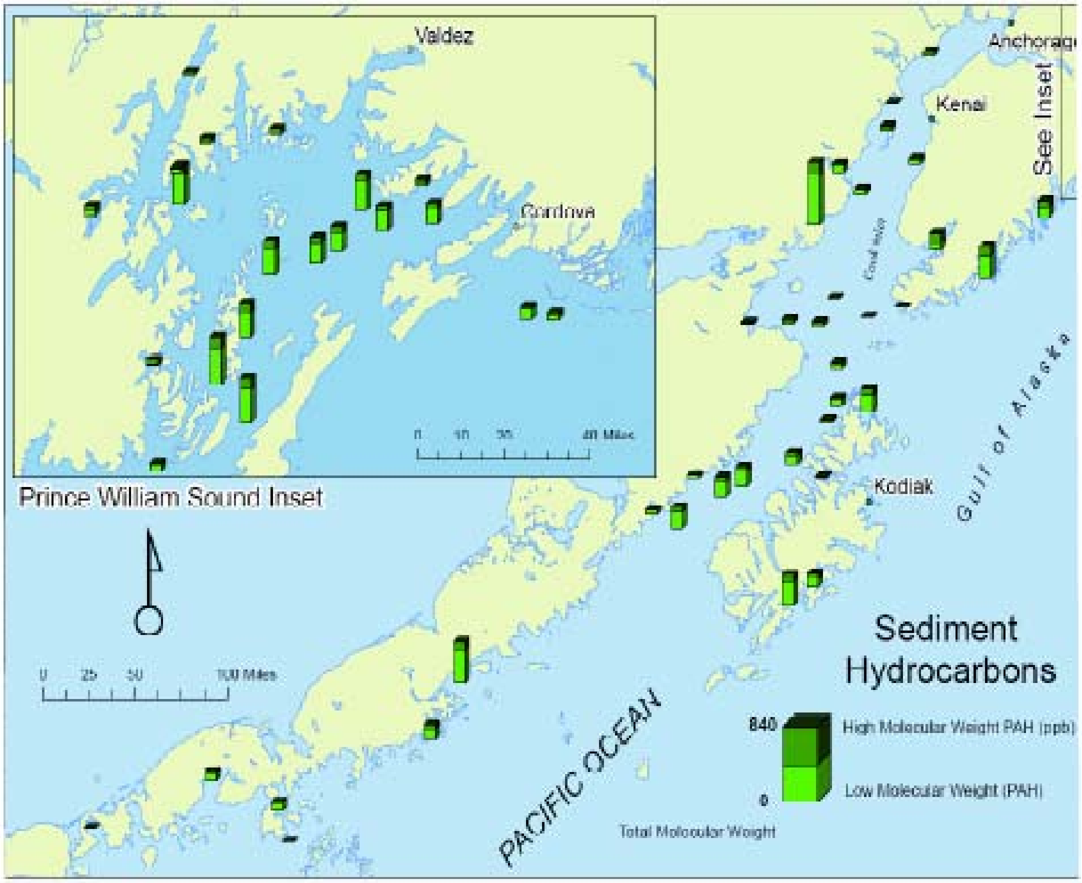


Figure 33. Sediment polynuclear aromatic hydrocarbon (PAH) concentrations (µg/g) at sampled stations across the EMAP study area, with low and high molecular weight PAHs shown as a fraction of total PAH (Saupe et al., 2005).

(ERL) of 4020 ng/g for 100% of samples in the study region (Long et al., 1995). Not all PAH analytes have associated ERL and Effects Range Median (ERM) values; however, for those with such standards, none exceeded the ERMs. Nonetheless, site AK02-003 in Chinitna Bay (off the LACL coast) had the highest PAH concentration found in the regional survey. The authors speculate that the source of the PAHs is from natural oil seeps that have been documented in the Chinitna Bay watershed (Becker and Manen, 1988). The evidence for this is that grain size analyses show that the Chinitna Bay sediments did not match the glacial fines that are characteristic of depositional areas from upper Cook Inlet, where there are oil industry operations and urban run-off.

No persistent organic pollutants were detected in sediments (Saupe et al., 2005). Sediment toxicity tests (bioassays based on a 10-day Ampelisca abdita amphipod survival test) showed only two stations (representing 1.1% of the study area) with amphipod survival rates of <80%, and these were not in the LACL coastal vicinity. Benthic infaunal communities near LACL were dominated by polychaetes, crustaceans, and oligochaetes (Saupe et al., 2005). Fish tissue analyses (95 samples from the 55 stations) of metals and organic pollutants showed that 100% of samples fell below the USEPA's Risk Guidelines for Recreational Fishers and also below the U.S. Food and Drug Administration's "Action Limits" for commercial fish.

SWAN I&M nearshore marine monitoring: At the core of the I&M program is the selection of a suite of vital signs (Appendix A) that were chosen based on ecological significance and relevance to SWAN resource management issues (Bennett et al., 2006). Protocols for the monitoring of vital signs associated with the marine nearshore, including marine water chemistry, kelp and eelgrass, marine intertidal invertebrates, marine birds, black oystercatcher, and sea otters, have been or are in the process of being developed (Bennett et al., 2006). Most parameters are expected to be monitored annually based on a stratified systematic or stratified generalized random-tessellation (GRTS; Stevens and Olsen, 2004) design. The GRTS is a spatially balanced probability sampling method that allows units to be easily added to existing samples and can incorporate stratification and units with unequal probabilities of selection (Bennett et al., 2006; Stevens and Olsen, 2004). The nearshore monitoring protocol was field tested at KATM in 2006 and 2007 and implemented in KEFJ in 2007. Initial sampling in LACL will occur in 2009, although it will be less extensive than in KATM; in LACL, sampling will likely be focused on soft sediments, while otters, oystercatchers, and kelp will not be included (Michael Shephard, NPS, written communication, 2008). Monitoring in LACL is expected to occur on a decadal basis (Page Spencer, NPS, written communication, 2008). In 2007, the SWAN I&M program completed vegetation and soil sampling and installed data loggers for soil temperature and water level in salt marshes in LACL (Jorgenson et al., 2008). Specifically, SWAN I&M established sites at Chinitna Bay and Silver Salmon to test the monitoring protocols, focusing on the physical (topography, sedimentation, water levels and storms), chemical (salinity and pH), biological (vegetation), and disturbed (debris and trails) components of coastal wetlands (Jorgenson et al., 2008). More information on the nearshore marine vital signs monitoring plan is provided in Bennett et al. (2006) and at the SWAN I&M website: http://science.nature.nps.gov/im/units/swan/index.cfm?theme=marine.

Freshwater

Overview of SWAN water quality component of I&M program: Several vital signs were selected for the SWAN I&M program that are directly related to freshwater resources. They include surface water hydrology, freshwater chemistry, and landscape processes (including snow cover and lake and coastal ice) (Bennett et al., 2006). The water quality monitoring design components are fully integrated into the SWAN vital signs monitoring program (Bennett et al., 2006). To provide specialized guidance on the water quality monitoring component, a cooperative project was established between the NPS, SWAN, and University of Washington School of Aquatic and Fishery Sciences (O'Keefe and Naiman, 2004). This collaborative effort developed an annotated bibliography of past and present freshwater research and monitoring in southwestern Alaska, summarized existing knowledge, and identified ongoing data collection efforts that are relevant to aquatic monitoring in SWAN (O'Keefe, 2005). Results of the water quality monitoring project review found no 303(d) waters present with LACL (or any other SWAN unit) and concluded that although water quality collection has been sporadic, conditions appear to be generally good with low nutrient levels and little evidence of anthropogenic impacts (Bennett et al., 2006).

The network has developed a strategy for long-term monitoring of freshwater aquatic resources within the SWAN units. Streams and lakes were categorized into three tiers by using a ranking procedure that considered access, level of use/management issues, and ecological and spatial cover (Bennett et al., 2006). Tier 1 lakes and streams are of the highest priority, have the easiest access, are heavily used by visitors, are of greatest management concern, and will be monitored annually. Tier 2 lakes are streams are of medium priority, less accessible, and will be randomly subsampled for less frequent monitoring (every 2-5 years). Finally, Tier 3 lakes and streams (low priority) will be sampled every ~10 years, if at all (depending on funding constraints), for the purpose of expanding the scale of inference of Tier 1 and 2 waterbodies. Vital sign metrics at Tiers 2 and 3 waterbodies may also be collected by seasonal park staff on an opportunistic basis. In the coastal LACL area, no waterbodies were identified as Tier 1, but the Crescent River system was designated as Tier 2 (Figure 34).

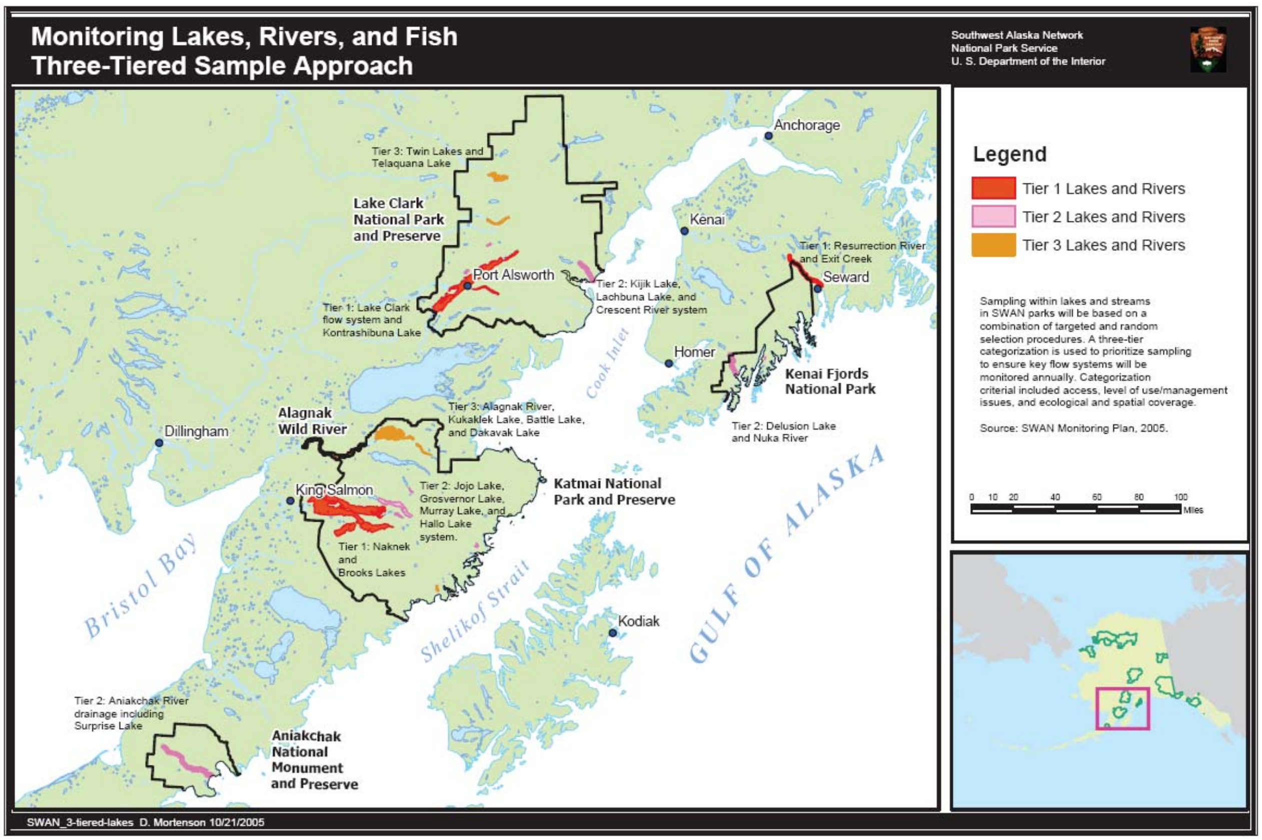


Figure 34. List and locations of proposed Tier 1, 2, and 3 lakes and rivers for monitoring aquatic resources in SWAN units. Within LACL, the Kijik Lake, Lachbuna Lake, and Crescent River are ranked as Tier 2 (Bennett et al., 2006).

Water quality of streams and lakes: A baseline water quality inventory study of LACL conducted by the NPS presents results of extensive data retrievals using six of the Environmental Protection Agency's (EPA) national databases: Storage and Retrieval (STORET) water quality database management system, River Reach File (RF3), Industrial Facilities Discharge (IFD), Drinking Water Supplies (DRINKS), Water Gages (GAGES), and Water Impoundments (DAMS) (NPS, 1997). This data retrieval effort yielded no water quality records for sites within the LACL coastal study region. However, a few records are provided for water quality samples collected in the Drift River and Chakachatna River basins, which begin within LACL and then leave the park boundary before emptying into Cook Inlet (Table 10). Drift River samples were taken from within the park, while the others, from the Chakachatna River basin, were taken outside the LACL boundaries (Figure 35).

Table 10. Summary of water quality data parameters available for sample sites in the Drift River and Chakachatna River basins, based on data retrievals in NPS (1997).

Site name	Station #	# of samples	Date	Parameters measured
Drift R.-Canyon Mouth	LACL 0006	1	4/25/1990	T,Q,SC,DO,pH,Ca,Mg,Na,K,Cl,SO4,Si,Fe
Drift R.-near Redoubt	LACL 0007	1	10/17/1991	T,Stage,Tub,Col,SC,DO,pH,Alk,P,Ca,Mg, Na,K,Cl,SO4,F,Si,As,Ba,Be,B,Cd,Co,Cu, Fe,Pb,Mn,Mo,Ni,Ag,Sr,Zn
Drift R.	LACL 0008	1 to 3	2/25/70-4/25/90	T,Q,Col,SC,DO,pH,CO2,Alk,Bicarb,Carb, NO3,Hard,Ca,Mg,Na,K,F,Si,B,Fe,TDS,Cl, SO4,Mn,Fe
Chakachatna R. below lake nr Tyonek	LACL 0011	1	3/30/1971	T,Q,SC,pH,CO2,Alk,Bicarb,Hard,Ca,Mg,Na,K, Cl,SO4,F,Si,Fe,Mn,TDS
Chakachatna R. Tyonek	LACL 0012	2 to 21		T,Q,Col,SC,pH,CO2,Alk,Bicarb,Carb,NO3-N, NO2-N,PO4,Hard,Ca,Mg,Na,K,Cl,SO4,F,Si,Fe,Mn, Mn,OP,TDS
Chilligan R.-nr Tyonek	LACL 0013	1	8/21/1960	T,SC,pH,CO2,Alk,Bicarb,Hard,Ca,Mg,Na,K,Cl,SO4, Si,Mg,Na,K,Cl,SO4,Fe,Mn,OP,TDS
Nagishlamina R.-nr. Tyonek	LACL 0014	1	8/21/1960	T,SC,pH,CO2,Alk,Bicarb,Hard,Ca,Mg,Na,K,Cl,SO4, Si,Mg,Na,K,Cl,SO4,Fe,Mn,OP,TDS

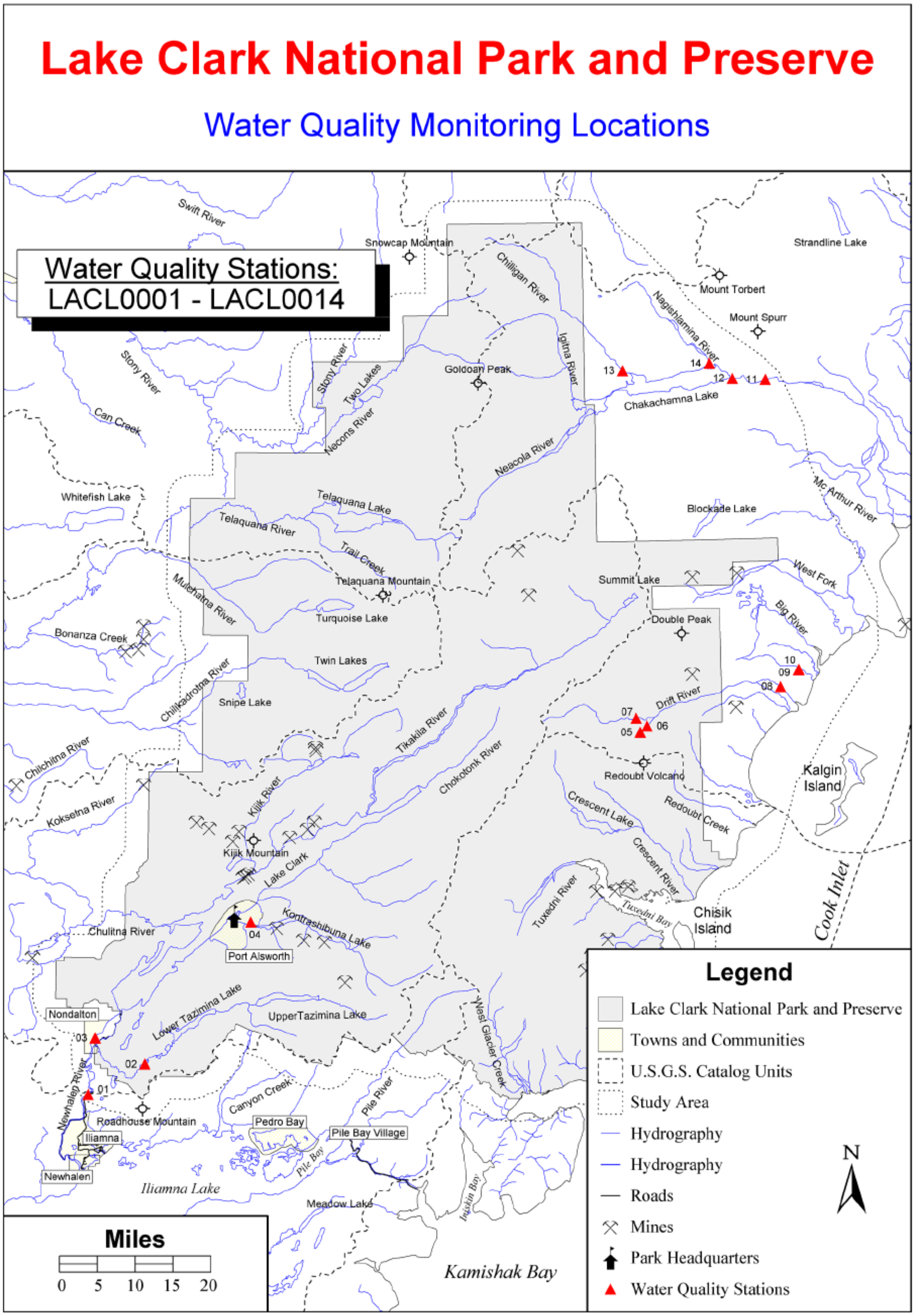


Figure 35. Location map of water quality samples collected in LACL, as compiled by the NPS (NPS, 1997).

The NPS (1997) report determined none of the above samples exceeded criteria-based water quality standards for pH, sulfate, and chloride, except for the single sample from station LACL0006. (However, it is very important to note that information on water quality standards are given here merely as a comparative reference for the conditions of these naturally-influenced water bodies and do not imply that these waters should be managed to meet criteria-based standards). In addition, the State of Alaska recognizes that some conditions naturally exceed state water quality criteria and are not subject to the same regulations as criteria violations caused by human activity (ADEC, 2006). At LACL0006, the pH value (5 units) was below the water quality limit of 6.5 pH units; chloride (870 mg/L)exceeded the freshwater acute criterion of 860 mg/L and the drinking water standard of 250 mg/L; and the sulfate concentration (980 mg/L) was about 4 times over the drinking water limit of 250 mg/L.

As with many glacial and volcanically- influenced streams in the Cook Inlet Region, streams in coastal LACL typically carry heavy loads of suspended and bedload sediment (Brabets et al., 1999). Rainstorm-induced stream flooding is common in the Cook Inlet region during August and September, and possibly during mid-winter thaw events, although floods may occur at any time of year and may be particularly powerful if induced by volcanic activity (Brabets et al., 1999).

Specific streams for which detailed information is available:

Johnson River

NAWQA study of the Johnson River: As part of the USGS National Water Quality Assessment (NAWQA) Program, the Cook Inlet region was studied between 1998 and 2001. The study entailed a water quality assessment of 15 streams, one of which was the Johnson River in LACL. An overview of the project and summary of major results is provided in Glass et al. (2004), and links and further information on results are available at the website: http://ak.water.usgs.gov/Projects/Nawqa/.

Physical, chemical, and biological characteristics of the Johnson River site (at the USGS gaging station, approximately 32 km (20 mi) from the mouth) were measured on August 18, 1998 (Frenzel and Dorava, 1999). Field water quality properties showed the river to be cold, well oxygenated, with low specific conductance (indicating few dissolved ions), and containing low (mostly undetectable) nutrient concentrations (Frenzel and Dorava, 1999). Data from the single sample are presented in Table 11 (Frenzel and Dorava, 1999). Water clarity, although not quantified, was described as "poor" due to the glaciers feeding the river upstream of the sampling location. Biological sampling of benthic macroinvertebrates is summarized in the *Aquatic invertebrates, chlorophyll, phytoplankton* section.

Additionally, the USGS's NAWQA Cook Inlet Basin study included the collection and analysis of streamwater, streambed sediment, fish tissues, and macroinvertebrates at 15 sites for trace elements, organochlorines, and semivolatile organic compounds (SVOCs) (in streambed sediment) (Brabets et al., 1999; Frenzel, 2000). Some sites, including the Johnson River, were sampled for only a portion of these parameters: organochlorines, SVOCs, and trace elements in streambed sediments. No detectable concentrations of organochlorines or SVOCs were found in

Table 11. Field and analytical water quality results for the Johnson River on August 18, 1998 (Frenzel and Dorava, 1999).

Water temperature (°C)	4.5
Specific conductance (µS/cm)	48
Dissolved oxygen (mg/L)	13.1
pH	7.3
Phosphorus (P) total as P	<0.01 mg/L
Orthophosphate (PO_4) dissolved as P	<0.01 mg/L
Phosphorus (P) dissolved as P	<0.01 mg/L
Nitrite + nitrate, NO_2+NO_3, dissolved as N	<0.05 mg/L
Ammonia, NH_3, dissolved as N	0.077 mg/L
Ammonia + organic nitrogen, total as N	<0.10 mg/L
Ammonia + organic nitrogen, dissolved as N	<0.10 mg/L

the Johnson River bed sediment (Frenzel, 2000). Although the watershed has been targeted for potential gold mining, the median trace element (As, Cd, Cr, Cu, Ni, Pb, Hg, Se, and Zn) concentrations in the sediments were not only below the Probable Effects Levels (PELs) (Canadian Council of Ministers for the Environment, 1999), but many were among the lowest of all the sites sampled in 1998. Only the copper concentration (75 µg/g) was relatively high compared to other Cook Inlet Basin samples.

Reconnaissance of Johnson River watershed by mining interests: In the early 1990s, Cook Inlet Region, Inc. (CIRI) and Westmin Resources, Limited (of Vancouver, British Columbia) conducted an environmental analysis of the Johnson River area as part of their interest in developing mineral resources on their private tract of land in the watershed (please see the *Potential mining in the Johnson River watershed* section for more information) (Cook Inlet Region Inc., 1993). They collected samples for total suspended solids, hardness as $CaCO_3$, nitrate-N, nitrite-N, sulfate, and alkalinity as $CaCO_3$ for total and dissolved metals from 15 locations throughout the watershed in late August, 1993. They compared their results to Alaska water quality standards and reported that Fe, Zn, and Mn exceeded the standards in or directly below the small creek draining the area where the ore body outcrops, and that Al exceeded standards at most sites (Cook Inlet Region Inc., 1993). Information on numbers of samples taken, quantitative results, and methods used are not given in the 1993 report. However, it is unlikely that in 1993 the researchers were using "clean method" techniques that were being developed for freshwater at about the time of the sampling. In the past 15 years, several studies have effectively invalidated much of trace metal work done for much of the last century due to the discovery of major contamination problems associated with previously standard sampling protocols (Benoit, 1994; Horowitz et al., 1994). These studies have demonstrated that by following meticulous "clean" (or "ultra-clean") sampling, processing, and analytical techniques, trace metal contamination of water samples can be drastically reduced. As a result, the data on elevated trace metals in the Johnson River area should be treated with skepticism, and new analyses using clean methods are warranted in order to accurately assess trace element water quality.

Crescent River: Deschu (2003) conducted a synoptic survey of the Crescent River on September 1, 1997 in response to concerns surrounding possible development in the watershed. Three sites—the North Fork, the Lake Fork, and at 1.9 km (1.2 mi) below their confluence—were photographed and sampled for pH, water temperature, conductivity, and TSS (Deschu, 2003). Additionally, periphyton chlorophyll-*a* and phaeophytin were measured from river rocks scraped for samples in the Lake Fork only. Data, shown in Table 12, indicate that there were major differences in several of the physical and chemical characteristics of the two forks of the Crescent River. The glacially-influenced North Fork had lower water temperature but substantially higher sediment loads than the Lake Fork. The confluence site exhibited values that were largely intermediate between the two tributary forks. Deschu (2003) emphasizes that potential logging within the watershed's private inholdings and the effects of a warming climate may have strong implications for water quality and volume, and she recommends that future monitoring and research begin with a much more detailed baseline water quality assessment.

Table 12. Crescent River data from Deschu (2003).

	Lake Fork	North Fork	Below confluence
Discharge (cfs)	487	432	919
Water temperature (°C)	11	8.5	11
Conductivity (μS)	25.5	56.2	38.6
TSS (mg/l)	3.4	216	98.6
pH	6.78	7.4	7.2
Periphyton chlorophyll-a (ug/cm^2)	11.74, 14.04	--	--
Periphyton phaeophytin (ug/cm^2)	10.52, 5.25	--	--

Shortly thereafter, a more detailed study of the Crescent River watershed was conducted by the USGS from May through October in 2003 and 2004 (Brabets and Ourso, 2006b). The watershed study was driven by interest in the river's productive sockeye salmon run that is important to the Cook Inlet commercial fishing industry and the risk of water quality degradation due to past and future logging activity (please see the *Potential logging in the Crescent River* section). The study entailed a biogeochemical characterization of both Crescent Lake and the Crescent River system (mainstem and two tributaries).

Three lake sites (4.6, 2.8, and 1.2 miles above the outlet) and three stream water sites (North Fork Crescent River, Lake Fork Crescent River, and Crescent River near mouth) were targeted for sampling (Brabets and Ourso, 2006). Samples were collected approximately monthly from May through October in both 2003 and 2004. Discharge was estimated using stream stage and comparisons with the nearby Johnson River (similar physically and gaged by the USGS). Stream water was analyzed for pH, specific conductance, water temperature, dissolved oxygen, major ions and dissolved solids, nutrients, organic carbon, and suspended sediment (Table 13). The report showed that based on surface measurements and depth profiles down to 9.1 m (30 feet), Crescent Lake was an efficient trap for sediment entering the lake via glacial-fed streams, and

Table 13. Physical and chemical parameters measured at the stream sampling sites in the Crescent River watershed (Brabets and Ourso, 2006). Additional tables with data on alkalinity, nutrients, organic carbon, anions, cations, and total dissolved solids in streamwater; depth profiles for lake water; and trace elements in streambed sediments are available in Brabets and Ourso (2006).

[all values in milligrams per liter, mg/L, unless otherwise noted; °C, degrees Celsius; µs/cm at 25° Celsius, microsiemens per centimeter at 25° Celsius; <, less than; ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile; NTU, Nephelometric Turbidity Unit; E, estimated; --, constituent not measured]

Date	Time	Dis-charge (ft^3/s)	Unit Discharge ($ft^3/s/mi^2$)	Dissolved Oxygen	pH (units)	Specific Conductance (µs/cm at 25° Celsius)	Water Temperature (°C)	Turbidity (NTU)	Suspended Sediment
North Fork Crescent River (site 1)									
5/16/2003	1330	89	2.6	9.3	7.0	55	8.0	4.1	20
7/2/2003	1630	E721	21.1	12.5	6.9	23	6.5	32.0	142
8/1/2003	1310	537	15.7	12.1	6.7	28	7.0	4.8	83
10/23/2003	1230	145	4.2	--	7.1	57	--	<2.0	11
8/11/2004	1350	501	14.6	12.8	6.0	25	8.2	54.0	318
9/8/2004	1350	E186	5.4	12.1	5.8	51	2.7	26.0	71
Lake Fork Crescent River (site 2)									
5/16/2003	1115	462	3.7	12.2	7.3	31	4.0	2.3	7.0
7/19/2003	1045	2730	21.8	10.8	6.7	26	10.0	7.1	10
8/14/2003	1025	2610	20.9	11.7	6.6	23	9.2	11.0	14
10/23/2003	1545	741	5.9	--	7.1	25	5.0	20.0	10
7/2/2003	1245	2140	17.1	13	6.3	31	9.6	16.0	13
7/29/2003	1130	2860	22.9	12.3	6.0	28	9.1	16.0	12
8/18/2003	1200	1380	11	9.8	6.2	25	13.2	13.0	11
9/13/2003	1225	560	4.5	10.8	6.0	24	9.5	--	8.0
Crescent River near mouth (site 3)									
5/16/2003	1615	742	3.0	13.6	8.0	58	7.9	3.7	10
7/2/2003	1120	E5250	21.1	10.9	7.1	34	10.0	20	277
8/1/2003	1730	3350	13.4	11.1	7.3	35	12.5	10	254
10/24/2003	1515	E1257	5.0	--	7.3	50	5.0	13	154
8/11/2004	1520	E3280	13.2	12.8	6.7	34	12.8	54	308
9/8/2004	1300	E1350	5.4	10.2	6.3	39	8.1	20	71

that the North Fork Crescent River is the main contributor of suspended sediment to the mainstem Crescent River (Brabets and Ourso, 2006b). Lake profiles during the summer of 2004 showed increased turbidity during peak glacial melt period in June, followed by declines in September and August. The report also provided general geochemical characterizations of the Crescent River water quality, including information showing that it is a calcium-bicarbonate dominated system with low concentrations of nutrients, dissolved organic carbon, major ions, alkalinity, and dissolved organic carbon.

Evaluation of 39 trace elements in streambed sediments (collected from the three sites on a single event) and comparisons to various standards showed some natural enrichment. Copper concentrations at all three sites and zinc at the lowermost site were elevated above the Threshold Effect Concentration (MacDonald et al., 2000), but all samples were below the Probably Effect Level (Canadian Council of Ministers for the Environment, 1999) and Probable Effect

Concentration (MacDonald et al., 2000) standards. Finally, the study also provided an overview of zooplankton and algal communities in Crescent Lake (see section *Crescent River watershed* under *Park Description, Freshwater Biological Resources*).

Specific lakes: Data on water quality characteristics of coastal lakes are available only for Crescent Lake, which is an important sockeye salmon nursery that has been studied by the Alaska Department of Fish and Game (ADFG) (Edmundson and Edmundson, 2002) and by the USGS (Brabets and Ourso, 2006a). The ADFG research was driven by a concern that salmon productivity declines were potentially linked with an apparent increase in lake turbidity. As a result, monthly samples (June-October) were conducted from three sites in the lake between1996-2000 and compared to data collected in 1979-1982. Parameters measured included underwater irradiance, light extinction coefficient, euphotic zone depth (EZD), Secchi disk measurements of water clarity, vertical temperature profiles, conductivity, pH, alkalinity, turbidity, color, Ca, Mg, total Fe, reactive Si, filterable reactive phosphorus (FRP), total phosphorus (TP), nitrate+nitrite, total Kjeldahl nitrogen (TKN), chlorophyll-a, and macrozooplankton counts and biomass. Edmundson and Edmundson (2002) pooled the 1996-2000 ("late period") water quality data and compared them to pooled data from 1979-1982 ("early period") to check for significant differences using ANOVA tests. Table 14 shows both the mean values for the parameters measured and the p-value of their statistical comparison between the two periods.

While results of ANOVA tests showed no significant differences in general water chemistry and nutrient levels between stations A and B (except for chlorophyll-a, which was lower at station B, closer to the glacier input), several significant differences were found between the early and late periods (Edmundson and Edmundson, 2002). Turbidity levels in the 1-m stratum in the lake varied highly, between 3-30 NTU in 1996-2000, and average values in 1996 and 1997 were three-times higher than in the early period. Turbidity values then decreased again in 1998-2000 to levels similar to those of the early period. The authors speculate that increases in turbidity may be linked to regional climate warming, which may be causing increasing glacier melt (although water column temperatures were not measurably different), or to potential differences in silt particle size (as opposed to silt input amount) from the meltwater sources, or to ash fallout from the 1989-90 volcanic eruption of Redoubt Volcano, which undoubtedly delivered ash fallout to the lake, albeit years before the sampling. The authors point to increasing turbidity in nearby Skilak Lake (Kenai Peninsula) since the mid-1980s as more evidence that sockeye productivity was associated at least partially with changes in glacier melt dynamics (Edmundson and Edmundson, 2002).

Other differences between the early and late periods were found: conductivity and alkalinity were higher and Ca and Mg were lower in the late period, although the authors viewed those differences as having little significance for sockeye salmon production (Edmundson and Edmundson, 2002). Larger differences were found for total Fe and TP, which increased 40% and 30%, respectively, and for inorganic N (nitrate + nitrite), which decreased 25%. The increases in total Fe and TP were credited to the rising turbidity levels, while the drop in inorganic N, while not explained, was not of concern to the authors who noted that the levels were still far from being productivity-limiting.

Table 14. Comparison of mean water quality variables in stations A and B in Crescent Lake (shown in Figure) and by period: early (1979-1982) and late (1996-2000). From Table 2 in Edmundson and Edmundson (2002).

Variable	Unit of Measure	Station Mean A	Station Mean B	P-value	Period Mean Early	Period Mean Late	P-value
Conductivity	μmhos cm $^{-1}$	26.30	26.20	0.782	23.90	27.70	< 0.001
pH	Units	6.70	6.70	0.652	6.70	6.70	0.870
Alkalinity	mg L^{-1}	10.40	10.20	0.408	10.00	10.50	0.028
Turbidity	NTU	9.90	10.80	0.016	2.43	13.00	< 0.001
Calcium	mg L^{-1}	3.90	3.90	0.759	4.10	3.80	0.011
Magnesium	mg L^{-1}	0.34	0.31	0.115	0.40	0.30	0.008
Iron	mg L^{-1}	3.30	3.30	0.984	2.65	3.69	< 0.001
Total phosphorus	μg L^{-1}	11.50	12.70	0.054	10.00	13.40	< 0.001
Total filterable phosphorus	μg L^{-1}	2.40	2.30	0.839	2.40	2.30	0.692
Filterable reactive phosphorus	μg L^{-1}	1.90	2.10	0.112	1.90	2.10	0.163
Total nitrogen	μg L^{-1}	233.00	238.00	0.514	271.00	214.00	< 0.001
Kjeldahl nitrogen	μg L^{-1}	45.00	49.00	0.341	47.00	47.00	0.987
Ammonia	μg L^{-1}	9.50	7.10	0.060	8.10	8.50	0.733
Nitrate + nitrite	μg L^{-1}	188.00	188.00	0.997	224.00	170.00	< 0.001
Reactive silicon	μg L^{-1}	2243.00	2242.00	0.961	2208.00	2263.00	0.022
Chlorophyll *a*	μg L^{-1}	0.51	0.41	0.033	0.42	0.48	0.143
Phaeophytin	μg L^{-1}	0.23	0.20	0.182	0.17	0.25	0.008

Maximum mid-summer surface temperatures in the lake typically varied between 10-12°C (with a maximum of 15°C in 1979), and no significant difference (p=0.441) was found between the early and late periods based on an ANOVA test. The report also notes that turbidity increases in the fall during heavy precipitation periods, and that the lake did not undergo thermal stratification during the open water period.

A recently-published report on the Crescent River watershed provides detailed information on Crescent Lake from 2003 and 2004 (Brabets and Ourso, 2006b). Zooplankton were collected from three sites on the lake (see the *Aquatic invertebrates, chlorophyll, phytoplankton, and zooplankton* section under *Park Description*). Water samples from both the lake and the stream (see previous section on *Crescent River*) were collected from May through October in 2003 and 2004. Turbidity profiles were taken to a depth of 30 feet throughout 2004 in order to track turbidity plumes from incoming glacial meltwater moving through the lake (Figure 36). Temperature, specific conductance, pH, and dissolved oxygen profiles were also measured at the three lake study sites. Temperature profiles of the lake showed that in addition to the overall warming of the lake throughout the summer, the upper portions were warmer than at depth in

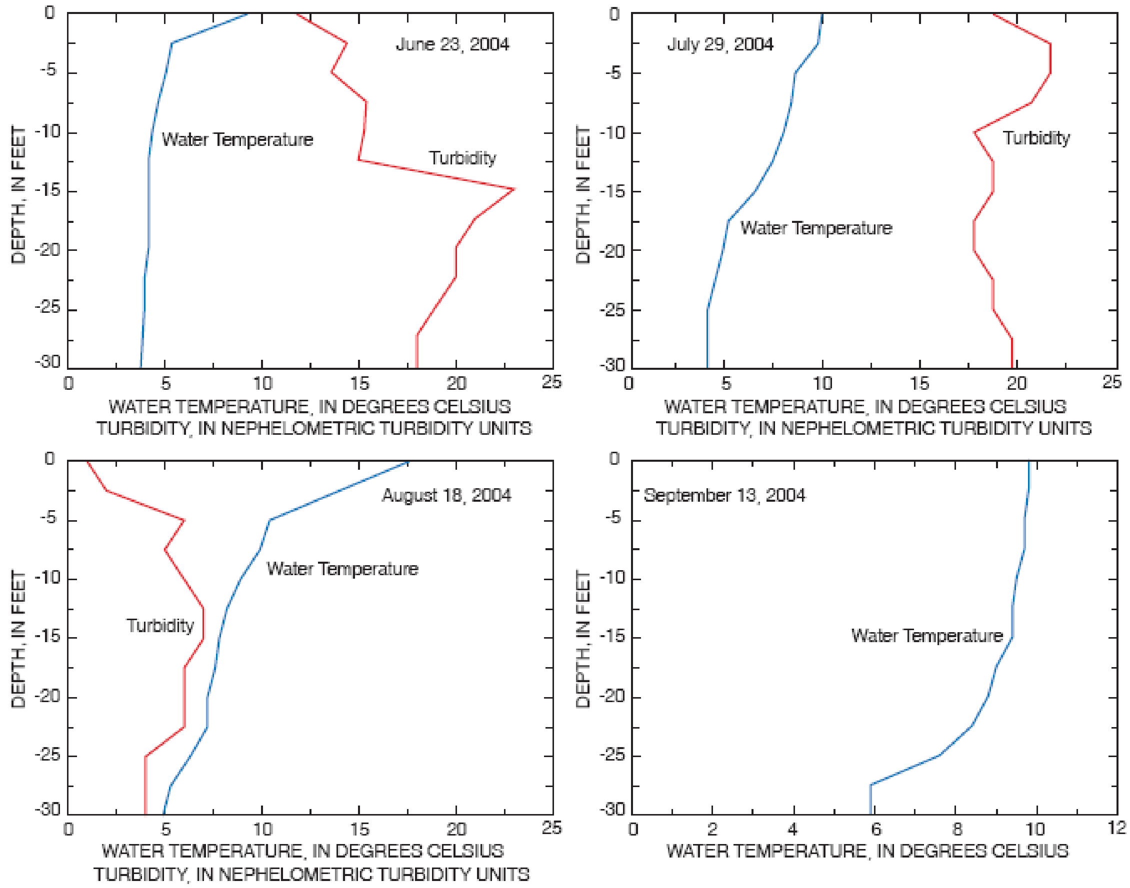


Figure 36. Temperature and turbidity profiles in Crescent Lake in June- September 2004. Source: Brabets and Ourso (2006).

June and August, while in July the lake was fairly well mixed, and in September the lake was isothermal (Brabets and Ourso, 2006b). Specific conductance profiles exhibited approximately uniform patterns with depth (values ranged from 20 to 39 µs/cm at 25°C). Lake pH profiles also showed only slight variations with depth (5.8-6.7, which is within the typical range for fish growth and survival). Dissolved oxygen was higher near the surface (up to 14.2 mg/L) and declined with depth down to a minimum of 8.4 mg/L, and all measurements showed adequate concentrations to support salmonid populations. Alkalinity readings were between 8-12 mg/L, indicating a low buffering capacity for the lake. Dissolved solid concentrations in the lake were also low (11-28 mg/L), as were nutrients and organic carbon. Brabets and Ourso (2006) provide complete data sets for all their water quality collections from the lake.

Groundwater: The lack of any information on groundwater resources in the LACL coastal region does not allow for an assessment of groundwater quality in the area. However, there is no reason to believe that groundwater quality is impaired by human factors due to the extremely low level of disturbance in coastal LACL. The nearest evaluation of regional groundwater resources comes from the U.S. Geological Survey's NAWQA Program's focus on the Cook Inlet Basin (Glass et al., 2001, 2004). However, information from the majority of the 34 wells sampled as part of that program was derived from urban areas and is therefore not applicable to LACL conditions.

Precipitation

At the current time, the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) provides continuous measurement and assessment of the chemical constituents in precipitation at more than 225 sites throughout the United States. This long-term, nationally consistent monitoring program provides critical information for evaluating the effectiveness of ongoing and future regulations aimed at reducing atmospheric emissions. There are four NADP sites in Alaska, two of which are administered by the NPS (Denali and Gates of the Arctic). The most representative NADP site for coastal LACL is the Juneau site located on the east coast of the Gulf of Alaska. Data from this site show a predominance of marine aerosols (chlorine, sulfate, and sodium) and very low levels of nitrogen (ammonium and nitrate) compared to sites in the contiguous United States. Data on precipitation chemistry in Alaska are available through the NADP website located at http://nadp.sws.uiuc.edu/sites/ntnmap.asp?

Water quality impairments and effects on biological resources

LACL has no waterbodies listed as impaired under the 303d section of the Clean Water Act. As discussed above, extremely little data are available regarding water quality in LACL's coastal watersheds. Threats to the health of fish, wildlife, and humans are likely limited to the waters directly influenced by naturally highly mineralized volcanic sources. The one sample logged by the NPS as exceeding water quality criteria (for pH, sulfate, and chloride) was from the Drift River near Mount Redoubt – outside, but adjacent to, the LACL boundary (see the *Freshwater, Water Quality of Streams and Lakes* section under *Water Resources Assessment*) (NPS, 1997). A much more thorough survey of water quality conditions throughout the coastal region is required before making any definitive assessments of the effects of water quality on biological resources.

Threats to Water Resources

Sources of past, current, and potential future pollutants

Oceanographic sources

Oil spills:

Potential threats of oil spills and oil residence index: The release of petroleum poses a great environmental threat, whether as catastrophic spills or chronic discharges. In addition to physical impacts of large spills, the toxicity of many of the individual compounds contained in petroleum is significant, and even small releases can kill or damage organisms. The impact of a release of petroleum would depend on the size of the spill, the location of the spill, the type of petroleum product, and the effectiveness of the response to the spill. Potential oil spills could result from tanker spill, pipeline spill, well blowouts, permitted discharges of produced water at platforms and shore treatment facilities, permitted discharges of drilling muds and work-over fluids during drilling and servicing of wells, permitted discharge of waste water from oil refinery, water discharge from storage tanks and ballast, chronic leakage from storage tanks and pipelines, municipal treatment plants, marine vessels—commercial and sport fishermen and merchant ships—, and natural oil seeps.

The ShoreZone mapping program computed an “Oil Residence Index” (ORI) along coastal LACL based on data on wave exposure levels and substrate types (Figure 37). Coarse sediments, unlike rock or sheet piling, are highly permeable and can trap and retain large volumes of oil. The level of wave exposure also regulates oil residence time because wave action is the most effective process for removing stranded oil from shore. Through its imagery of physical attributes of the LACL coastline, areas were identified that are particularly sensitive to oil spills, such as estuaries and wetlands, which have fine and organic sediment and have a low amount of wave exposure. Michel et al. (1978) classified 52% of the LACL coast as highly vulnerable to oil spill damage.

Bennett (1996) emphasizes the importance of the Tuxedni and Chinitna Bay mud flats as critical feeding areas for bears and birds, and that potential contamination or destruction of these areas would have tremendous impact on a large proportion of Western sandpipers and dunlins in the region. “Birds that use the Lake Clark-Cook Inlet Coastline are at high risk from both acute and chronic oil spills. Pollution that interferes with the production of organic detritus, which supports filter and depost- feeding fauna, could have more serious long term consequences to the birds than oiling…” (pg. 53). The oil residency is expected to be high in salt marsh and estuarine environments that are an important source of organic detritus (Figure 37).

Exxon Valdez *oil spill*: Swift currents and large tidal ranges can quickly transport released petroleum great distances and over wide coastal zones, as evidenced by the *Exxon Valdez* Oil Spill (EVOS) in 1989. The grounding of the *Exxon Valdez* oil tanker on Bligh Reef in Prince William Sound in March 1989 released 10.8 million gal (35,500 metric tons) of crude oil which was transported through Prince William Sound, along the northern Gulf of Alaska, and *southwest* into Shelikof Strait (Figure 38). LACL was spared from this oil spill (Bennett, 1996); however, Katmai National Park and Preserve (KATM), located nearby, was not as lucky. Two to four percent of the released oil came ashore on Shelikof Strait within KATM (Wolfe et al., 1994),

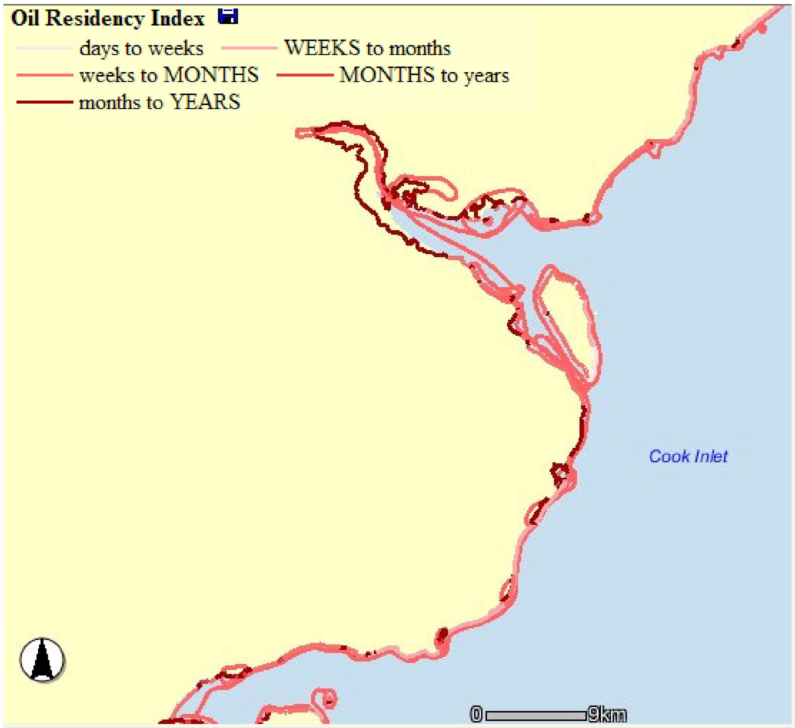


Figure 37. Oil Residence Index along the LACL coast. Source: ShoreZone Interactive Mapping website at http://mapping.fakr.noaa.gov/Website/ShoreZone/viewer.htm

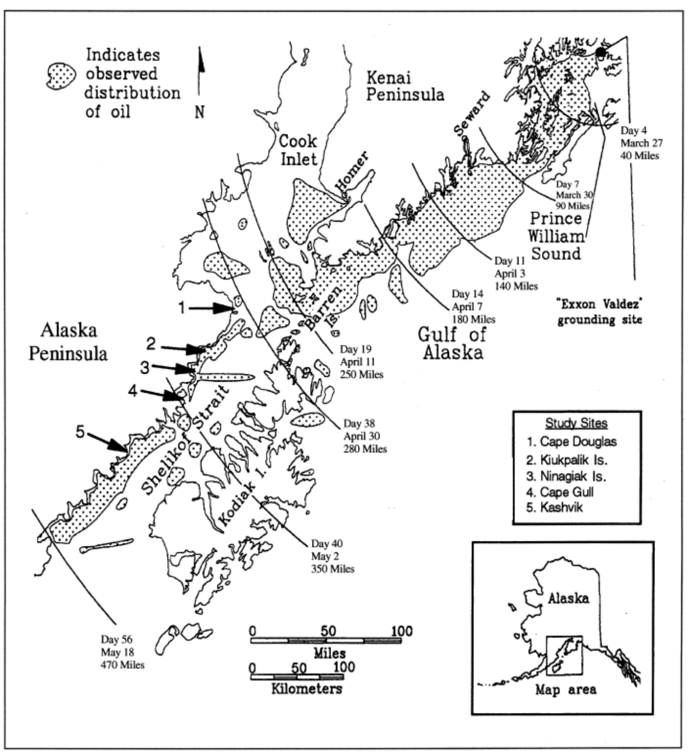


Figure 38. Geographic extent of the *Exxon Valdez* oil spill through time—24 March 1989 to 20 June 1989 (Irvine et al., 1999).

resulting in the most extensive single human-caused disaster to strike a National Park (NPS 1990). Patches of unweathered oil mousse have persisted and retained their toxicity along exposed, rocky shorelines with boulder armored beaches in KATM (Irvine et al., 1999; Peterson et al., 2003). Ecological communities in Prince William Sound (and likely Shelikof Strait) have been slow to recover from this catastrophic disturbance, and even fourteen years after, many species and communities show limited signs of recovery relative to baseline conditions (see review by Peterson et al., 2003).

Location of Cook Inlet oil production facilities: Future oil spills similar in scale to that of EVOS continue to be possible in the region. Potential source areas include the Valdez Marine Terminal (Prince William Sound), Drift River Marine Terminal (Cook Inlet), Nikiski Oil Terminal and Refinery (Cook Inlet), Anchorage International airport jet fuel pipeline, and seventeen gas and seven oil producing fields within Cook Inlet (Figures 39 and 40, Table 15). Several more oil and gas sales are currently proposed for development over the next five years in the Cook Inlet region, and steady or rising demands for these fuels may prompt further long-term development (2006-2011; information at http://www.dog.dnr.state.ak.us/oil/index.htm). Many billions of barrels of oil and gas are potentially releasable into the environment from these petroindustrial areas, posing potentially major pollution threats to the marine, estuarine, tidal and intertidal environments in the region, including along the LACL coast (Andres and Gill, 2000). The Valdez terminal receives approximately 24 billion gallons ($1.1x10^{11}$ L) annually via the TransAlaska Pipeline; the privately-owned Drift River Marine Terminal (with an offshore oil loading platform and onshore storage facility) stores approximately 1 million barrels of crude oil received via the 68 km-long (42 mi) Cook Inlet Pipeline (which in turn has an annual capacity of 82 million barrels); the Nikiski station has an annual capacity of 260 million barrels (averages 183 million barrels); and the subsurface pipeline that runs beneath the intertidal zone between the Port of Anchorage and the Anchorage International Airport funnels 13 million barrels of jet fuel annually (Weeks, 1999; Andres and Gill, 2000; Alaska Divison of Oil and Gas, 2003; Chevron Corporation, 2006; Kozlowski, in preparation). The Port of Anchorage may soon be expanded. Not only are these activities subject to inevitable human error, but they are located along an extremely active volcanic and seismic area. Earthquakes, volcanoes, and tsunamis (see the *Physical Hazards* section under *Threats to Water Resources* for more information) may destabilize any of these petroleum-related infrastructure and cause massive spills. It is important to note that most of these oil development activities occur upstream of LACL, and the predominant currents transport marine waters out of Cook Inlet along the western boundary, immediately along the LACL coastline (Figure 40). Therefore, an oil spill in upper Cook Inlet, where most oil development and activities are located, would likely have large impacts in LACL.

Geographic response strategies: Geographic Response Strategies (GRS) are developed for coastal areas of LACL (Figure 41). These spill response plans are tailored by a workgroup made up of local, state, and federal agencies (including NPS), spill response experts, oil spill contingency plan holders, and the Cook Inlet and Prince William Sound Citizens advisory councils. The GRSs are map-based strategies that locate sensitive areas where oil spill responders should prioritize their efforts following a spill. GRS locations in LACL are shown as sites CCI10-CCI13 (West Glacier Creek, Crescent River, Tuxedni River, and Polly Creek) in Figure 41and were selected based on their levels of environmental sensitivity, risk of being impacted from a water borne spill, and feasibility of successfully protecting the site with existing

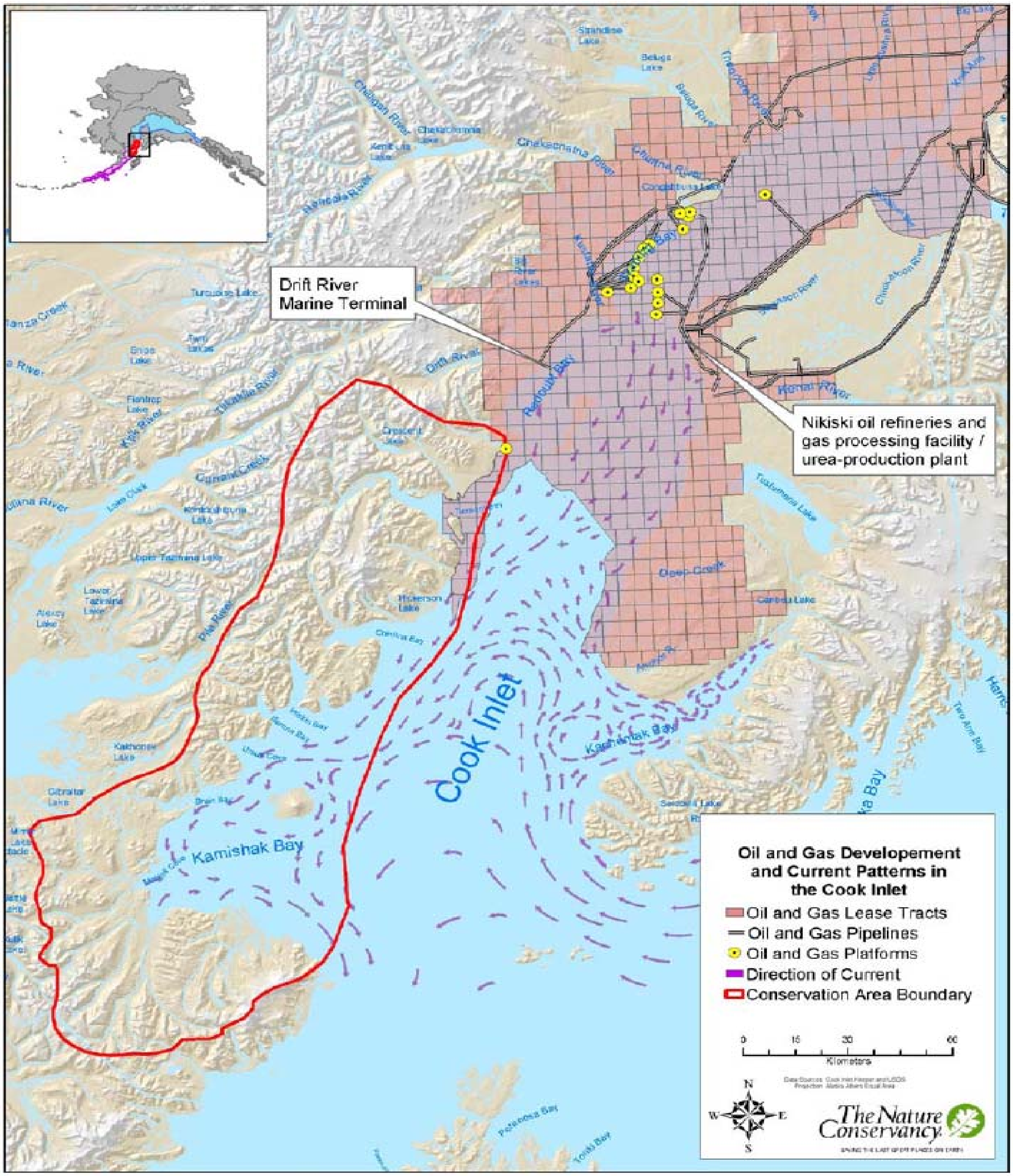


Figure 39. Oil and gas development and current patterns in Cook Inlet, Alaska. Red line indicates Nature Conservancy conservation area which encompasses coastal region of LACL (Witten, 2003).

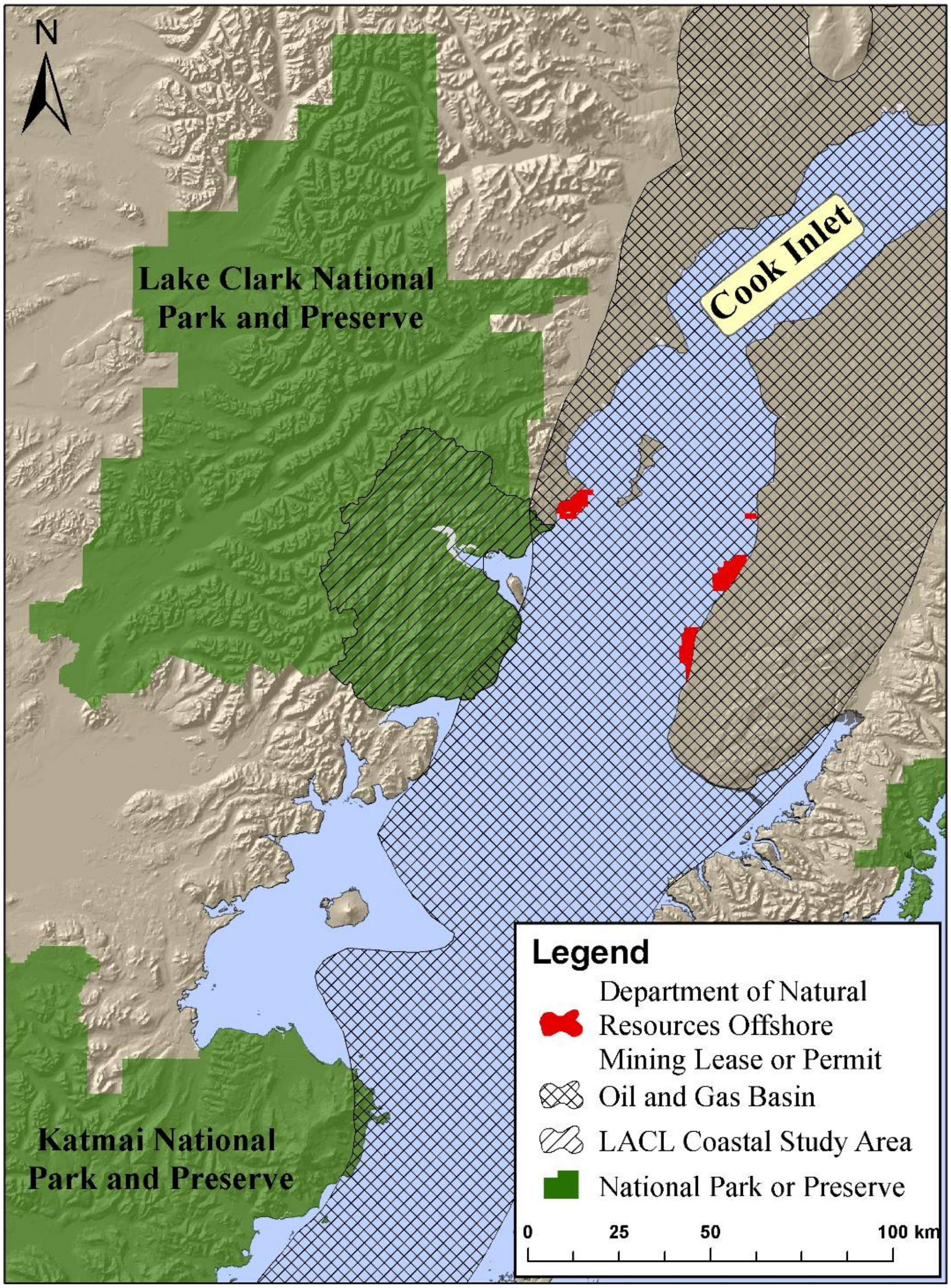


Figure 40. Locations of offshore mining permits and leases in the Cook Inlet area adjacent to the LACL coastal watershed study area.

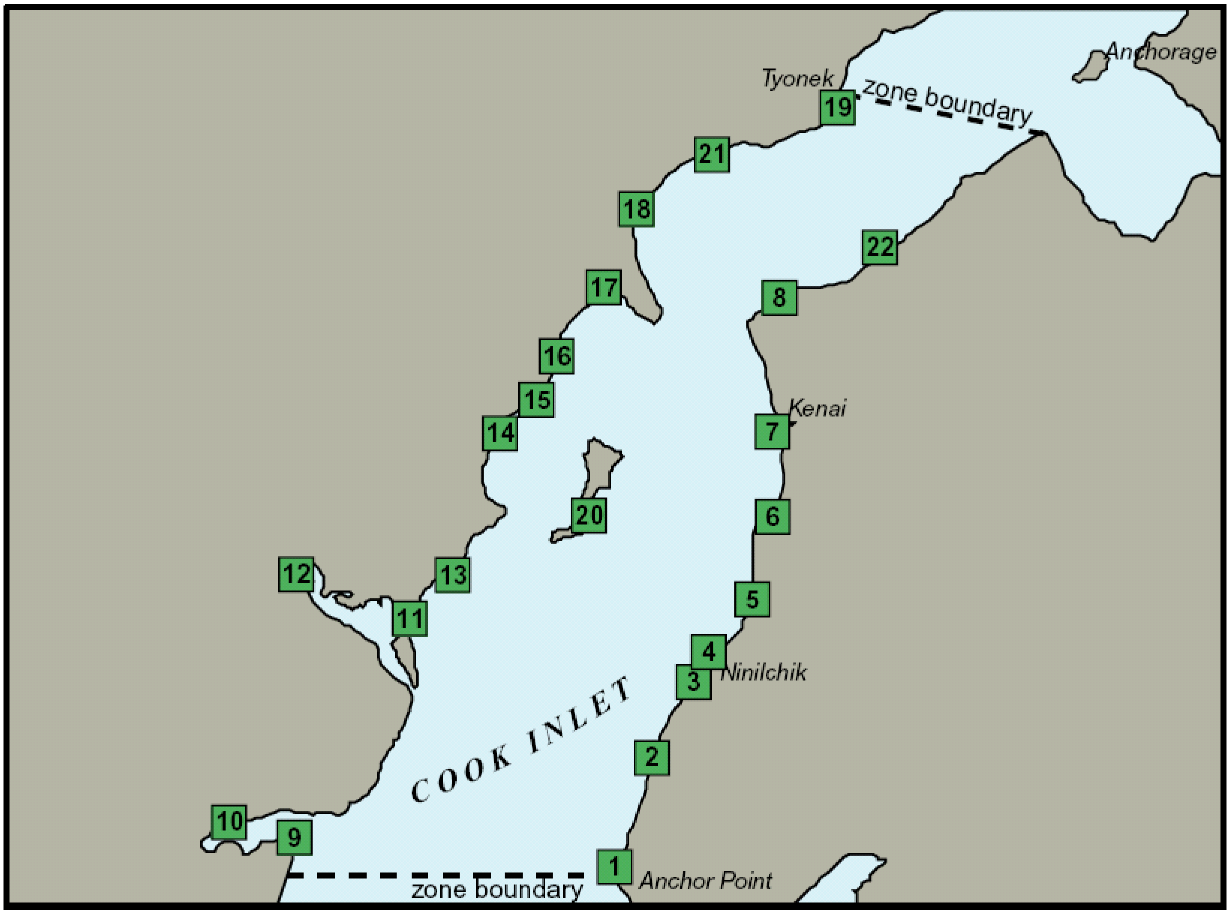
Table 15. Oil and gas facilities in the Cook Inlet Region (Tetra Tech, 2006). Note that Chevron now owns facilities operated previously by Unocal and Baker and Dillon are no longer in service.

Facility Name	Operator	Facility Type	Latitude/ Longitude	Distance to Shore (km/st.mi)[d]	Water Depth (meters MLLW)	Number of Oil Service Wells	Number of Gas Wells	Oil Production (bpd)	Gas Production (1,000xCFD)	Mud and Cuttings (bbl/well)	Produced Water (bbl/day)		Produced Water Discharge Location
											Peak	Avg.	
Anna	Unocal	Production Platform	60°51'37"N 151°18'46"W	4.0/2.5	23	20 oil, 8 injection	0	2,700	210	15,000	2000	1500	Platform
Baker	Unocal	Production Platform	60°49'45"N 151°29'01"W	12.1/7.5	31	11 oil, 4 service	1	1,000	280	26,000	55	30	Platform
Bruce	Unocal	Production Platform	60°59'46"N 150°17'52"W	2.4/1.5	19	11 oil, 8 injection	0	600	370	15,000	700	160	Platform
Dillon[a]	Unocal	Production Platform	60°44'08"N 151°31'45"W	6.0/3.7	28	10 oil, 3 service	0	400	150	27,000	3000	2650	Platform
NCIU Tyonek "A"	Phillips	Production Platform	61°04'36"N 151°56'54"W	8.9/5.5	21	0	12	0	165,000	NA	185	170	Platform
SWEPI "A"	Shell Western	Production Platform	60°47'45"N 151°29'44"W	9.5/5.9	30	16	1	3,100	1,000	NA	2700	1700	E. Foreland Facility
SWEPI "C"	Shell Western	Production Platform	60°45'50"N 151°30'08"W	7.1/4.4	21	15	0	3,000	1,000	11,600	2000	1000	E. Foreland Facility
Granite Point	Unocal	Production Platform	60°57'30"N 151°19'53"W	5.8/3.6	23	11 oil, 6 water injection	0	2,600	1,000	26,500	1000	300	Granite Pt. Facility
Spark[b]	Marathon	Production Platform	60°55'42"N 151°31'50"W	2.9/1.8	18	4 with 1 shut-in	0	300	NA	NA	5000	3900	Granite Pt. Facility
Spurr[c]	Marathon	Production Platform	60°55'10"N 151°33'26"W	2.6/1.6	20	5, with 1 shut-in	1 shut-in	300	NA	NA	500	200	Granite Pt. Facility
Grayling	Unocal	Production Platform	60°50'13"N 151°36'47"W	5.8/3.6	41	24 oil, 10 service, 1 abandoned	2	6,800	9,200	20,000	39000	37000	Trading Bay Facility
Dolly Varden	Unocal	Production Platform	60°48'28"N 151°37'58"W	6.4/4.0	34	24	1, with 1 shut-in	6,700	Platform use only	13,500	33800	31300	Trading Bay Facility
King Salmon	Unocal	Production Platform	60°51'54"N 151°36'18"W	3.9/2.4	24 (MSL)	19	1	5,000	6,000	15,000	42000	40300	Trading Bay Facility
Monopod	Unocal	Production Platform	60°53'49"N 151°34'44"W	2.4/1.5	19	29 oil, 2 service	0	2,800	2,500	5,800	6,000	4800	Trading Bay Facility
Steelhead	Unocal	Production Platform	60°40'54"N 151°36'08"W	7.1/4.4	56	3	11	2,000	165,000	13,500	1000	800	Trading Bay Facility
Osprey	Forest Oil	Production Platform	60°41'46"N 151°40'10"W	2.9/1.8	14	In development	In development	In development	In development	In development[g]	In dev.	In dev.	To be Reinjected
Granite Point[c]	Unocal	Onshore Separation	60°01'14"N 151°25'14"W	3.1/1.9[e]	14[f]	NA	NA	NA	NA	NA	5200	4400	Spark Platform
Trading Bay	Unocal	Onshore Separation	60°49'05"N 151°46'59"W	3.1/1.9[e]	11[f]	NA	NA	NA	NA	NA	1.2E5	1.15E5	Outfall
East Forelands	Shell Western	Onshore Separation	60°44'09"N 151°21'13"W	0.24/0.15[e]	11[f]	NA	NA	NA	NA	NA	5000	3100	Outfall

Source: MMS (2002).

[a] Shut down June 1992 (MMS 2003).
[b] Shut down January 1992 (MMS 2003).
[c] Shut down May 1992 (MMS 2003).
[d] Distance from nearest shore measured from low water mark in kilometers/statute miles.
Notes: bpd (barrels per day); CFD (Cubic feet per day); bbl (barrels)

[e] Distance of discharge point from shore
[f] Water depth at location of discharge outfall.
[g] Muds and cuttings to be injected into underlying formation.



Central Cook Inlet
Geographic Response Strategies

CCI-01 – Anchor River	CCI-12 – Tuxedni River
CCI-02 – Stariski Creek	CCI-13 – Polly Creek
CCI-03 – Deep Creek	CCI-14 – Little Jack Slough
CCI-04 – Ninilchik River	CCI-15 – Drift River
CCI-05 – Clam Gulch	CCI-16 – Big River
CCI-06 – Kasilof River	CCI-17 – Kustatan River
CCI-07 – Kenai River	CCI-18 – McArthur River
CCI-08 – East Foreland	CCI-19 – Chuitna River
CCI-09 – Gull Island	CCI-20 – Swamp Creek
CCI-10 – West Glacier Creek	CCI-21 – Middle River
CCI-11 – Crescent River	CCI-22 – Swanson River

version: December 2001

Figure 41. Geographic Response Strategies for Central Cook Inlet, including the LACL coast. Source: ADEC, 2008 at http://www.dec.state.ak.us/spar/perp/grs/ci/cic/home.htm

technology (Table 16). More specific information on each site is available at http://www.dec.state.ak.us/spar/perp/grs/ci/cic/home.htm, including site access, staging area, response resources, and special considerations.

Discharges from oil production facilities: Although the Clean Water Act prohibits discharges from oil production facilities, in Cook Inlet these facilities are exempt from this requirement (Figure 42). The following discharges are allowed under NPDES permit number AKG-31-5000 (Tetra Tech, 2006). As the oil production facilities are all upstream of LACL, these wastes may impact LACL water quality and resources.

- Produced water
- Drilling fluids and drill cuttings
- Deck drainage
- Sanitary wastes
- Domestic wastes
- Desalination unit wastes
- Blowout preventer fluid
- Boiler blowdown
- Fire control system test water
- Non-contact cooling water
- Uncontaminated ballast water
- Bilge water
- Excess cement slurry
- Mud, cuttings, cement at seafloor
- Completion fluids
- Workover fluids
- Test fluids
- Storm water runoff from onshore facilities
- Waterflooding discharges
- Well treatment fluids

Potential threats to water resources by Drift River oil storage facility

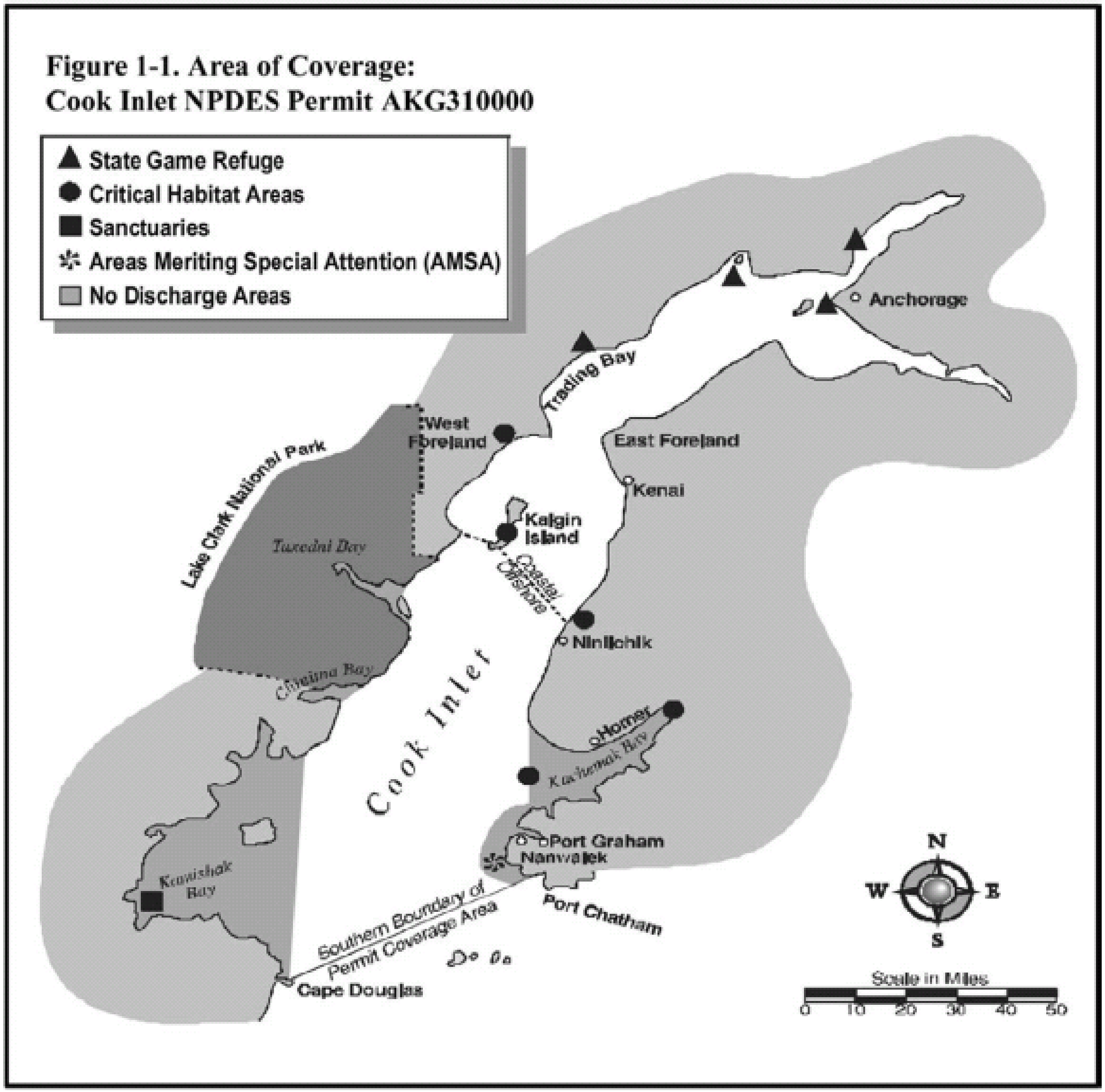
The Drift River oil storage terminal is located along the banks of the Drift River, near its mouth to Cook Inlet. The facility temporarily stores oil from approximately ten oil platforms in Cook Inlet before being pumped into tankers offshore, and it has a storage capacity of up to 1.9 million barrels (Dorava and Meyer, 1994). The facility, owned by Cook Inlet Pipeline Company, consists of seven above-ground storage tanks (270,000 barrels each), pipeline pumps and piping systems, a ballast water treatment system, office, an industrial maintenance building, housing, an airstrip, a hangar, and an offshore loading platform (USEPA, 2005). Although the storage terminal is outside of the LACL coastal study area, its presence is a major issue for the LACL coastline due to the risk of oil spills from the potential damage or destruction of the facility from seismic activity upstream the Drift River at Redoubt Volcano.

Table 16. Site selection criteria for GRS sites in the Central Cook Inlet region that encompass LACL. See Table 17 for legend. Source ADEC, 2008 at http://www.dec.state.ak.us/spar/perp/grs/ci/cic/home.htm

Location	Lat. N	Lon. W	Marine Mammals	Anadromous Fish	Eagle Nests	Sea Otters	Intertidal Spawning	Herring Spawning	Subsistence	Cultural Resources	Sea Birds	Waterfowl and Shore Birds	High Recreational Use	Commercial Fishing	Land Mgt. Special Designations	Coastal Habitat
East Side																
Anchor River	59° 47	151° 52		X	N				F	I	F		X		SCH	M
Stariski Creek	59° 52	151° 48		X	N					S		C	X			M
Deep Creek	60° 02	151° 42		X	N					S	F		X			M
Ninilchik River	60° 03	151° 40		X	N		S			S	F		X			M
Clam Gulch	60° 14	151° 24			N					S			X		SCH	
Kasilof River	60° 24	151° 19		>60K	N		S		F	I		C	X			M
Kenai River	60° 33	151° 16	B, S>10	>60K	N		S		F	S		C				M
East Forelands	60° 44	151° 25			N					S		*				
Nikiski Bay	60° 45	151° 19	B		N							*				
Bishop Creek	60° 46	151° 04		X	N							C				M
Swanson River	60° 48	151° 01		X	N		S			I		C	X		SP	M
Leaf Creek	60° 50	150° 55			N											
Otter Creek	60° 52	151° 52		X	N							C				M
Moose Point	60° 57	150 °41	B		N											M
Nearshore, Tidalflats and Beaches; Anchor Point to Possession Point														X		
West Side																
Gull Island	59° 50	152° 59	S>10			X				S	N				WF	
Chinitna Bay	59° 51	152° 60	B, S		N	X	S	S				C				M, STF
Fitz Creek	59° 48	153° 09		X		X										M, STF
West Glacier Creek	59° 51	153° 12		X	N	X	S			S		C				M, STF
Middle Glacier Creek	59° 52	153° 09				X						C				M, STF
East Glacier Creek	59° 53	152° 54		X		X										
Shelter Creek	59° 53	152° 48		X	N	X										M
Red River	59° 56	152° 42				X										M
Johnson River	60° 01	152° 42		X	N	X										M, STF
Chisik Island	60° 08	152° 35				X					N				MR	STF
Tuxedni Bay	60° 12	152° 43	B, S>10				S	S				C			NP/WA	M, STF, SRS
Crescent River	60° 13	152° 34	B, S	>60K	N		S		I	S		*			NP	M
Tuxedni River	60° 15	152° 54	S>10	X	N		S			M		C			NP	M, STF, SRS
Polly Creek	60° 17	152° 27		X			S		I	I		*	X	X	NP	M
Harriet Point	60° 24	152° 15	S						I, M			*				
Redoubt Bay	60° 29	152° 14	B		N							C			SCH	M, STF
Little Jack Slough	60° 32	152° 16	S>10	X	N				I, M	S		C			NP	M
Drift River	60° 36	152° 07	B	X	N				I, M	S		C			SCH	M, STF
Seal River	60° 39	152° 03		X	N				M			C			SCH	M, STF
Big River	60° 40	152° 02	B, S>10	X			S		M	S		C			SCH	M, STF

Table 17. Key for symbols used in Table 16. Source ADEC, 2008 at http://www.dec.state.ak.us/spar/perp/grs/ci/cic/home.htm.

Marine Mammals	Anadromous Fish	Eagle Nests	Sea Otters	Intertidal Spawning	Herring Spawning	Subsistence	Cultural Resources	Sea Birds	Waterfowl and Shore Birds	High Recreational Use	Commercial Fishing	Land Mgt. Special Designations	Coastal Habitat
S = Seal	> 50 K = more than 50,000 Spawners	N = Nest Present, Agency Verification	X = May be Present	S = Spawning	S = Spawning	F = Fishing	S = Standard (REPORT any cultural resources found during operations to the FOSC Historic Properties Specialist.)	F = Feeding Areas	C = Seasonal Concentrations	X = Heavy Recreational Use Occurs	X = Commercial Fishing Occurs	SCH = State Critical Habitat	M = Marsh
B = Beluga	X = Listed in Anadromous Catalog	n = Nest Present, Local Knowledge				B = Birds	I = Inspection (FOSC Historic Properties Specialist should INSPECT site prior to operations.)	N = Nesting Areas	* = Spring Onshore			MR = Maritime Reserve	STF = Sheltered Tidal Flats
S>10 = Seals more than 10 Individuals						I = Intertidal	M = Monitor (FOSC Historic Properties Specialist should MONITOR on-site operations)					NP = National Park	SRS = Sheltered Rocky Shoreline
SL = Sea Lions						M = Marine Mammals						WA = Wilderness Area	
						O = Otters						GR = Game Refuge	
												SP = State Park	
												SRA = State Recreation Area	
												AMSA = Areas Meriting Special Attention	
												WSR = Wild and Scenic Rivers	
												WF = Wildlife Refuge	
												ANCSA = ANSCA Conveyed Lands	
												CT = conveyed Tidelands	
												TL = Tideland Leases, Permits and Right-of-Ways	
NMFS, ADF&G	ADF&G	FWS, ADF&G	USFWS	ADF&G	ADF&G	ADF&G	ADNR	UFWS, ADF&G	UFWS, ADF&G	ADNR	ADF&G	ADNR, NPS, ADF&G, Municipalities, Tribal Organizations	NOAA



(Source: USEPA 2004)

Figure 42. Boundary delineating area within Cook Inlet in which NPDES permit allows discharge of oil production wastes (Tetra Tech, 2006).

Redoubt Volcano stands at 3100 m (10,197 ft), is glacier-covered, and has been active numerous times in the past century and beyond (most recently in 1881, 1902, 1933, 1966, and 1989). The 1966 and 1989 eruptions were major eruptions that were well studied and generated massive floods and volcanic mud/debris flows (lahars) that surged down the Drift River. The Alaska Volcano Observatory (AVO) maintains records and continues to monitor activity on Redoubt and other Alaska Range-Aleutian arc volcanoes in Alaska. The reader is referred to the AVO website for more detailed information on the eruptive history of Redoubt Volcano. (Over 500 sources of information on volcanic activity on Redoubt Volcano are listed at http://www.avo.alaska.edu/volcanoes/volcbib.php?volcname=Redoubt.)

Although the 1966 eruptions predated the infrastructure at the Drift River oil storage facility, explosive activity continued through April 1968. Nonetheless, the Drift River Oil facility was constructed in 1967, even though the fresh debris flows in January 1966 pointed to the destructive potential of the flooding Drift River. An estimated 60 million cubic meters of ice were “blasted, melted, scoured, or washed away by the cumulative events of 1966-68” (Sturm et al., 1986). As snow, slush, ice, and rock debris avalanches were released off the Drift Glacier and entrained in the flows, flow volumes increased further downstream by incorporation of seasonal snowpack on the lower glacier surfaces and in the flooded river valley (Trabant and Meyer, 1992b). Discharge in the Drift River 22 km from the vent was estimated to reach 20,500 m^3/s (720,000 cfs) (Trabant and Brabets, 1990). A group of 22 seismologists working along the lower Drift River at the time of the eruption in January 1966, reported that following the initial eruption, the ice-bound river broke up suddenly, raising the water level 1 to 1.2 m (3.2 to 4 feet) in only 15 minutes (Unknown, 1966). Follow-up studies on the recovery of the Drift Glacier noted that the glacier’s regrowth following the eruption had the potential to dam the Drift River, forming a glacier-dammed lake that would be unstable and cause sudden flooding if it were to break loose, posing another obvious hazard to the tanker terminal downstream (Strum et al., 1983; Trabant and Brabets, 1990).

During the most recent major eruption series, between mid-December 1989 and April 1990, Redoubt Volcano underwent approximately twenty volcanic explosive events, scouring and rapidly melting snow and glacier ice and triggering at least 14 debris flows and floods in the Drift River, which by then hosted the Drift River oil storage facility along its banks (Janda et al., 1990; Figure 43). In addition to sudden melting of snow and ice, the growth and subsequent collapse of lava domes on Redoubt added to the generation of the lahars, some of which swept all the way (22 miles/ 35km) to Cook Inlet (Dorava and Meyer, 1994). The first debris flow, generated December 15, 1989, entrained ice blocks up to 10 m (33 ft) across and crested approximately 8 m (26 ft) above the Drift river channel at the oil storage facility (Waitt et al., 1994). The largest debris flow (occurring on January 2, 1990) mobilized an estimated 70 million m^3 of sediment, including lithic blocks as much as 3 m in diameter, in a flow which peaked at an astounding 30,000 m^3/s (1,060,000 cfs) and filled the 2 km-wide valley “wall to wall” (Janda et al., 1990; Major and Janda, 1990). This flow resulted in flooding of up to 75 cm in some buildings in the oil storage facility, causing a temporary closure of operations (Casadevall, 1994). The massive floods reworked primary volcanogenic sediments, leading to more instability that continued to threaten the integrity of the Drift River oil storage facility after the conclusion of the eruptive events (Major and Janda, 1990; Figure 44).

As part of the USGS’s Volcano Hazards Program, scientists installed newly developed acoustic flow sensors in multiple locations along the Drift River valley during the final month of volcanic activity (April 1990). Using these instruments, the scientists were able to successfully detect and track the movement of lahars moving downstream in real time. Although such technology is helpful in terms of providing warning to the oil storage facility (Dorava and Meyer, 1994), they do not protect the oil transfer facility from sudden lahar surges.

Not only is the Drift River oil facility a danger to the LACL coastline due to potential flooding and debris flows from the Redoubt Volcano, but it also has a history of being investigated for contamination by petroleum-related chemicals. Although the contamination was determined

Figure 43. The oil storage tanks of the Drift River oil storage facility located along the banks of the Drift River. Photograph by J. Major in 1990 (USGS Volcano Hazards Program, http://volcanoes.usgs.gov/Imgs/Jpg/Redoubt/30210600_023_large.jpg)

Figure 44. Eruption on Redoubt Volcano. Photograph by R.J. Clucas on April 21, 1990. Photograph taken from the USGS Volcanoes Hazards Program website at http://volcanoes.usgs.gov/About/What/Monitor/Hydrologic/AFMRedoubt.html

to be of relatively minor scale with no recommended corrective action at two sites, one site did require remedial action (USEPA, 2005). At a former burn pit at the site, elevated concentrations of benzene and diesel range organic compounds were found in soil and groundwater that required corrective action. Remedial action included a combination of excavation of impacted soils and bioremediation, and the USEPA stated that no further action is currently necessary to address those environmental impacts (USEPA, 2005). While that contamination issue has been resolved, future contamination risk will be present as long as the facility exists.

Marine vessel impacts: The effects of marine vessels to water quality along coastal LACL are most likely temporary and limited to the immediate area of vessel traffic. Snug Harbor is the only good harbor within the coastal region of LACL, and therefore, vessel traffic is highly limited (Colleen Matt, NPS-Port Alsworth, personal communication, 2005). Cruise ship traffic along the coast is minimal in comparison to the large cruise ships that travel in southeast Alaska and up to the Kenai area, and most tourists arrive by air transport. No analyses of marine vessel impacts have been conducted for the LACL coast, but based on an NPS study in Glacier Bay National Park in Preserve in southeast Alaska, marine vessels have the potential to degrade water quality by the accidental release of petroleum products, the release of wastewater or other discharges, or by resuspension of sediments. Wastewater generated by marine vessels that may serve as a source of marine pollution includes graywater (laundry, shower, and galley sink wastes), blackwater (treated sewage), hazardous waste, solid waste and marine debris (NPS, 2003). Private vessels may not be able to treat their wastewater before it is discharged; however, NPS (2003b) reports that because of the small volumes and large dilution factor, the effects of this wastewater would not be significant. An Alaska Department of Environmental Conservation report on the impact of marine vessels on Alaska water quality reports that dilution levels for small marine vessels that treat and continuously discharge their wastewater are extremely high, and the only contaminant likely to be measured above ambient water levels would be fecal coliform bacteria (ADEC, 2002). Another potential pollution source from vessels is solid waste, including food waste, plastic and glass containers, and paper products; however, plastics and any garbage except dishwater, graywater, and fresh fish parts may not be legally dumped within 5 km (3 mi) of the coast. Finally, vessels can affect water quality by resuspending sediments in marine waters through vessel movement, interfering with filter feeding organisms and decreasing water quality by reducing light penetration. The amount of sediment resuspension depends on the speed and size of the vessel, the sediment size, and the stability of the water column (NPS, 2003).

Marine-derived biologic sources of pollutants: The benefits incurred by the contributions of salmon carcasses to the nutrient levels in aquatic systems (see the *Freshwater biological resources, Fishes* section under *Park Description, Biological Resources*) may be partially offset by another contribution by the salmon: marine derived contaminants such as Hg and persistent organic pollutants (POPs). Mercury, a strongly toxic heavy metal, is emitted primarily by fossil fuel burning (Pacyna and Pacyna, 2002). POPs comprise a long list of highly toxic and very stable organic compounds such as polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), dioxins, furans, and chlordane that are used as pesticides, industrial chemicals and industrial waste products (EPA, 2002). As salmon develop their biomass (95% in the pelagic environment), they incorporate marine contaminants such as the Hg and POPs and transport them into watersheds where they spawn (Ewald et al., 1998; Krümmel et al., 2003; Senkowsky, 2004; Zhang et al., 2001).

Krümmel et al. (2003) report strong correlations between the density of salmon runs with PCB concentrations in lake sediments in southwestern Alaska. Eight lakes in the Alaska Peninsula and on Kodiak Island were studied; one of the lakes (Lake Iliamna) is directly southwest of LACL (approximately 15 miles from the coastal study area boundary) and two of the lakes, Becharof and Ugashik Lakes, are approximately 265 and 300 km (165 and 188 mi), respectively, southwest of LACL (Figure 45).The researchers found that the input of PCBs by spawning salmon can result in a six-fold increase above atmospheric loading in these remote areas with high density salmon returns.

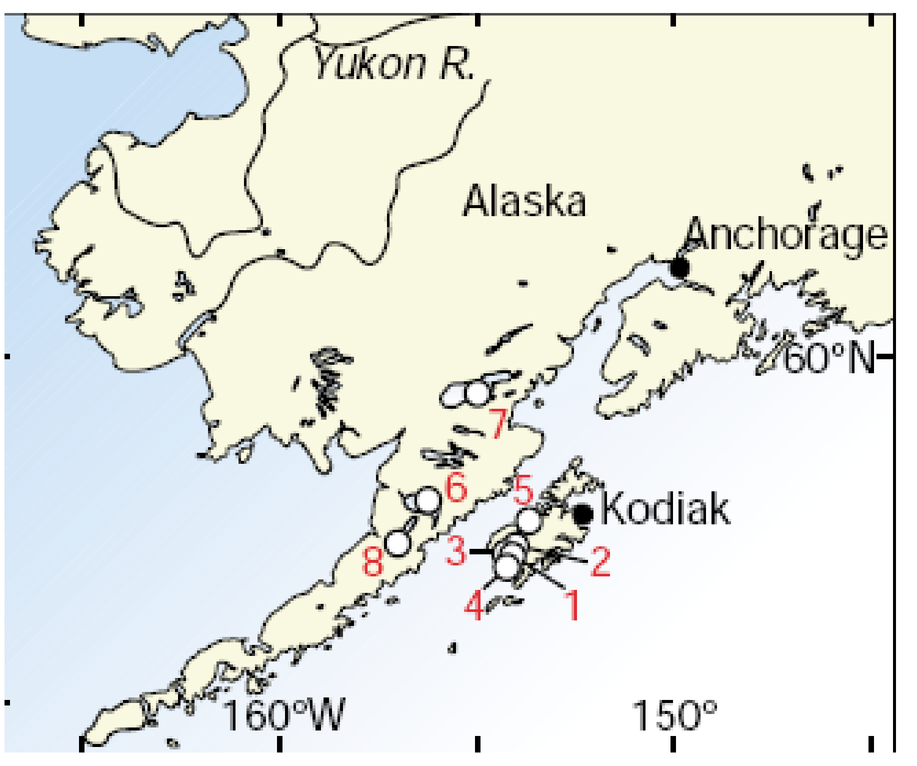


Figure 45. Sample locations of the eight lakes' surface sediments and sockeye salmon were collected for PCBs. Lake 1: Frazer; Lake 2: Karluk; Lake 3: Red; Lake 4: Olga; Lake 5: Spiridon; Lake 6: Becharof; Lake 7: Iliamna; Lake 8: Ugashik (Krümmel et al., 2003).

There is little published information on the direct contribution by spawning salmon to the Hg concentrations in streams, but a study of Bering Sea salmon returning to spawn in the Bristol Bay watersheds of southwestern Alaska (Kvichak, Naknek, Egegik, Ugashik, Wood, Igushik, Nushagak, and Togiak Rivers- ca. 140 – 320 km [90 - 200 mi] from LACL) showed that salmon may be major transporters of marine-derived Hg into freshwater environments (Zhang et al., 2001). This research combined analyses of methylmercury concentrations in Bristol Bay salmon tissues with escapement data (ADF&G, 1999) to conclude that biotransport of methylmercury by the salmon may have accounted for as much as 21 kg (46 lb) of methylmercury transported into eight Bristol Bay watersheds over the past 20 years. Another study more directly tested the effect of salmon carcasses on stream Hg concentrations in several tributary streams of Lake Ontario (Sarica et al., 2004). Comparing stream segments with variable salmon carcass densities, these researchers detected significantly higher concentrations of nutrients, total aqueous Hg and methylmercury, particulate Hg, and Hg in terrestrial invertebrates along stream segments with high salmon carcass densities compared to areas with low salmon carcass densities.

The available data indicate a strong likelihood that salmon are an important— and possibly the dominant—contributor to both the POPs and Hg budgets in streams where they spawn in areas such as LACL in southwest Alaska. These contaminants are not only released into the waters where they spawn, but they can enter the food chain. For example, a study on grizzly bears in British Columbia, Canada, found that salmon delivered 70% of the organochlorine pesticides, up to 85% of the lower brominated PBDE congeners, and 90% of PCBs measured in salmon-eating grizzly bears. These pollutant levels in the salmon-eating bears were significantly higher than in their vegetarian counterparts in inland areas (Christensen et al., 2005).

Atmospheric sources of pollution

Mercury and POPs are the two major subjects of concern for much of Alaska in terms of atmospheric contaminants, as well. They are global pollutants, crossing international borders and reaching remote areas that should otherwise be pristine (Nriagu and Pacyna, 1988; Fitzgerald et al., 1998; AMAP, 2004). Anthropogenic mercury deposition to Alaska appears to be similar in magnitude to that in temperate latitudes (Fitzgerald et al., 2005). Hg and most POPs are carried to Alaska via long-range atmospheric pathways (Strand and Hov, 1996; Wania and Mackay, 1996; Schroeder and Munthe, 1998), and upon deposition can biomagnify as they pass up trophic levels (EPA, 2002). Mercury and POPs in northern latitudes show significant concentration increases over the last few decades, and these trends are reflected in the extraordinarily high concentrations of some of these chemicals in the bodies of otters, whales, seals, bears, eagles, and indigenous peoples who rely on subsistence harvests (AMAP, 2004). Few studies on contaminants in southwest Alaska exist; however, the evidence available indicates that the region is accumulating many potentially toxic chemicals imported atmospherically from afar.

Although there are no significant industrial sources of mercury (Hg) in southwest Alaska, Hg deposition to Alaska as well as to virtually all remote places on the planet has at least doubled since pre-industrial times (Engstrom and Swain, 1997; Fitzgerald et al., 1998). Mercury deposition (through dry or wet processes) is particularly favored in high altitude and high latitude regions due to cold condensation mechanisms (Fitzgerald et al., 1998; Schindler, 1999; Lindberg et al., 2002). Mercury and POPs have not been studied in coastal LACL specifically, but several studies in southern coastal Alaska indicate the region is being impacted by these contaminants.

Part of the 1998-2001 NAWQA study of the Cook Inlet Basin included an evaluation of Hg concentrations in streambed sediments, fish tissues, and water in five watersheds as part of a national pilot study of Hg distribution (Frenzel, 2000). The researchers report that the Deshka River, a remote, undeveloped basin in the upper Cook Inlet Basin about 120 km (75 mi) from LACL had some of the highest streambed sediment methylmercury concentrations found, not only in Alaska, but nationally. It also had one of the greatest percentages of wetlands in its drainage. Studies elsewhere have shown that the percentage of the landscape covered by organic matter-rich wetlands (where mercury-methylating bacteria thrive) is positively correlated with both the methylmercury concentrations in outflowing streams and the methylmercury accumulation in fish (St.Louis et al., 1994; Hurley et al., 1995; St.Louis et al., 1996; Brumbaugh et al., 2000). The presence of wetlands in coastal LACL (see the *Snow, ice, and glaciers* section under *Park Description, Hydrologic Information*) increases the likelihood that methylmercury concentrations in the region may be of concern; however, there are no known data investigating this potential problem.

Another study examined contaminants in sea bird eggs and showed that concentrations of POPs in common murre eggs from two islands in the Gulf of Alaska (including East Amatuli Island, only 112 km [70 mi] from LACL coast) were significantly higher than in eggs from three colonies in the Bering Sea (Kucklick et al., 2002; Vander Pol et al., 2004). Mercury was also evaluated in the seabird egg studies (Day et al., 2006), which indicated that mercury pollution may also be more of a concern in Gulf of Alaska compared to the Bering Sea region (Figure 46). The highest mean concentrations of mercury in murre eggs were from St Lazaria Island in southeast Alaska and East Amatuli Island near LACL. These had the highest individual sample concentration (Figure 47; Day et al., 2006). The authors of these studies speculate that higher mercury concentrations in the Gulf of Alaska sites may be due to the relatively warm temperatures, abundance of organic matter in forested areas and wetlands in southern Alaska, and presence of estuaries—all factors that stimulate mercury methylation processes—as well as strong freshwater discharge and high erosion rates.

The SWAN I&M program is currently conducting analyses of total Hg in sediment samples from the following SWAN lakes: Lake Clark, Naknek, Brooks, Kontrashibuna, and Idavain (Munk et al., 2008). The age-dated cores are expected to produce multi-decadal profiles tracking Hg accumulation over time in the lakes. Results from the study will be comparable to two published studies of dated sediment cores collected in southeast Alaska—from lakes in Glacier Bay National Park (GLBA) and in neighboring Chichagof Island—which show that Hg accumulation rates through the 1980s in sediments are two to three times preindustrial accumulation rates (Engstrom and Swain, 1997; Fitzgerald et al., 2006). Additionally, Hg deposition in GLBA did not show the recent declines (since the1960s) observed at sites in the continental U.S. where regional mercury emissions have been reduced. An updated study of mercury accumulation in sediment cores through the 1990s and into the 2000s, which shows that mercury deposition continues to be on the rise in Alaska, is expected to be published in 2008 (Dan Engstrom, St. Croix Watershed Research Station, Minnesota, personal communication, 2007). These results suggest that southern Alaska is being affected by mercury emissions from remote sources (e.g. in Asia), which are steadily increasing their output (Pacyna and Pacyna, 2002).

The NPS Air Resources Division, in cooperation with the EPA, USGS, U.S. Forest Service, and several universities, has recently begun to address the issue of global pollutants through a project called the Western Airborne Contaminants Assessment Project (WACAP) that aims to characterize the extent of airborne pollution to remote NPS units in the western U.S. and Alaska (NPS, 2005). Snow, fish tissue, water, lake sediment, lichen, vegetation, and subsistence native foods were collected by WACAP at eight NPS units, including three in Alaska: Denali National Park and Preserve; Gates of the Arctic National Park and Preserve; and Noatak National Preserve. Samples were analyzed for a group of semi-volatile organic compounds, which include a variety of POPs, and mercury and other trace metals (but not all sample media received full analyses). Information from the 3 NPS units elsewhere in the state provide important indications of the extent and magnitude of the contaminants' threats to park ecosystems. Results of the WACAP study showed that contaminants were found in all park units studied (Landers et al., 2008). In the Alaska park units, very low concentrations of most current-use chemicals were found; however, the occurrence of historic-use compounds in Alaska matching levels found in the lower 48 further suggests that Alaska is being impacted by atmospheric transport from global sources (Landers et al., 2008).

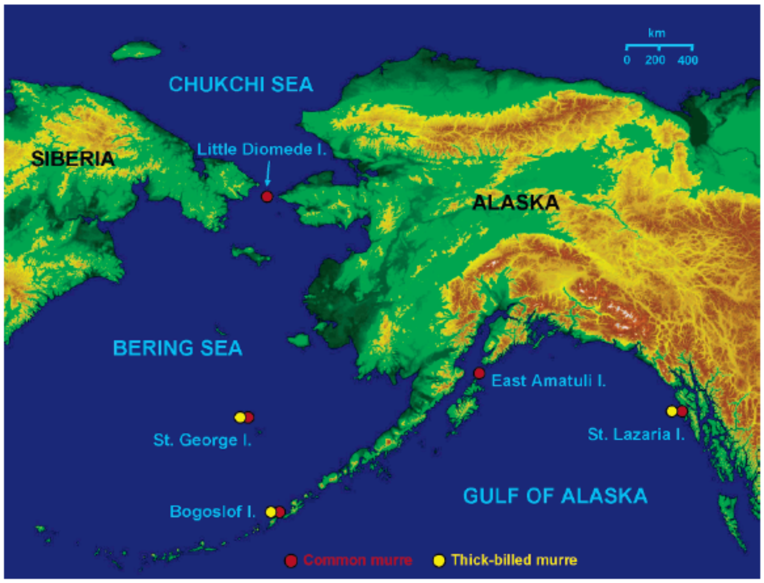


Figure 46. Map of the study area for Day et al.'s (2006) research on Hg (Munk et al., 2008) in eggs from five murre (Uria spp.) colonies.

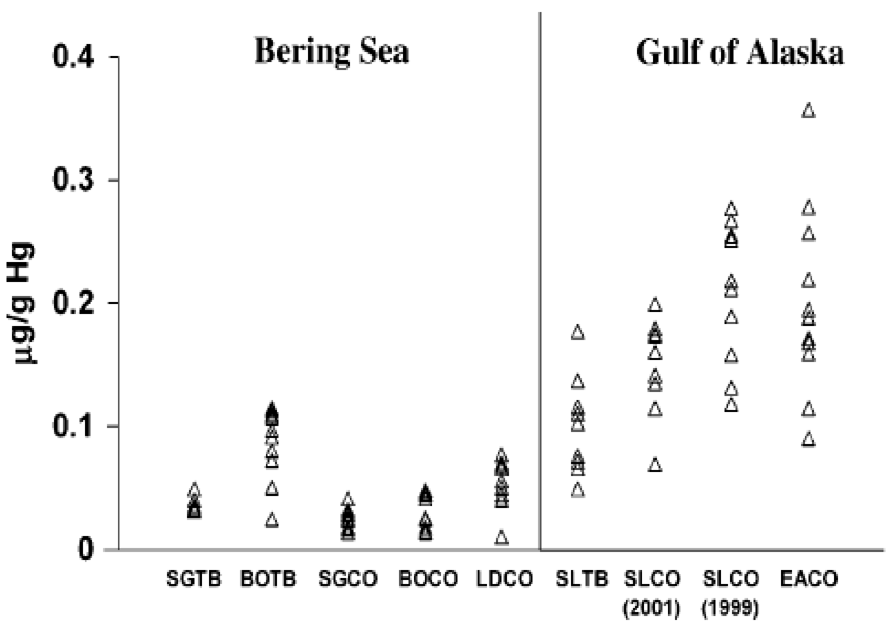


Figure 47. Total Hg concentrations (wet mass) for murre eggs for each collection event in the Day et al. (2006) study. The first two letters of the four letter code indicate location (BO= Bogoslof, LD= Little Diomede, SG= St. George, EA= East Amatuli, SL= St. Lazaria), and the second two letters indicate species (CO= common murre, TB= thick-billed murre).

In DENA, the park closest to LACL, notable findings include (Landers et al., 2008):

1. Median mercury concentrations in both lakes (Wonder and McLeod Lakes) sampled exceeded contaminant health thresholds for piscivorous birds (kingfishers), and one lake (Wonder Lake) also exceeded the thresholds for mammals (otter and mink).

2. For current-use SOCs, median dieldrin concentrations in Wonder Lake fish and in some individual fish in McLeod Lake exceeded contaminant health thresholds for subsistence fishers.

3. Primary contaminants detected in air were historic-use pesticides (HCB and a-HCH).

4. In snow, contaminant deposition was among the lowest in all the parks.

5. In vegetation, DENA had the lowest concentrations of SOCs, nutrients, metals, and mercury among the parks, after NOAT and GAAR.

6. In sediments, most SOCs were below detection in DENA lakes. PCBs were present but at low concentrations. Wonder Lake showed enrichment of mercury and lead since the 1920s, probably due to rising global emissions.

The full report of the WACAP study is available online at http://www.nature.nps.gov/air/Studies/air_toxics/wacap.cfm.

Contaminant monitoring has begun in the SWAN as part of the SWAN I&M program. In addition to the lake sediment core work mentioned above (Munk et al., 2008), fish were collected for analyses of heavy metals and organics in the drainage of Lake Clark proper (outside, but adjacent to, the coastal study region) in 2005 (Dan Young, NPS-Port Alsworth, personal communication, 2007). The sampling consisted of lake trout (n=9), burbot (n=3), grayling (n=5), and northern pike (n=5), all of which received heavy metals analyses. Due to the high cost of analyses, only the lake trout received both heavy metals and organic pollutant analyses. Northern pike were collected from Chulitna Bay, lake trout and grayling from the outlet of the Kijik River, and burbot from Sucker Bay. Results of the data collection are not expected to become available until further development of database management and reporting that will be part of the monitoring program (Jeff Shearer, NPS-Anchorage, personal communication, 2007). In addition, the network has initiated a small pilot project to collect stair-step moss (*Hylocomium splendens)* in LACL, KEFJ, and ANIA, with the goals of designing a larger project and getting a better baseline of airborne contaminants across the SWAN (Michael Shephard, NPS, personal communication, 2008).

Finally, the state of Alaska Department of Environmental Conservation (DEC) is currently establishing two Mercury Deposition Network stations: in Unalaska and in Kodiak (Heidi Strader, Alaska DEC-Anchorage, personal communication, 2007). The Kodiak site has been running since mid-September 2007, although data are not yet available through the MDN website (http://nadp.sws.uiuc.edu/mdn/). The Unalaska site is expected to initiate monitoring in the very near future. Additionally, the Southeast Alaska Network of the NPS is planning to establish an MDN site in Bartlett Cove, in GLBA, in early 2008. The data generated by these future studies will be instrumental in tracking Hg levels in southern Alaska. To date, wet deposition information is limited to one year of data collected in GLBA by Fitzgerald et al. (2006), who provide preliminary data (published data expected in 2008) on Hg concentrations in precipitation (mean: 2.6 ng Hg/L) and estimated atmospheric wet deposition rates (mean: 4.6 µg m^{-2} y^{-1}).

Climate change

Climate change is increasingly being recognized as an important natural resource issue for national parks in Alaska. For example, a *Backpacker* magazine "Report Card" on climate change threats to national parks ranked two Alaskan parks (Glacier Bay and Wrangell-St. Elias) as among the 15 most threatened in the United States (Spence, 2007). Moreover, recent scientific research suggests that changes in climate may dramatically impact water resources in Alaskan parks (Kyle and Brabets, 2001). On a global scale, mean surface air temperature has risen by about 0.6 ºC (1.1 ºF) in the last century. Recent climate change is dominated by human influences, and there is now a relatively broad scientific consensus that the primary cause of climate change is human-induced changes in atmospheric composition (Karl and Trenberth., 2003). In particular, there have been rapid increases in the concentration of greenhouse gases such as carbon dioxide and methane, which absorb and counter-radiate outgoing terrestrial longwave radiation. Over the last fifty years, there is evidence of anthropogenic warming on every continent except Antarctica (Figure 48; IPCC, 2007). This warming trend is projected to continue throughout the coming century. The best estimates of the International Panel on Climate Change is that temperatures will rise by another 1.8-4.0 ºC (3.2-7.2 ºF) by 2100, depending on trends in emissions of greenhouse gases (IPCC, 2007).

Models and recent observations both suggest that climate warming is amplified at higher latitudes (Hall, 1988; Serreze et al., 2000) and future changes in temperature are projected to be proportionally higher in high-latitude ecosystems (Roots, 1989). Over the past fifty years, Siberia, Alaska and northern Canada, and the Antarctic Peninsula have warmed more than any other regions on Earth, and the 20th century arctic is the warmest of the past 400 years (Overpeck, 1997; Serreze et al., 2000). Alaska's climate has warmed by approximately 2.2 ºC (4º F) since the 1950s and is projected to rise an additional 2.8-10 ºC (5-18 ºF) by 2100 (Parson et al., 2000). Moreover, stations north of 60º N indicate that the average surface temperatures have increased by approximately 0.09 ºC/decade (0.15 ºF/decade) during the past century, which is 50% greater than the 0.06 ºC/decade (0.11 ºF/decade) increase averaged over the entire Northern Hemisphere (Figure 49; ACIA [300 authors], 2006). This analysis by the Arctic Climate Impact Assessment team further suggested that climate models project greater temperature increases at high northern latitudes than anywhere else in the world in the coming century (Table 18; ACIA [300 authors], 2006). The reasons for the larger temperature increases at high latitudes are not fully understood, but are thought to involve cryospheric effects such as the snow/ice albedo feedback effect (Sturm et al., 2005), coupled with changes in the atmospheric circulation, and possibly ocean currents. In addition, some analyses suggest that much of the recent warming occurred coincident with the most recent of the large-scale Arctic atmosphere and ocean regime shifts in the mid 1970s (Weller and Anderson, 1997).

Although there are no long term climate records within LACL, a recent dendroclimatic study suggests that there was a warming trend within the park in the second half of the 20th century.

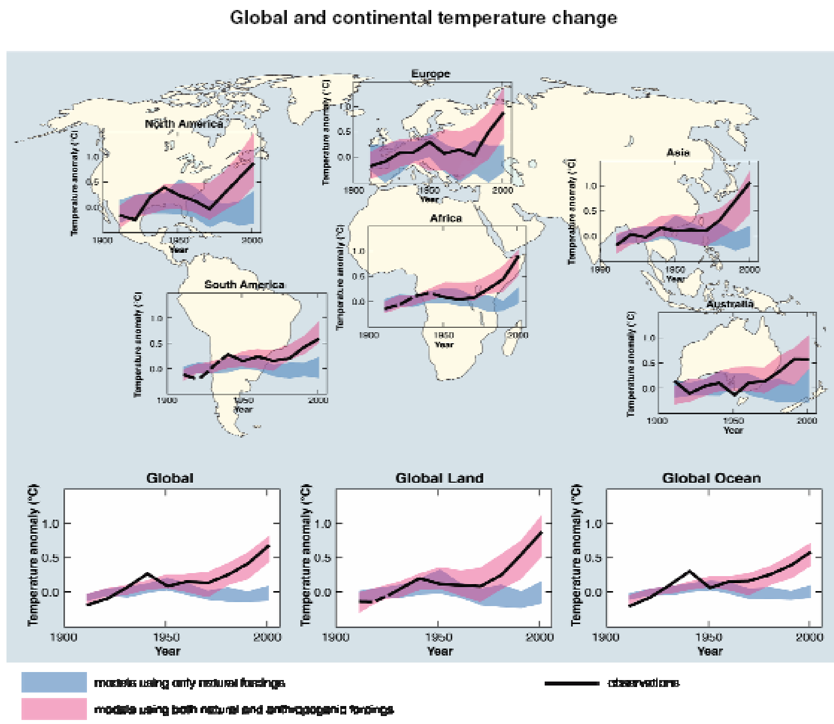


Figure 48. Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using either natural or both natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906-2005 (black line) plotted against the centre of the decade and relative to the corresponding average for the period 1901-1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5-95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5-95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings (IPCC, 2007).

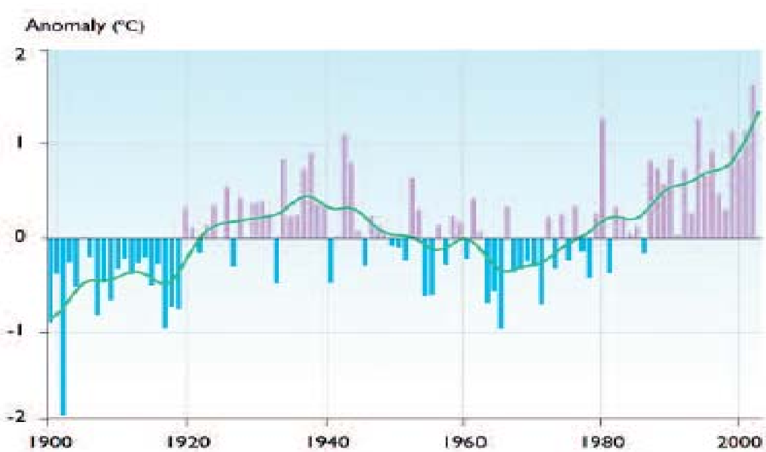


Figure 49. Annual anomalies of land-surface air temperature in the Arctic (60˚ to 90˚ N) for the period 1900 to 2003. From the Arctic Climate Impact Assessment (ACIA [300 authors], 2006).

Table 18. Increases in mean annual surface air temperature in the Arctic (60˚ to 90˚ N) for the period 2011-2090 as projected by five models used by the Arctic Climate Impact Assessment (ACIA [300 authors], 2006).

	Temperature change (°C)					
	CGCM2	CSM_1.4	ECHAM4/OPYC3	GFDL-R30_c	HadCM3	Five-model mean
2011–2030	1.2	1.5	1.3	1.0	1.1	1.2
2041–2060	2.5	2.2	3.2	2.5	2.2	2.5
2071–2090	3.7	2.8	4.6	3.8	4.0	3.7

White spruce tree ring-width chronologies were sampled from four sites along a 30 km north-south transect within LACL (Driscoll et al., 2005). Two of the chronologies show internally consistent positive growth responses to increasing April-July summer temperatures after 1950. The other two chronologies contain two subpopulations, one showing an increased growth response and one demonstrating a decreased growth response after 1950. It is thought that the trees showing growth declines were influenced by temperature induced drought stress (Driscoll et al., 2005). Nevertheless, the results from this study suggest that unprecedented climatic changes within LACL are triggering diverse growth responses in park vegetation.

Climate warming is already affecting the physical landscape in Alaska. The most obvious effects of climate change on hydrologic resources in Alaska are changes in the extent of permafrost, snow cover, glaciers, and sea and lake ice cover (Oswood et al., 1992). LACL's environment and water resources are thought to be very susceptible to climate change (Brabets et al., 1999; Weeks, 2001a). LACL contains substantial area of glaciers and permanent snowfields are common in north and northeast facing basins in the coastal mountains within the park. These glaciers and snowfields are an important source of summertime streamflow in park watersheds and the balance of accumulation and ablation in these hydrologic reservoirs is being altered by climate change. Data from the past half century suggest that the most dramatic climate warming in Alaska has occurred during winter months (Weller et al., 1997). In coastal LACL, winter temperatures are typically close to the freezing point of water (see the *Climatic Setting* section under *Park Description, Hydrologic Information*). As a result, climate warming has the potential to alter patterns of snow accumulation within the park. For example, as winter temperatures increase, the incidence of rain events during winter increases and the hydrologic storage of water in seasonal snowpacks decreases. The result of this trend is a shift toward higher winter streamflows and lower streamflows during snowmelt runoff in the spring and summer.

A shift in the timing of springtime snowmelt towards earlier in the year has already been observed in lower latitude western rivers in the Cascades and Sierra Nevada, and models suggest that temporal centroid of streamflow (mid-point of runoff volume) will occur 30-40 days earlier in these rivers by the end of the current century (Stewart et al., 2004). At present, there are no long term hydrologic data available for LACL to evaluate climate driven shifts in streamflow. However, long-term discharge data from the Kadushan River near Tenakee Springs, Alaska suggest that climate warming can increase winter streamflows and decrease streamflow in the summer and fall (Figure 50). The Kadushan River may be an appropriate analog for seasonally snow covered watersheds in coastal LACL because it is located at a relatively similar latitude (57˚N) and also has a maritime climate. A decrease in the volume (depth and extent) and duration of seasonal snowcover and associated lower summer streamflows may also lead to increased streamwater temperatures in the late summer and fall. Recent research on the Lower

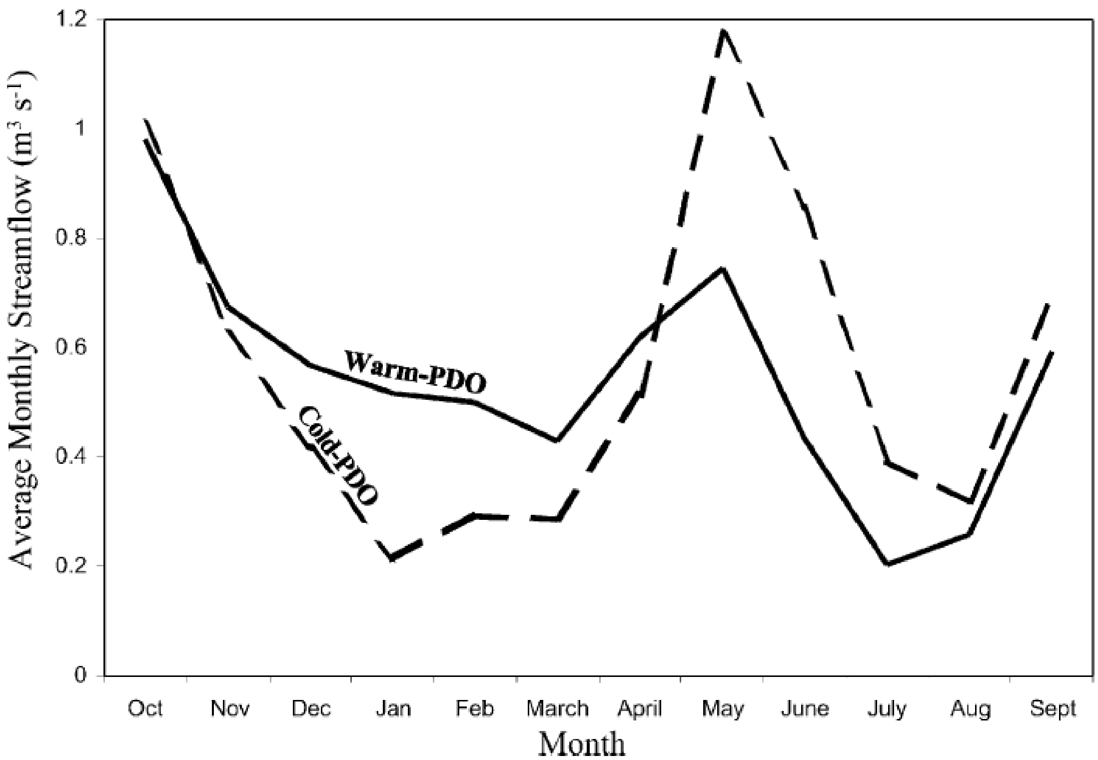


Figure 50. Annual streamflow patterns for the Kadashan River near Tenakee, Alaska during warm and cold periods of the Pacific Decadal Oscillation (Neal et al., 2002). Warm PDO years are associated with an increase in winter streamflow and a decrease in summer streamflow.

Kenai Peninsula has shown that water temperatures in salmon streams in this area regularly exceed 13˚C, which is the State of Alaska standard for egg and fry incubation (Mauger, 2005). Additionally, a USGS study (Kyle and Brabets, 2001) analyzed water temperature data from 32 sites in the Cook Inlet Basin north and west of LACL and showed that streams draining low land areas are the most at risk to be affected by climate warming. They also modeled future climate scenarios based on a doubling of atmospheric carbon dioxide levels and found that 15 of the 32 streams had a predicted water temperature increase of 3 degrees Celsius or more, an increase that is considered significant for the incidence of disease in fish populations. Within coastal LACL, Edmundson and Edmundson (2002) studied sockeye salmon production in Crescent Lake and speculated that between the periods 1979-1982 and 1996-2000, the decline in sockeye productivity was associated at least in part with the effects of accelerated glacier melt on turbidity within the lake. Taken together, these studies suggest that climate warming and attendant shifts in the timing and quality of streamflow within LACL have the potential to influence the spawning success of salmon within the park.

In addition to snowcover, climate warming is also affecting the dynamics of LACL glaciers. Glaciers in coastal LACL have been retreating since the end of the Little Ice Age in the late 1800s. In recent decades, glaciers in both maritime and continental regions of Alaska are thinning and retreating at increasingly rapid rates. Giffen et al. (2008) have demonstrated substantial decreases in glacier extent in nearby KATM and KEFJ (see the *Snow, ice, glaciers* section under *Park Description, Hydrologic Setting*). Arendt et al. (2002) compared recent laser altimetry surveys with historic USGS maps from the 1950s to determine changes in glacier thickness for glaciers throughout Alaska and the Yukon. Results from seven glaciers contained partially or wholly with LACL (Tuxedni, Shamrock, Turquoise, Glacier Fork Tlikakila, North Fork Tlikakila, Double, and Tanaina Glaciers) suggest that glacier thinning rates within LACL over the second half of the 20th century were on the order of 0.2 to 1.0 m/yr (0.7 to 3.3 ft/yr) (Arendt et al., 2002). Interestingly, the Double, Tuxedni, and Shamrock glaciers appear to have thickened slightly (~0.1 m/yr or 0/3 ft/yr) during a recent period between 1995-2001. The loss of ice volume from Alaska glaciers has global consequences because of the contribution of glacial meltwater to sea level rise. Arendt et al. (2002) estimated that in the last decade of the 20th century, Alaskan glaciers contributed at least 0.24 mm/yr to sea level rise, which is 8% of the total sea level rise during this period (and nearly double the contribution from melting on the Greenland Ice Sheet).

The recent increase in the wastage rate of Alaska glaciers is consistent with other glaciated regions of the world. For example, the satellite-derived Swiss glacier inventory revealed that mean glacier area loss per decade from 1985 to 1998/99 has accelerated by a factor of seven compared to the period 1850–1973 (Paul et al., 2007). Further, Paul et al. (2007) note that for Swiss glaciers "many of the observed changes (growing rock outcrops, tongue separation, formation of pro-glacial lakes, albedo lowering, collapse structures) are related to positive feedbacks which accelerate further glacier disintegration once they are initiated. As such, it is unlikely that the recent trend of glacier wastage will stop (or reverse) in the near future." Because of the control that glacial runoff exerts on the physical and biological characteristics of aquatic ecosystems within LACL, monitoring and predicting future volume changes in glaciers within LACL will become increasingly important. A Swiss research team has recently developed a simple method for calculating and visualizing future glacier extent for a large number of individual glaciers (> 100) according to different climate change scenarios (Paul et al., 2007). This method is automated and requires only digital glacier outlines (available from satellite images) and a digital elevation model (DEM) and calculates new glacier geometries from a given shift of the steady-state equilibrium line altitude (ELA_0) by means of hypsographic modeling. The resulting visualizations of glacier change (Figure 51) are useful for resource managers and also represent an excellent tool for communicating research results related to glacier changes to the general public (Paul et al., 2007). Ultimately, the effectiveness of such a modeling effort for glaciers in LACL would be limited by the availability of a relatively high-quality DEM (<30 m spatial resolution) for the park.

An important hydrologic effect of increased glacier melt is an increase in the volume of runoff from glaciers. Increased runoff can lead to the creation of new streams and can alter the sediment, streamflow, and temperature regimes in surrounding streams (Oswood et al., 1992). Changes in runoff and sediment loads can change stream channel morphology and stability, as well as the composition of stream substrates and habitat complexity (Williams, 1989). Non-glacial streams may experience increased stream temperatures as a result of reduced streamflows and climate warming; however, glacial streams are likely to have lower stream temperatures as a result of increased glacial runoff. Decreases in stream temperature can depress primary

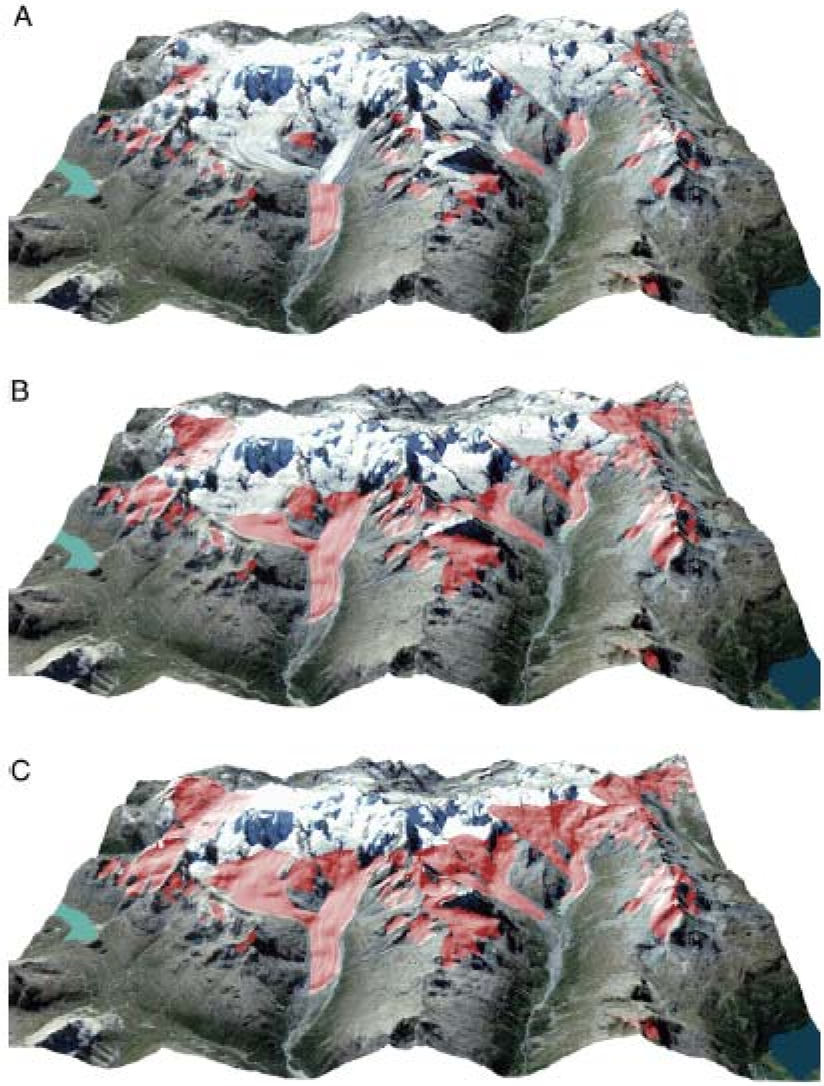


Figure 51. Visualization of new modeled glacier size in the Swiss Alps for Equilibrium Line Altitude upward shifts of 100m (a), 300 m (b), and 500 m (c). Areas of ice lost are shown in the red shaded color.

production, impact or eliminate certain invertebrates, and lower salmonid rates of production (Lloyd, 1987; Lloyd et al., 1987). Over longer time scales, water yields from glacial watersheds in LACL may decrease as glaciers continue to thin and recede.

Climate warming within LACL also has the potential to affect the occurrence of lakes and ponds within the park. Recent research from the Seward Peninsula and Kenai Peninsula has demonstrated a substantial landscape-level trend in the reduction of surface water area as well as the number of closed-basin ponds (Riordan et al., 2006). Since the 1950s, the surface water area of closed-basin ponds in eight boreal regions in Alaska has decreased by 4-31% and the total number of closed-basin ponds has decreased by 5-54%. This loss and shrinkage of ponds is hypothesized to be due to increased drainage from warming permafrost and increased evapotranspiration during a warmer and extended growing season (Riordan et al., 2006). Like lakes and ponds, wetlands in LACL are also at risk from climate warming. Increased evapotranspiration and lower water levels have the potential to decrease the area of shallow wetlands within the park. The loss of surface water bodies and wetlands within LACL has the potential to affect park fauna, such as migratory waterfowl, that depend on these resources.

The effects of climate change on the chemistry of lakes and streams are unknown. Research on linkages between terrestrial and aquatic systems suggests that elevated temperatures and carbon dioxide levels will affect the distribution and productivity of plants,which will in turn affect the amount and quality of leaf litter entering streams and rivers (Meyer and Pulliam, 1992). Increases in woody debris entering streams are also predicted (Sweeney et al., 1992). Because soil microbial activity is linked to soil temperature, moisture, and soil organic matter, climate shifts will affect microbial processing of organic material in terrestrial systems, which will in turn affect the flow of nutrients from terrestrial to aquatic ecosystems. In addition, surface water quality could also be altered by predicted changes in the frequency of disturbances such as forest fires, wind storms, and coastal floods (Meyer and Pulliam, 1992; Parson et al., 2000). Ultimately, changes to the quality and quantity of runoff from terrestrial ecosystems will affect nearshore marine systems in LACL because the productivity of these nearshore ecosystems is influenced by the input of nutrients from coastal terrestrial watersheds.

Physical hazards: volcanoes, earthquakes, tsunamis

Volcanic activity

Iliamna and Redoubt Volcanoes in LACL are at the northeastern end of the 2500-km (1560-mi) Aleutian volcanic arc, which is one of the world's most active volcanic areas, making LACL's coastal resources ever vulnerable to the effects of potentially massive volcanic eruptions (Miller and Smith, 1987; Neal, 2005; NPS, 2006). Not only do Iliamna and Redoubt have the potential to erupt, but several other active volcanoes (e.g. Augustine and Spurr) in close proximity to LACL could easily affect the coastal waters of the unit as well. Subduction of the Pacific plate under the Alaska section of the North American plate generates frequent earthquakes and volcanic activity throughout the Aleutian chain (Figure 52). In the past century, one to two volcanoes in Alaska have erupted each year, most notably Novarupta (1912)—the largest 20th century eruption in the world, and the largest rhyolite eruption in recorded history—, Redoubt (1989), Mount Spurr (1992), Pavlof (1996), Okmok (1997), and, most recently, Augustine and Fourpeaked in 2006 and Pavlof in 2007 (Alaska Volcano Observatory, 1998, 2006, 2007a). Of the two volcanoes in LACL, Redoubt has been more recently active, with substantial explosive activity in 1902, 1966, and 1989 (Alaska Volcano Observatory, 2007b). In contrast, Iliamna (Figure 53) has no documented historical (past ~150 years) eruptions (Waythomas and Miller, 1999). There is a wealth of scientific information on Redoubt Volcano, particularly on the topic of the 1989-90 eruption that goes beyond the scope of this report (Gardner and Neal, 1990; Kienle et al., 1990; Miller and Waitt, 1990; Neal et al., 1990; Nye et al., 1990; Waitt et al., 1990a; Waitt et al., 1990b), plus the entire August 1994 volume of *Volcanology and Geothermal Research* devoted to the Redoubt eruption.

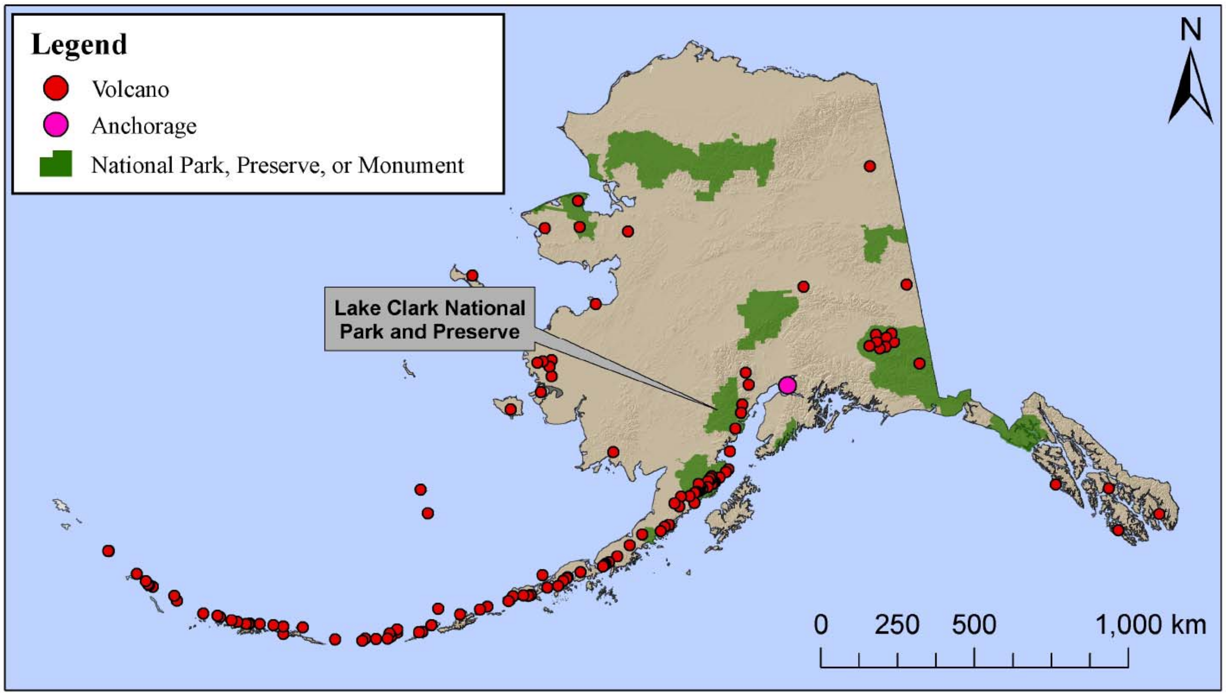


Figure 52. Location of volcanoes in Alaska.


Figure 53. Iliamna Volcano, as viewed from Augustine Volcano in December 2005 (Photo by Game McGimsey, AVO/USGS.)

Future volcanic eruptions releasing ash clouds and lahars and pyroclastic flows in the LACL area and adjacent regions are certain and unavoidable. According to a USGS assessment of volcano hazards for Redoubt, the greatest hazards, in order of importance, are volcanic ash clouds, which may endanger aircraft traffic in particular; volcanic ash fallout, which may disrupt traffic, school, and business in Anchorage and may cause respiratory problems; lahars and floods, which may again inundate the Drift River valley downstream and pose a hazard to the Drift River Oil Terminal; and pyroclastic flows and surges, which pose serious hazards in areas within about 15 km of the volcano (Waythomas et al., 1997). Less likely hazards predicted with future eruptions of Redoubt include debris avalanches, direct blasts, volcanic tsunamis, and volcanic gases (Waythomas et al., 1997). Similar hazards are identified with Iliamna Volcano; the volcano hazard assessment for Iliamna prioritizes the following main hazards: volcanic ash clouds, volcanic ash fallout, lahars and floods, debris avalanches, and pyroclastic flows and surges (Waythomas and Miller, 1999). Directed blasts, volcanic gases, and lava flows are listed as the less likely, but possible consequences of an Iliamna eruption (Waythomas and Miller, 1999). For more detailed information and maps on all these hazards, the reader is referred to the two USGS volcano hazard assessment reports for Redoubt and Iliamna (Waythomas et al., 1997; Waythomas and Miller, 1999).

Due to these risks to natural resources and to air safety traffic and to enhance scientific understanding of volcanic processes, the Alaska Volcano Observatory (AVO) in Anchorage continues to monitor and research volcanic activity throughout the region (Murray, 2005). Volcanoes along the Aleutian chain are actively monitored at 19 stations, including Iliamna and Redoubt Volcanoes, by the AVO (visit http://www.avo.alaska.edu/ for more information). Monitoring is conducted using “webicorders” (computerized seismographs) at all stations, webcams at some stations (not including Iliamna and Redoubt), and real-time Seismic Amplitude Measurement (at Pavlof Volcano only). The AVO is also conducting detailed volcanic hazard assessments for many of Alaska’s other potentially active volcanoes. Most hazards are identified as ash clouds, ash fall, pyroclastic flows and surges, mudflows (lahars—which are of special concern in Alaska due to the risk of rapid melting of snow and ice, as demonstrated by the 1989-90 eruption of Redoubt), lava flows, and volcanic gases (Neal, 2005).

As part of the USGS NAWQA study of the Cook Inlet basin, the hazards posed to watersheds by volcanic eruptions was considered (Brabets et al., 1999). Brabets et al. (1999) summarize the impact of volcanic eruptions on watersheds as follows:

> Volcanic eruptions disturb watersheds primarily by depositing rock, debris, and ash on land or directly in the water and by substantially increasing the water flow and temperature in local rivers and lakes. Deposits of material in the watershed can accumulate in streams and impede movement of fish or create high concentrations of suspended sediment that can be lethal to fish. Increases in streamflow generated by melting of snow and ice on a volcano can scour streambeds where salmon have placed their eggs, or debris moving in the stream can be deposited over the spawning areas and incubating eggs can suffocate. Subsequent high-flow velocities greater than about 6 ft/s can wash juvenile salmonids downstream before they have developed sufficiently. Extreme temperature increases resulting from hot volcanic material entering a stream can kill incubating eggs, developing fry, or mature fish.

The impacts of volcanic eruptions on water quality may also be more subtle, providing longer-time influences on biological productivity within lakes and streams due to ashfall contributions. For example, a study of sediment cores from two lakes on Afognak Island (160 km (100 mi) from coastal LACL) showed that volcanic ashfalls, such as those derived from the 1912 Novarupta eruption, stimulated diatom growth in the lakes due to the increase in silica supply (Barsdate and Dungdale, 1972). An earlier study (Eicher and Rounsefell, 1957) argued that despite immediate destructive effects of volcanic eruptions on plant, fish, and wildlife populations in lakes and streams, there appears to be a long-term net benefit to the watersheds from volcanic eruptions. Eicher and Rounsefell (1957) report that volcanic ashfall is relatively rich in key nutrients such as phosphorus, which can be utilized by algae at the base of the food chain in aquatic systems, and which can enrich soils, and they show that several years following the Novarupta eruption in 1912 there was accelerated plant growth and a fast rebound in salmon abundance in lakes and streams in the LACL region (although no data were derived specifically from coastal LACL). t is notable that some of the world's richest salmon runs are in the Bristol Bay region adjacent to LACL, and this region is regularly impacted by ashfall from volcanic events along the Aleutian chain.

Earthquakes and tsunamis

The Aleutian seismic zone, which follows the southern border of the Alaska Peninsula and the Aleutian islands, is one of the most active seismic zones in the world (Stevens and Craw, 2004; see information and map at http://quake.usgs.gov/prepare/alaska/index.html). The "Shumagin" segment of the volcanic zone, located along the southwestern Alaska Peninsula, has been predicted to have a 74-84% chance of a magnitude 7.4 earthquake between 1988 and 2008 (Nishenko and Jacob, 1990), and many other scientists expect this zone is due for a major earthquake in the next few decades (Moran et al., 2005; Stevens and Craw, 2004). An earthquake in the Shumagin seismic gap may generate extensive tsunamis along the southern coast of the Alaska Peninsula and Aleutian Islands (Kowalik and Murty, 1989).

In 1964, the largest earthquake in North America—and the second largest earthquake ever recorded— occurred in the northern Prince William Sound (Sokolowski, 2006). The earthquake raised some land areas up to 8 m (30 ft), triggered landslides and avalanches, which in turn set off tsunamis that killed 115 people, and caused extensive structural damage in Anchorage and other Alaskan communities (Sokolowski, 2006). While large-scale earthquakes along the Aleutian chain are often remotely triggered by regional tectonic processes (Power et al., 2005), earthquakes of smaller magnitudes are common, particularly during a build-up to a volcanic eruption (Fierstein and Hildreth, 2000; Moran, 2003; Ward et al., 1991).

Tsunamis striking coastal LACL may originate from tectonic movement almost anywhere along the convergent Pacific plate boundary off Alaska's southern coast, from along the strike-slip boundary along southeast Alaska, or from far more distant sources along the massive Pacific plate. Submarine landslides and/or volcanic eruptions that release pyroclastic flows or other materials from a volcanic collapse into the ocean, may also initiate a tsunami in the Gulf of Alaska (Kowalik and Murty, 1989; Waythomas and Watts, 2003; Beget and Kowalik, 2006). For example, the volcanic eruption ~3,500 years ago that formed the Aniakchak Caldera resulted in the release of large-scale (>50 km^3) pyroclastic flows that set off major tsunamis (up to 7.8 m (26 ft) high) in Bristol Bay (Waythomas and Neal, 1998; Waythomas and Watts, 2003).

Pacific tsunami warning systems are in place and are currently being enhanced due to efforts motivated by the Indian Ocean tsunami that killed more than 200,000 people in Asia in December 2004. Relevant tsunami warning centers are the West Coast and Alaska Tsunami Warning Center based in Palmer, Alaska (http://wcatwc.arh.noaa.gov/) and the Pacific Tsunami Warning Center in Ewa Beach, Hawaii (http://www.prh.noaa.gov/ptwc/). The AVO also operates seismic networks throughout the Aleutian chain and has recorded and located approximately 5600 earthquakes at Redoubt Volcano and 2300 at Iliamna Volcano since 1989 (Moran et al., 2005).

Uplift, accretion, and erosion

The complex interplay of tectonic, isostatic, and global eustatic effects in the Gulf of Alaska results in highly spatially variable sea level histories along the southcentral and southwestern Alaska coast. Earthquakes leading to sudden coastal uplift events are common along the tectonic setting of the Alaska Peninsula coast. During the 9.2 magnitude Good Friday earthquake in 1962, for example, some portions of the coastal southcentral Alaska were uplifted over 8m, while other areas subsided up to 2.25 m (7.40 ft) (Harper and Morris, 2005).

Shoreline change is one of the Vital Signs being monitored by the SWAN I&M program (Bennett et al., 2006). Coastal erosion from wave energy can be strong in exposed areas, while natural accretion may result from storm-driven waves, high tides, nearshore currents, rainfall and runoff, landslides, and earthquakes (Cusick and Bennett, 2005). Uplift of the land due to tectonic activity is superimposed upon isostatic rebound from deglaciation, a process which raises the land and reshuffles successional processes on a much more gradual time scale (Mann et al., 1998; Bennett et al., 2006).

In an effort to track such coastal dynamics, ten across-shore profiles along the LACL coast were established and profiled along representative coastal segments in 1992 and 1994 (Schoch, 1996), and seven of the ten profiles were re-measured by Cusick and Bennett (2005) in 2004 (Figure 54). At five of the seven sites (Polly Creek, Crescent River, Spring Point, Clam Point, and Glacier Spit), net erosion and landward migration of mean high water was found, and seaward migration of mean high water was observed at two sites – Slope Mountain and Red River (aka. Silver Salmon Creek; Figure 55). Average annual rates of erosion ranged from -0.18 to -0.50 m/yr (-0.6 to -1.6 ft/yr), and accretion rates ranged from 0.55 to 3.13 m/yr (1.8 - 10.3 ft/yr). These results reveal that although sediment transport along the LACL portion of coastal Cook Inlet generally follows a southwest trajectory, complex local features (e.g. shoreline orientation, bathymetry, tides, sediment supply, and circulation patterns) exert powerful forces that govern the loss or gain of coastal sediment (Cusick and Bennett, 2005).

Figure 54. Cross-shore beach profile locations re-surveyed in 2004 by Cusick and Bennett (2005).

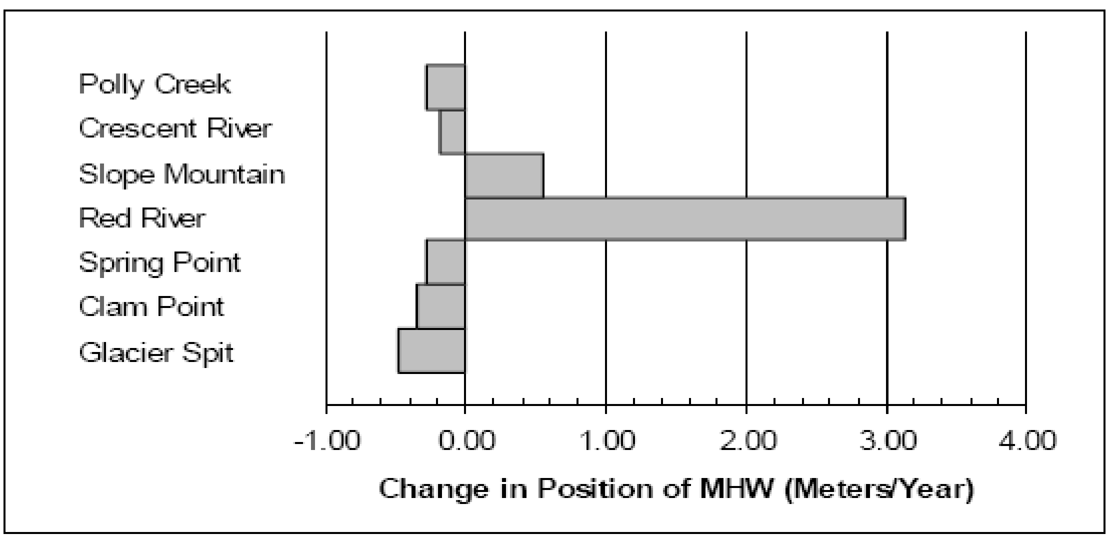


Figure 55. Annual rates of erosion and accretion (in terms of change in position of mean high water) from 1992-2004 at the seven cross-shore beach profiles measured by Cusick and Bennett (2005).

Changes in relative sea level can affect not only the composition, relative abundance, and distribution of coastal habitats, but may also have jurisdictional implications for park management (Cusick and Bennett, 2005). Ongoing shifts in the elevation of the land surface also have implications for the hydrology of small coastal streams, many of which support salmon populations. As water tables drop in response to uplift events, it is possible that coastal streams fed by groundwater may experience reduced seasonal or perennial flows and become impassable for fish, limiting the range of certain anadramous stocks.

Along the LACL coast, salt marshes are currently being lost to Sitka spruce as the land rises due to isostatic rebound and tectonic uplift (Figure 56; Page Spencer, NPS-Port Alsworth, personal communication, 2007). This shift is particularly pronounced in the region between Silver Salmon Creek and Shelter Cove and in Chinitna Bay. Salt marshes play an extremely important ecological role along the LACL coast, and so their loss likely will have dramatic effects on wildlife, particularly on brown bears in the spring and early summer. Salt marshes are being tracked under the SWAN I&M program under the "sensitive communities" vital sign, and monitoring work began with the establishment of permanent transects in 2007 (Page Spencer, NPS-Port Alsworth, personal communication, 2007).

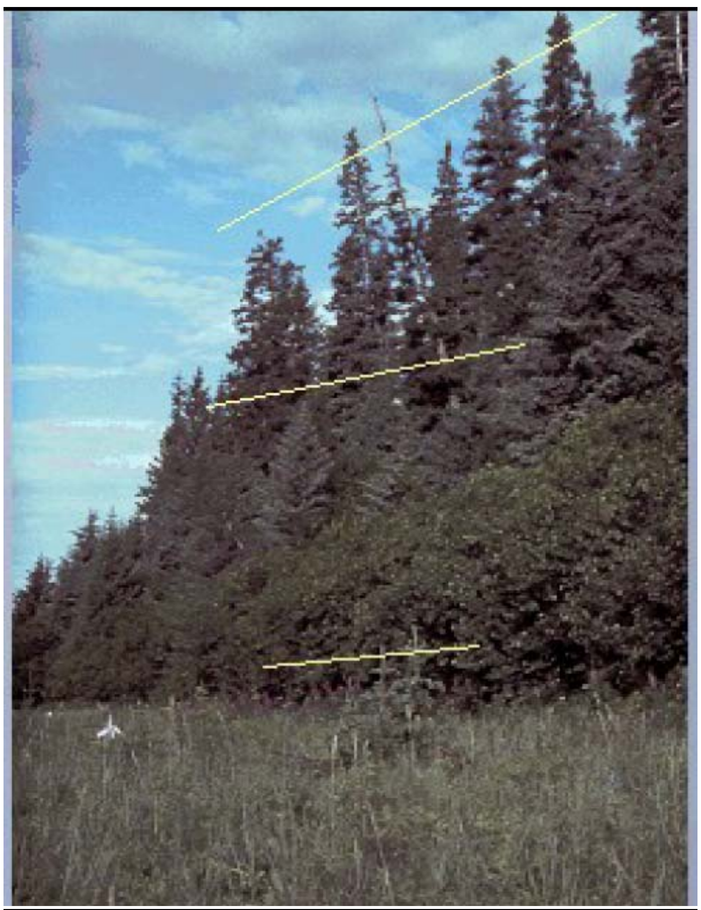


Figure 56. Terraced age layers of young sitka spruce along the LACL coast. Uplift of the land is causing loss of salt marshes and sequential transitions into Sitka spruce forest. Photo courtesy of Page Spencer, NPS, 2007.

Visitor impacts

Visitor use of the LACL coast has been on the rise for the past decade and comes mainly in the form of sport fishing and bear viewing/photographing, mainly at Silver Salmon Creek and Chinitna Bay (Figure 11; NPS, 2007b). Potential impacts from visitor use includes wildlife disturbance and displacement, damage to soil and vegetation, and noise disturbance associated with motorized vehicle/airplane use. Wheeled planes land on beaches and bring visitors (many of which are cruise ship passengers) to the coastal salt marshes and the several lodges located within private inholdings (e.g. two lodges within the Silver Salmon Creek watershed, a lodge in Chinitna Bay, and the Redoubt Bay Lodge near Lake Clark Pass). There are no public use cabins within the park, but a ranger station at Silver Salmon Creek is staffed from June-September to help manage the summer use in that area, and the Chinitna Bay Ranger Station is voluntarily staffed during the summer as well (Page Spencer, NPS-Port Alsworth, personal communication, 2007). (Note: there are 2 Silver Salmon Creeks in LACL—one just south of Iliamna Point and the other on the southern edge of the coastal boundary near West Glacier Creek. The Silver Salmon Creek issues mentioned in this section refer to the former).

Accurate data on the number of total visitors to the coastal region are unavailable. Nonetheless, the NPS collects data on commercial permits, and the most recent such information comes from 2007. Sportfishing and bear viewing (1,162 and 1,012 commercial user days, respectively) dominated the use type, followed closely by combined Photography/Bear Viewing (969 commercial user days) (Table 19 and Figure 57). By far, the most heavily used area (accounting for just over 50% of the use) was Silver Salmon Creek (2,156 user days), followed by the Lake Clark area (677 user days) and Twin Lakes (370 user days), both in the interior of the park (Figure 57). Crescent and Hickerson Lakes saw relatively light visitor use in 2007, with 69 and 11 user days, respectively, for Photography/Bear Viewing (Table 19).

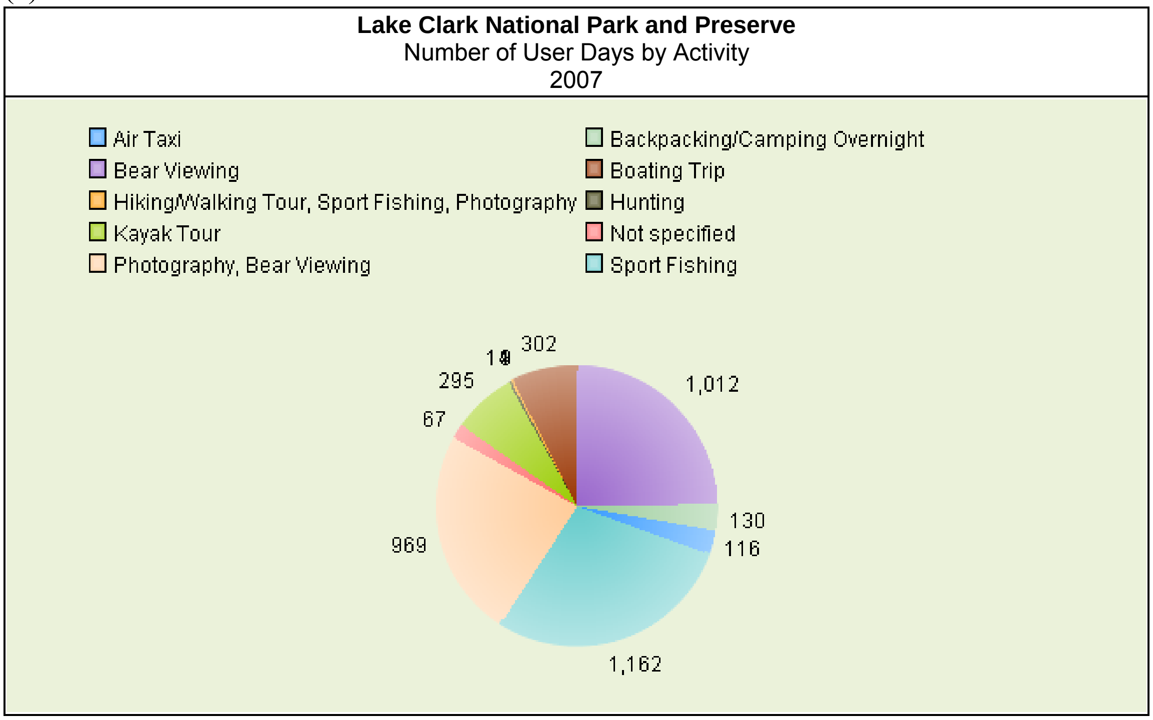
Off-road vehicle use in Silver Salmon Creek area

The relatively heavy amount of visitor use in the Silver Salmon Creek area has resulted in extensive off-road vehicle (ORV) trails. ORVs are used both by the fly fishing clients, many of whom stay at one of the lodges, and also by cruise ship passengers and other tourists who are taxied on ORVs to bear-viewing areas on day trips. The impacts of the ORV use is most pronounced in riparian areas, where ORVs can erode streambanks, cause vegetative damage, alter flow and structure of the stream through changes in bed morphology, and damage macroinvertebrates and fish eggs buried in the streambed (Colleen Matt, NPS-Port Alsworth, personal communication, 2005). ORV use also occurs on the beaches and in some salt marshes, potentially incurring long-term damage. In response to these issues, the NPS is developing maps of ORV trails, has begun working with the community to distinguish accepted from abandoned routes, and plans to develop an ORV access plan for the whole LACL unit within the next few years (Page Spencer, NPS-Port Alsworth, personal communication, 2007).

Table 19. Table of user days by location and activity in the LACL coastal region for 2007, the most recent year for which data are available. Taken from the NPS Office of Concession Operations website, which also provides data for 2005 and 2006 and for LACL locations outside the coastal region, at http://science.nature.nps.gov/im/units/swan/vs/hum_visit_use/cua_index.cfm?theme=cua_download_data&park_code=LACL

Year	Park Code	Park Location	Activity Name	User Days
2007	LACL	Crescent Lake	Air Taxi	3
2007	LACL	Crescent Lake	Backpacking/Camping Overnight	18
2007	LACL	Crescent Lake	Photography, Bear Viewing	69
2007	LACL	Crescent Lake	Sport Fishing	152
2007	LACL	Other: Hickerson Lake	Photography, Bear Viewing	11
2007	LACL	Silver Salmon Creek	Bear Viewing	1012
2007	LACL	Silver Salmon Creek	Kayak Tour	15
2007	LACL	Silver Salmon Creek	Not specified	3
2007	LACL	Silver Salmon Creek	Photography, Bear Viewing	745
2007	LACL	Silver Salmon Creek	Sport Fishing	381

(a)



(b)

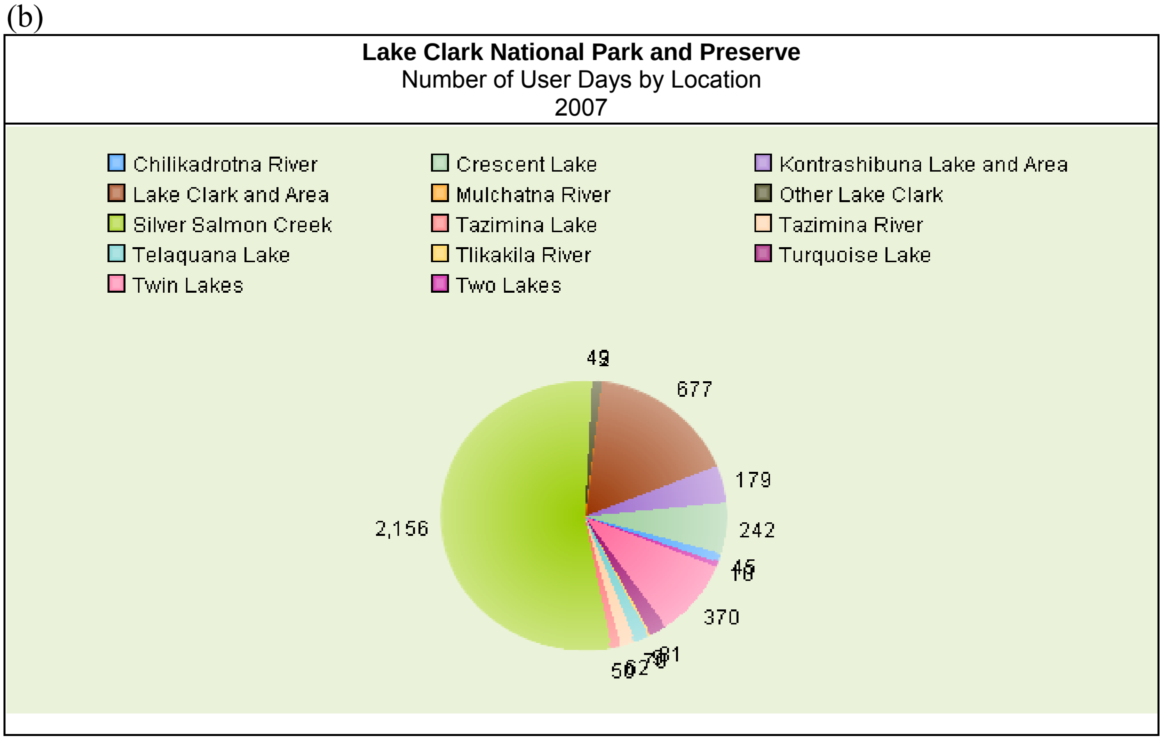


Figure 57. Pie charts showing commercial use data by (a) activity and (b) location at LACL for 2007, the most recent year for which data are available. Source: http://science.nature.nps.gov/im/units/swan/vs/hum_visit_use/cua_index.cfm?theme=cua_location_park_activity&park_code=LACL&year=2007

Sport and commercial fishing and clamming

Sport fishing and clamming may impact coastal resources. The shallow and strongly tidally-influenced waters of the LACL coastal region allow only for small vessels (except for some larger vessel access in Snug Harbor in Tuxedni Channel) and airplanes to directly access the coast. Tourists fly into the coast mainly for day-use fishing trips, and most of them arrive from Homer or Kenai (Colleen Matt, NPS-Port Alsworth, personal communication, 2005). A portion of the visitors use the Crescent Lake Lodge for fly-in fishing trips, and both Silver Salmon Creek and Shelter Creek see the majority of the sport fishing use (Lee Fink, NPS-Port Alsworth, personal communication, 2005). In addition, recreational clammers are known to fly to the LACL coast to clam in extreme low tides (Dan Young, NPS-Port Alsworth, written communication, 2008). Reliable data on volume, location, and type of sport fishing activity, are not available because license survey forms are voluntary and therefore sparse (Lee Fink, NPS-Port Alsworth, personal communication, 2005).

Commercial fishing activity along the LACL coast primarily focuses on salmon and clamming, although a herring fishery used to exist in the region. The Chisik Island cannery closed in the 1960s, as onshore canneries became largely obsolete with modern technology. Currently, there is a set-net and drift net-gill fishery for silver salmon along the west side of Cook Inlet. Commercial clamming occurs in the Polly Creek area, on LACL beaches near cabins, and along some beaches to which harvesters gain access via airplane. The NPS boundary is designated as the mean high tide line; therefore, clamming activity occurs outside but immediately adjacent to the NPS's jurisdiction. The Polly Creek commercial clamming operation, which has been ongoing for almost 20 years, employs workers who live in tin camps on the shore (Alan Bennett, NPS-Anchorage, personal communication, 2005). Quantitative data on commercial fisheries are not specifically available for the LACL coast.

Hiking and camping

The lack of public use cabins and the voluntary submission of camping permits do not allow for accurate estimates of the numbers of hikers, campers, and other backcountry users in LACL (and other Alaskan NPS units that were formed by ANILCA and have no entrance fees). However, the difficult and expensive access to the coastal region, as well as the abundance of brown bears and impenetrable alder, likely results in very light use by day-hikers, backpackers, and campers.

Exotic species and disease

Exotic aquatic invasive species that have been introduced or are moving into Alaskan waters include multiple species of fish, plants, and invertebrates (Appendix B). Water bodies of Alaska are more likely than terrestrial habitats to be invaded by exotic species because the temperature ranges of oceans, rivers and lakes vary much less than terrestrial temperature ranges (ADFG, 2002a). The introduction of invasive species into Alaskan waters may be either accidental, purposeful, or due to negligence, and pathways of introduction include fish farms, aquaculture, transport on or in ballast water from ships or fishing vessels, live seafood trade, or sport fishing gear (ADFG, 2002a). In order to minimize the impact of invasive species in Alaska, the ADFG developed an Aquatic Nuisance Species Management Plan (ADFG, 2002a) with the purpose of focusing on preventing the proliferation of those invasive species that are considered the highest threat (see the ADFG Invasive Species Website at http://www.adfg.state.ak.us/special/invasive/invasive.php.)

The presence and scale of exotic species in the coastal waters of LACL is not known or documented (A. Bennett, NPS-Anchorage, personal communication, 2005). The potential for the spread of invasive species is substantial, with sources that include marine vessels, float planes, and aquaculture in Cook Inlet. Bennett et al. (2006) highlight the particular concern surrounding the continued northward migration of escaped farmed Atlantic salmon *(Salmo salar),* expansion of the Northern Pike *(Esox lucius)* from the Susitna River drainage basin, and the introduction of other non-native migrating species. Farmed Atlantic salmon in Washington State and British Columbia are accidentally released into the North Pacific Ocean each year and may affect native populations through disease, colonization, interbreeding, predation, habitat destruction, and competition (ADFG, 2002b). These farmed fish are thriving in the wild with recoveries in both British Columbia and Alaska, with the first catches of Atlantic salmon in Southeast Alaska in 1991 (ADFG, 2002b). While ADFG has documented over 700 recoveries of Atlantic salmon in Alaskan waters, representing an estimated 3,000 immigrants per year, no Atlantic salmon have been documented in southcentral/southwestern Alaska (T. Hamon, NPS-King Salmon, personal communication, 2005). The risk posed by Northern Pike to Cook Inlet watersheds stems from their propensity to prey on small salmon and trout, thereby potentially restructuring fish communities (Bennett et al., 2006; Mann et al., 1998). If Northern Pike colonized coastal lakes and watersheds, they could impact the natural pattern of colonization, succession, and niche specialization that would occur as fish species successfully gain access to coastal lakes following glacial recession (T. Hamon, NPS-King Salmon, personal communication, 2005). It should be noted that Northern Pike are native to Bristol Bay drainages of SWAN parks (J. Shearer, NPS-Anchorage, personal communication, 2008). Their ability to migrate to coastal drainages is restricted due to their intolerance for changes in salinity. New Zealand mudsnails represent a threat to freshwater systems, as they may impact the food chain for native trout and the physical characteristics of streams themselves (ADFG, 2002b).

Little is known about the potential threat of invasive species in the marine environment, but the best known invasive marine invertebrate species of concern is the green crab (*Carcinus maenas*), which is originally from northern Europe, became established in California in the 1990s, and has since become established in estuaries as far north as British Columbia. Bacteria, viruses, and parasites are also a threat to Alaskan waters because these can be introduced easily through exotic species.

Other concerns include unchecked spruce bark beetle (*Dendroctonus rufipennis*) outbreaks; the most recent epidemic in Southcentral Alaska started in the early 1990s. Spruce bark beetles are native and play important roles in ecosystem processes; however, a build-up of weakened trees may be conducive to spruce beetle population outbreaks, which may become destructive on a large scale (Manski, 1986) As part of the Vital Signs monitoring activities, a tree-ring study is being conducted in KATM and LACL to determine the extent of historic and modern bark beetle outbreaks. Spruce beetle-caused tree mortality is high on parts of the LACL coastline. The beetle has killed most of the white spruce (*Picea glauca*) in LACL but had a lesser impact on Sitka spruce (*Picea sitchensis*) (Page Spencer, NPS-Port Alsworth, personal communication, 2007). Resultant large-scale tree mortality affects water resources through changes in vegetative cover to streams, rates of soil adsorption of precipitation, extent of large woody debris contributions to streams, and nutrient cycling in watersheds.

Another disease of concern, the avian flu virus, has not been detected in North America; however, the potential exists for it to enter Alaska via migratory birds, particularly those coming from Asia. The Alaska Departments of Fish and Game, Health and Social Services, and Environmental Conservation are currently collaborating with the U.S. Fish and Wildlife Service to closely monitor wild birds, primarily in western Alaska, for the presence of the virus (State of Alaska, 2006). An outbreak of the virus has the potential to decimate bird populations in the LACL region and elsewhere and have cascading effects on the food web; however, it is difficult to foresee significant impacts on the quality and quantity of water resources if the virus remains limited to birds and does not spread to other species. Conversely, water bodies may support the spread of the virus because it can be transmitted through water contact. As a result, the extensive coastal wetlands and ponds in LACL may be potential breeding grounds and source areas of the virus if they were to become infected by carrier birds.

Chytridiomycosis is an emerging infectious disease caused by a waterborne fungus that, alone or in consort with other environmental stressors, has caused amphibian declines globally. This disease probably poses a threat to resident wood frog populations in LACL, although it has not been reported there. It has, however, been detected on the Kenai National Wildlife Refuge and many other remote parts of Southeast Alaska (S. Pyare, personal observation).

An invasive plant summary was completed in 2008 and inventoried 71.5 acres of LACL, the majority of which is focused on the Port Alsworth area and outside the scope of this report (Rapp, 2008). The inventory identified 20 invasive plant species within LACL and suggested that a handful of invasive plant species are present in the coastal area of LACL.

Harmful algal blooms

Harmful algal blooms (HABs) are caused by a few dozen marine phytoplankton that produce toxins. Although commonly called red tides, this term is misleading, as with many HABs, there is no discoloration to the water, and many seaweeds produce colored blooms. HABs cause significant ecosystem, human health, and economic impacts (Anderson et al., 2000). HABs have become a national and international research focus in the past decade. Most areas of the world have some form(s) of harmful algal bloom, although the frequency, severity and diversity vary greatly. What is certain is that although HABs have documented for centuries, they have been occurring more frequently and in more areas during the past few decades (Anderson, 1995; Burke et al., 2000). HABs have caused mass mortalities of marine bird, mammal, and fish populations, and they cause a variety of human illnesses that vary by type of toxic phytoplankton or diatom. HABs are known to cause a variety of shellfish poisoning (SP), including paralytic (PSP), diarrhetic (DSP), neurotoxic (NSP), and a fifth human illness, caused by finfish and not shellfish, is Ciguatera Fish Poisoning (CFP).

The largest problem caused by HABs in Alaska is paralytic shellfish poisoning (PSP) from shellfish that have bioaccumulated the dinoflagellate *Alexandrium* sp. Alaska has one of the highest incidences of reported PSP in the world (Gessner and Schloss, 1996). Paralytic shellfish poisoning can cause paralysis, gastrointestinal problems, and respiratory arrest and can be fatal if prompt medical care and respiratory support is not available. There is no antidote. People have died in Alaska from PSP as recently as a decade ago, and there is at least one human health incident per year. Since 1973, there have been 176 incidences of PSP in Alaska from 66 outbreaks, with the majority in Southeast Alaska (Figure 58; Gessner, 1996).

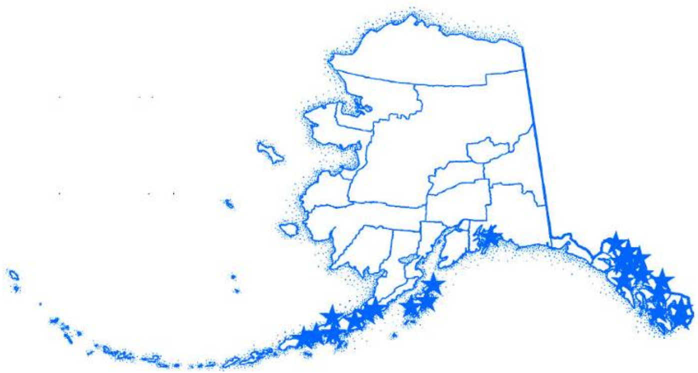


Figure 58. Location of PSP outbreaks in Alaska Each star represents one or more outbreaks (Gessner, 1996).

Little is known about the distribution or abundance of PSPs in LACL. The Alaska Department of Environmental Conservation (ADEC) is responsible for testing shellfish for PSP. Due to the geographic extent of Alaska (over 81,000 km (50,000 mi) of coastline) and the remote nature of many regions of the state, shellfish are only tested for PSP in association with a commercial harvest or mariculture facility. Non-commercial harvests are not tested, and people are advised not to eat shellfish that they collect. More information is needed in order to evaluate if HABs are an issue of concern in LACL. Any unusual incidences of mass mortalities of marine bird, mammal, and fish populations should be suspected as possible HAB-related events. NPS should advise against non-commercial harvests of shellfish because of the risks associated with PSP.

Abandoned structures

The many thousands of hectares of private inholdings within the LACL coastal area contain approximately a few dozen cabins (Page Spencer, NPS, written communication, 2008), some of which may contain hazardous materials such as batteries, fuel, and generators that could pose local contamination threats. The closed cannery on Chisik Island (adjacent to LACL) has a caretaker and likely poses no threat to the park. The logging operation in the Crescent River basin removed all structures when it left; old airplanes that have crashed in the past burned and left little trace; and the few cabins that exist on the coast are largely still in use at least intermittently and not abandoned. In general, however, abandoned structures are not considered to be of significant concern for LACL resources (Page Spencer, NPS, written communication, 2008).

Coastal debris and garbage

No studies have been conducted to evaluate the quantity and impact of coastal debris on LACL's natural resources. However, accumulations are generally observed to be of far smaller magnitude than those on the outer coast (e.g. along the KEFJ beaches) and are considered to be of very small concern (Page Spencer, NPS-Port Alsworth, personal communication, 2007). There are no known efforts by the NPS to rid the coastline of debris and garbage.

Future development

Potential logging in Crescent River

Although the entire Crescent River watershed lies within LACL, large tracks of inholdings along the North Fork Crescent River and between Crescent Lake and Cook Inlet are owned by the Cook Inlet Region Incorporated (CIRI) and three Native village corporations (Figure 59).

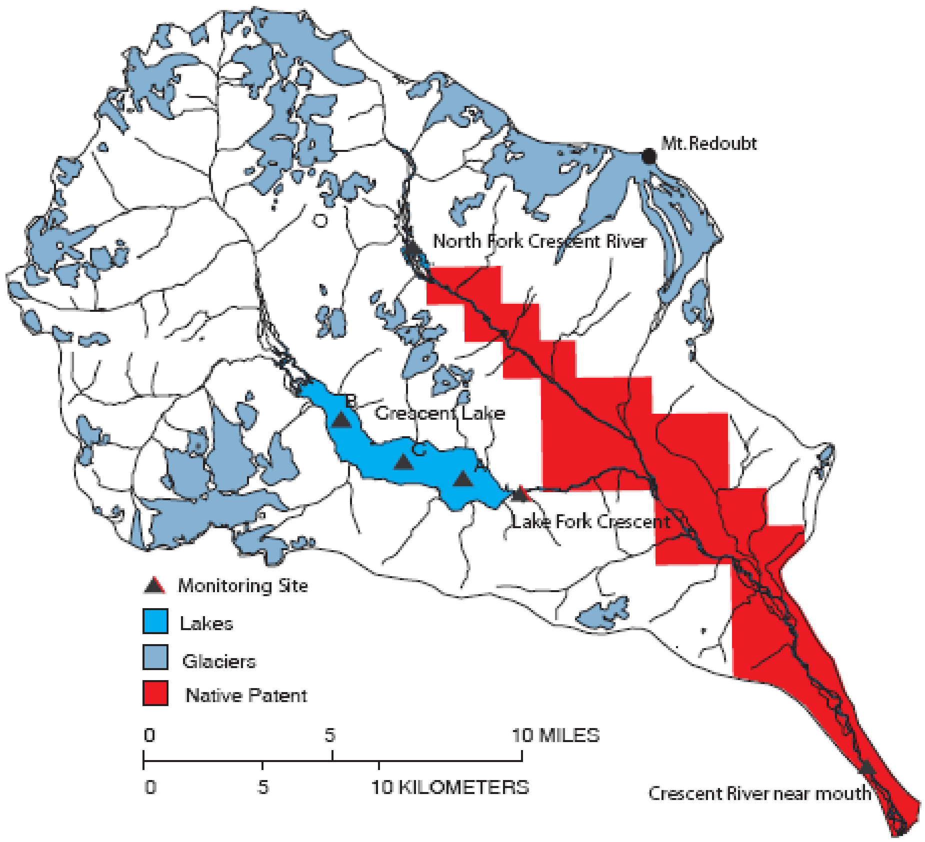


Figure 59. Crescent River basin showing sites sampled by Brabets and Ourso (2006) as well as Native inholdings (in red). Figure from Brabets and Ourso (2006).

As reported in Brabets and Ourso (2006), about 700 acres of land were selectively harvested for timber during 2000-2001, out of about 42,000 acres of the inholdings whose timber rights were sold in 1997 to a logging company (Figure 60). The timber company selectively logged spruce trees, which were extensively killed by the spruce bark beetle that swept through the region in the late 1990s, and left behind the birch trees (Page Spencer, NPS-Port Alsworth, personal communication, 2007). The infrastructure built for the operation (e.g. log transfer facility, grounded docks, airstrip) have been removed since the operation ended, leaving a primary access road and several secondary roads. The Brabets and Ourso (2006) study was motivated by the need to characterize the water quality of the Crescent River after this logging event and before any future logging might occur, in order to help fulfill the NPS's responsibility to maintain the sockeye salmon habitat and to protect the pristine quality of lakes and rivers in LACL. The report concluded that past logging has had a negligible influence on water quality and that if logging were to recommence using the mandated 66 foot setback rule, it is again unlikely to

Figure 60. Logged areas of the Crescent River watershed (aerial view looking southeast to Cook Inlet). Photographs by Penny Knuckles, NPS, 2002, published in Brabets and Ourso (2006).

strongly influence water quality (Brabets and Ourso, 2006). The authors point out that the flow and temperature dynamics of the stream are overwhelmingly driven by glacier and snowmelt, and that suspended sediment dynamics are regulated by trapping in Crescent Lake. The report also states that if concentrations of major ions, nutrients, and dissolved organic carbon were to become elevated due to logging along the mainstem, these parameters would easily be diluted by contributions from the North Fork and Lake Forks of the river. The authors of the report do note, however, that future logging activity does have the potential to increase suspended sediment loads to the river, and this in turn may depress the biological diversity of algal communities. Currently, however, it appears unlikely that logging would resume in the foreseeable future (Dan Young, NPS-Port Alsworth, personal communication, 2005).

Potential mining in the Johnson River watershed

The Cook Inlet Regional Corporation (CIRI) owns title to approximately 21,000 acres of land in the Johnson River watershed. This land, split into two tracts (northern tract of 3,885 hectares [9,600 acres] of mineral estate and southern tract of 4,590 hectares [11,342 acres] of surface and subsurface estate), has been of interest to prospective miners for decades, and several exploratory programs in the area have revealed a high-grade copper, silver, lead, zinc, and gold deposit (Weeks, 2001). Although the land is not on the coast, ANILCA guarantees CIRI right of access to the water (Alan Bennett, NPS-Anchorage, personal communication, 2005). In the early 1990s, CIRI partnered with Westmin Resources Limited and conducted exploratory engineering and economic feasibility access studies (Cook Inlet Region Inc., 1993), and the NPS and USGS became involved with conducting baseline water quality studies and stream gaging on the

Johnson River. If a mine were to be developed, it would likely pose a serious threat to the Johnson River due to its close proximity to the ore body, and the required support network of roads and ore stockpiles would potentially lead to fuel spills, enhanced erosion, and contamination from leaching of ore stockpiles (Brabets et al., 1999; Weeks, 2001a).

However, Westmin Resources eventually pulled out of the development plans, and currently there is no lease on the deposit and no activity at the site except for occasional checks in the summer on the buildings and airstrip that remain at the site (Page Spencer, NPS-Port Alsworth, personal communication, 2007). The projected high cost of constructing an access road to the coast and the lack of an immediate deep water port (necessitating road construction to Tuxedni Channel) have kept away serious development efforts (Alan Bennett, NPS-Anchorage, personal communication, 2005). In addition, most investment in the area is focused on the potential development of the Pebble Mine, which is a much larger and more easily accessible project compared with the Johnson River tract (Page Spencer, NPS-Port Alsworth, personal communication, 2007). Nonetheless, the potential for a mine development continues to exist as long as the land remains in private ownership.

Potential Chuitna Coal Project

Of high regional concern for LACL is the potential development of the Beluga Coal Fields, located approximately 72 kms (45 mi) west of Anchorage, by PacRim Coal (USEPA, 2006). The proposed 25-year (minimum) project would target the mining of up to 1 billion metric tons of subbituminous coal from approximately 77 km^2 (30 mi^2) of land, which would make the project the third largest strip mine in the U.S. and the largest strip mine in Alaska history (Cook Inletkeeper, 2008). Potential environmental impacts from the project range from local surface and groundwater quality degradation to disruptions to wildlife, anadromous and resident fish, and Cook Inlet beluga whales (USEPA, 2006). Although the area of proposed development is outside NPS boundaries, LACL likely would be affected by coal dust air pollution and the increased shipping traffic (by coal transport vessels) off the LACL coast. PacRim Coal is expected to submit a complete application to the Alaska Department of Natural Resources (the lead state agency involved in permitting coal projects) by late 2008 or early 2009 (ADNR, 2008).

Potential Pebble Mine development

One of the most important issues with potentially serious impacts on LACL resources is the proposed development of the Pebble mine, located approximately 36 km (20 mi) southwest of the LACL border, just north of Lake Iliamna. The development, owned by the Pebble Limited Partnership (a 50-50 partnership between Anglo American PLC and Northern Dynasty Minerals Ltd), would exploit one of the world's largest discovered gold-copper-molybdenum deposits. According to Northern Dynasty's website (www.northerndynastyminerals.com), the current plans are to complete a pre-feasibility study in December 2008, a feasibility study by 2011, and commercial production starting in 2015. The main threats from the mine concern the inland area of LACL (particularly on the Chulitna River and downstream to Lake Clark itself), but the coastal LACL study region may be impacted as well.

Development details are unclear, and the Pebble Partnership is in only the initial phases of conducting environmental impact studies. Therefore, it is difficult to assess at this point in time how natural resources in coastal LACL may be affected. (The magnitude of environmental impact on the inland portion of LACL likely would be extensive with a mine of the proposed scale; however, such discussion is beyond the scope of this report). What is certain is that the mine's immense size would require tremendous power generation, which would probably need to be met through hydroelectric sources or gas or coal combustion, as locally developed power sources are nonexistent. Early versions of the mine's development proposal stated that one potential means of providing power to the mine would be through transmission lines that would cut through LACL boundaries—up the Big River and through Lake Clark Pass (Page Spencer, NPS-Port Alsworth, personal communication, 2007). Currently, the Pebble Limited Partnership does not specify this location as a potential power access route, but simple states that "various options for the supply and delivery of power to the project and to nearby communities" are being evaluated (Pebble Limited Partnership, 2008) One potential source of power currently being evaluated by the Pebble Partnership and the Homer Electric Association is a new natural gas-fired generating plant on the Kenai Peninsula (Pebble Limited Partnership, 2008). Another development proposal in the region that may be related to the Pebble Mine development is a proposal filed to the Federal Energy Regulatory Commission (in May 2006) to dam Chakachamna Lake (Figure 17). Although this lake is outside of LACL, several major LACL streams that feed into it could be adversely affected by a downstream dam. Before such a project were to go through, these streams would need to be subjected to ecological and hydrological reconnaissance studies, as very little information about them currently exists.

Another concern for the LACL coast related to the Pebble Mine project is the location of a tidewater port, which would be needed for shipping of mineral concentrates and for receipt of supplies (Figure 61). As of this writing, the Pebble Partnership states on its website that "Copper concentrate at Pebble will be sent via a pipeline to a port site and dewatered before shipment, with the water returned through a separate pipeline to the mine site for re-use…. Supplies will be trucked over a [104 mile] single-lane industrial road with restricted access. The pipeline will parallel the road, and both will terminate at a deep-water port on Cook Inlet. Alternative sites for the port are being evaluated." Although the LACL coast does not have adequately deep water ports, it is clear that the Pebble Partnership will be seriously considering using ports immediately south of the LACL border. No studies have been done to date to evaluate the potential impact of a nearby port, but inherent risks would inevitably include oil spills from vessels using the port, spills of mineral concentrates, processing materials, and tailings, and disturbance of wildlife, fish, birds, and marine mammals.

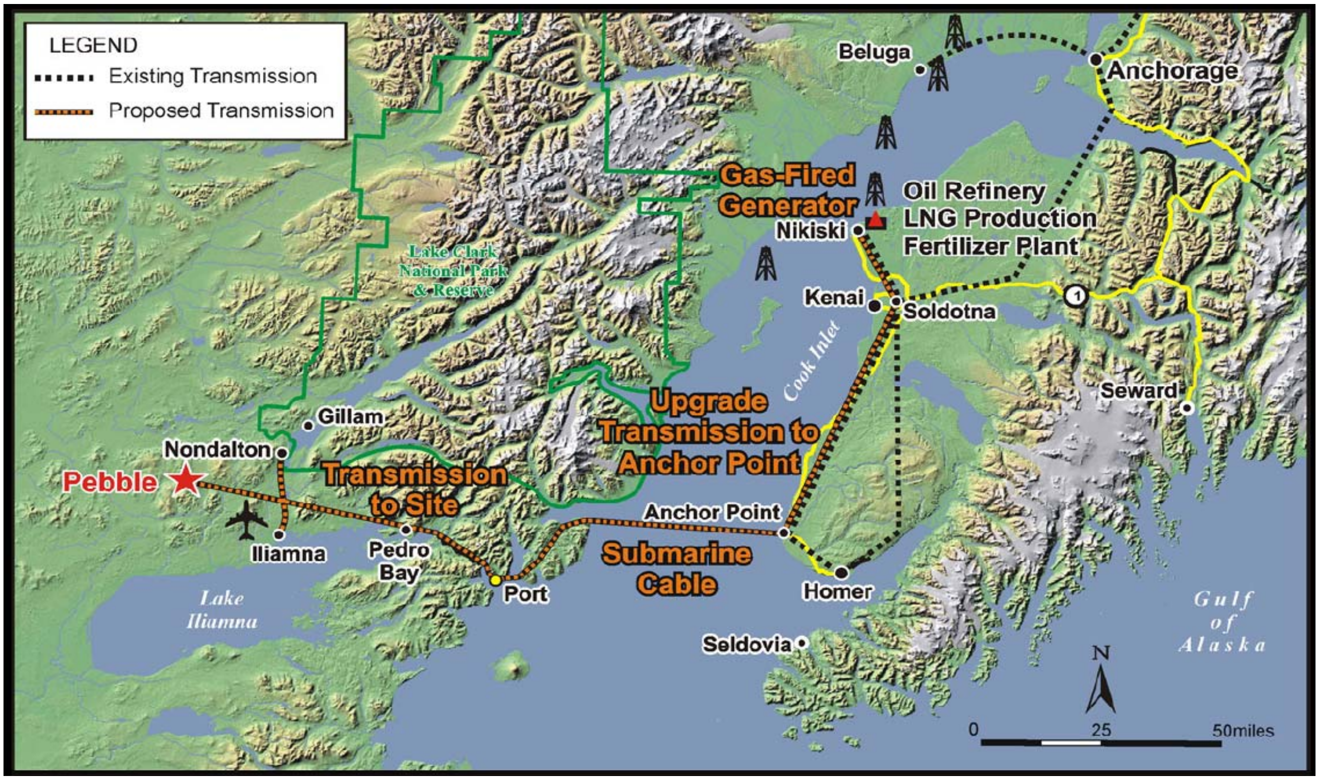


Figure 61. Possible transmission line route for the proposed Pebble Mine, as posted on the Pebble Partnership website in January 2008. This route crosses Cook Inlet and enters the Alaska Peninsula immediately south of LACL (green border). The figure is taken from Pebble Partnership's website at: http://www.pebblepartnership.com/pages/project-information/road-port-power.php

Condition Overview and Recommendations

Condition overview

Based on our research of available data and our best professional judgment, we summarize the potential and existing stressors of aquatic resources in LACL in the following table (Table 20).

Table 20. Water resources-related indicators and current/potential stressors of aquatic resources in Lake Clark National Park and Preserve.

Indicator	Freshwater	Intertidal, Bays, Estuaries & Salt Marshes	Coastal waters
Water Quality			
Nutrients/ Eutrophication	OK	OK	OK
Contaminants	PP	PP	EP
Hypoxia	OK	OK	OK
Turbidity	OK	OK	OK
Pathogens	OK	OK	OK
Habitat Disruption			
Coastal development	PP	PP	OK
Water quantity/ withdrawals	OK	OK	OK
Shoreline modification by humans	OK	PP	OK
Natural geologic hazards	IP	IP	IP
Natural coastal uplift and erosion	OK	EP	OK
Mining impacts	PP	PP	PP
Logging in private inholdings	PP	OK	OK
Power development, coal and hydro	PP	PP	OK
Recreational usage			
Tourism (Fishing and bear viewing)	PP	PP	OK
ORV usage	PP	PP	OK
Other Indicators			
Oil spills	NA	PP	PP
Harmful algal blooms	NA	PP	PP
Aquatic & marine invasive species	PP	PP	PP
Climate change	EP	EP	EP
Coastal trash	NA	PP	NA

Definitions: EP= existing problem, IP= Intermittent Problem, PP = potential problem, OK= no detectable problem, shaded =limited data, NA= not applicable.

Freshwater and marine ecosystems in and adjacent to LACL are dominated by natural influences with few potential problems of concern; however, in many cases, few data are available (Table 20).

Recommendations

The SWAN is currently implementing their Vital Signs Monitoring Plan, which is based on a tremendous research and planning effort that is certain to greatly expand on the current level of understanding of water (and other) resources in the network. We highly commend the SWAN I&M team for their efforts. Most of the main issues and data gaps that we initially identified throughout our research for this project are being addressed, or will be addressed, according to the Vital Signs Monitoring Plan. During the course of writing this report, we identified data gaps and areas in which further investigation or monitoring is warranted, or at least recommended, if resources become available beyond the I&M program. These recommendations are listed and then described below.

Recommendations:

Data access/management

1. Online archives of NPS publications and reports, publicly accessible
2. Integration and development of information into centralized and web-accessible GIS
3. Derivation of a GIS-based ecological classification system for coastal watershed conditions
4. Derivation of a higher-resolution Digital Elevation Model (DEM) for LACL

Water quality

1. Assess threat from oil production waste in Cook Inlet
2. Oil spill response planning
3. Assess threat from atmospheric and marine-derived contaminants
4. Continue and expand on efforts to establish baseline freshwater water quality and watershed condition
5. Evaluate and monitor impacts of tourism and recreation on coastal water quality
6. Maintain close communications with potential developers within and adjacent to LACL

Biological resources and habitats

1. Harbor seal status evaluation
2. Recreational sport fishing data
3. Coastal wildlife data
4. Invasive species survey
5. Planning for natural hazards

Hydrology/Oceanography

1. Physical scientist hire for LACL
2. Climate/weather stations
3. Glacier monitoring
4. Streamflow gaging

Data access/management

Online archives of NPS publications and reports, publicly accessible: A large number of NPS-related documents are available in electronic format online through NatureBib, an excellent searchable database. However, while many citations are listed for LACL, only a small minority have downloadable files attached to the citation information. In addition, this database is not yet publicly accessible (as of November 2008).

Integration and development of information into centralized and web-accessible GIS: Data from surveys, monitoring activities, impairments, and inventories should be integrated into a centralized and publicly-accessible web format, with study locations geographically referenced and integrated with the current web-accessible NPS GIS clearinghouse (http://www.nps.gov/akso/gis/).

Derivation of a GIS-based ecological classification system for coastal watershed conditions: GIS and remote sensing data for LACL coastal study area could be improved, particularly through development of an ecologically-based classification system of coastal watershed conditions. This and other useful classified products for water resource monitoring could be developed through a stepwise remote-sensing procedure that first involves development of a training dataset derived from a combination of existing ecological/physiographic data sources, including wetland (e.g. national wetland inventory) and ShoreZone data sets, both of which have been reasonably ground-truthed and mapped at reasonable spatial resolutions; and coastal-marsh mapping efforts (Tande, 1996). With regards to remote sensing imagery that could be used in consort with training data to adequately classify the entire coastal study area, moderate resolution, multispectral IKONOS imagery is already available for ~40-50% of the coastal study area of LACL (Manley et al., 2007; Manley et al., 2008). We recommend acquisition of a complete set of this imagery for the coastal study area (e.g. including inland portions of coastal watersheds). The imagery could be acquired through cooperation with other interested agencies (e.g. NOAA, AVO, DNR) with jurisdiction adjacent to or near LACL or other research scientists (e.g. INSTAAR). This imagery could also be useful for monitoring other hydrologic parameters within the park, such as the extent of permanent snowfields and the number and aerial coverage of lakes and ponds.

Derivation of a higher-quality Digital Elevation Model (DEM) for LACL: We recommend acquisition of a complete, consistent, and accurate digital elevation model at a higher resolution (e.g. 10m) than what is currently available for the LACL. Topographic data is currently provided in piecemeal fashion by either a 30-m digital terrain model (DTM) of unknown accuracy and derived from stereographic interpretation (Manley et al., 2008), a statewide 60-m USGS DEM of moderate accuracy, and/or a 90-m DEM from the Space Shuttle Radar Topography Mission (SRTM), which is not available for portions of the LACL shoreline and apparently contains inaccuracies in LACL (Manley et al., 2008). Although these may be sufficient for basic terrain visualization and orthorectification of imagery (Manley et al., 2008), a high quality DEM would be more valuable for analytical purposes relating to the monitoring of coastal watershed conditions. In particular, a high quality DEM would be beneficial for a more accurate delineation of coastal watersheds and drainages, the monitoring of glacial recession, as well as supporting a fine-scale ecological classification for terrestrial portions of coastal watersheds, as described above. A sub-meter scale, LIDAR-based DEM is currently planned for another SWAN park on the Kenai Peninsula (KEFJ) and this type of DEM could also be acquired for the LACL area for numerous research and management applications.

Water quality

Assess threat from oil production waste in Cook Inlet: The Clean Water Act prohibits discharge of oil production waste in coastal and offshore waters; however, oil production facilities in Cook Inlet are exempt from this requirement. The EPA acknowledges that these wastes likely impair water quality but have determined the likely impacts are minor. The NPS should assess the threat to water quality and resources in LACL from these oil production wastes. As a first step, the NPS could conduct marine water quality sampling to investigate the possible presence of oil production pollutants.

Oil spill response planning: The NPS should continue their partnership with other responsible agencies, Coast Guard, ADEC, etc., to further develop and maintain geographic response strategies (GRS) and oil spill response plans, for the LACL coast. NPS and their partners may want to collaborate with organizations developing circulation models for Cook Inlet to predict potential oil spill trajectories.

Assess threat from atmospheric and marine-derived contaminants: LACL (along with other SWAN units) should continue its recently initiated efforts to assess the threat from global-scale pollutants such as mercury and POPs. Because these pollutants are not derived from localized sources, monitoring these pollutants in one park within the network would provide information that would be useful for assessing potential impacts in the other parks. However, data specifically from LACL would be best, as distances and landscape differences among park units are large. Contaminant monitoring in fish from the Lake Clark drainage (conducted as part of the Vital Sign Monitoring Program) should be continued into the long term. Ideally, fish from the coastal study area should be added to the monitoring effort, as well. Recently published results of the WACAP project also provide important information on contaminants in the region, as well as protocols for sampling of parameters other than fish (snow, lake water, sediment, lichens, fish, and other subsistence foods) that may be of use for future contaminant monitoring plans. SWAN should also move forward with efforts to install a National Atmospheric Deposition Program (NADP) site in King Salmon to track changes in regional precipitation chemistry over time. In addition, the network should monitor forthcoming results from the Mercury Deposition Network sites currently being established by the Alaska DEC in southcentral and southwestern Alaska and by the NPS in GLBA in southeastern Alaska. On a more local level, the NPS should closely monitor plans to develop the nearby Chuitna Coal Fields and assess the project's potential impacts to park resources.

Continue and expand on efforts to establish baseline freshwater water quality and watershed condition: Very little information is available on water quality in the LACL coastal region. Although the implementation of the vital signs monitoring plan for the SWAN will greatly enhance the understanding of baseline freshwater water quality in LACL, no water bodies in the coastal LACL zone have been categorized as "Tier 1," which would receive annual monitoring. The selected coastal water body (Crescent River) is ranked as Tier 2 (sampling planned every 2-5 years) and should be considered for additional funding support in order to increase the likelihood of monitoring it more regularly and over the long term. Crescent Lake has been relatively heavily studied for a LACL coastal water body, and it would therefore be informative to continue occasional monitoring for water quality, physical habitat, and biological variables in this lake, as well (especially in terms of the apparent declines in copepod species *Cyclops scutifer,* which may be linked to climate warming and increased glacial melt and turbidity). In addition, a water quality survey of a subset of coastal streams would be beneficial for establishing baseline information on conditions in those watersheds. Physical, chemical, and biological parameters would include turbidity (streams), Secchi depth (lakes), temperature, conductivity, total dissolved solids (TDS), dissolved oxygen (DO), pH, organic and inorganic nitrogen and phosphorus, sulfate, dissolved organic carbon (DOC), DOC quality, trace elements, organic pollutants, and inventories of macroinvertebrate communities (the current plan does not call for sampling of contaminants in water bodies). Streams draining a variety of environments, such as glacial, volcanic, non-glacial, wetland-rich, and wetland-poor should be measured for the above water quality parameters. Streams near volcanic areas should be prioritized because those are most likely to have highly mineralized, acidic waters that may warrant drinking water warnings to the rare visitor to those areas. All of this information should be stored in a database as a way to facilitate data access.

Evaluate and monitor impacts of tourism and recreation on coastal water quality: The popularity of fly-fishing trips and accompanying disturbances, such as ORV use, in parts of the LACL coastal region has been on the rise in the past decade. In response, the NPS has been mapping ORV trails and is working on developing an ORV access plan for the Silver Salmon Creek area. The NPS should continue these efforts to educate ORV users, designate trails, and to enforce restrictions on ORV use in riparian and coastal areas. We also recommend that the NPS conduct studies to identify the location and density of recreational and tourism visits to other parts of the coastal area and investigate potential water quality impairments due to disposal of garbage and human waste, oil spills and leaks from boats and float planes, use of (unmaintained) camping sites and trails along stream corridors, and accelerated streambank erosion/vegetation trampling due to fly-fishing and bear-viewing activities. In addition, the NPS would benefit from more data on the recreational sport fishing harvest in coastal watersheds to better manage those activities and stocks.

Maintain close communications with potential developers within and adjacent to LACL: Potential development issues exist in the LACL coastal region—from cabins within private inholdings, to mining in the Johnson River watershed, logging in the Crescent River watershed, and to the routing of power lines and construction of ports to support the proposed Pebble Mine project near Lake Iliamna. Therefore, the NPS should diligently track any efforts that could disrupt the natural properties and functions of the Park and Preserve and be prepared to respond in a manner that will protect and preserve the unit, in keeping with the original mandate from ANILCA.

Biological resources and habitats

Harbor seal status evaluation: The SWAN I&M program should continue to partner with other organizations that are monitoring harbor seals. Given that harbor seals have declined in other areas of Alaska, special attention should be paid to harbor seal haul-out populations to evaluate if these populations might be experiencing similar declines.

Recreational sport fishing data: Additional data is needed to evaluate impacts of recreational sport fishing harvest in coastal streams.

Coastal wildlife data: Coastal wildlife, including brown bears, black bears, wolves and moose are not included in the LACL wildlife program. Information is needed on these important biological resources.

Invasive species survey: Aquatic and marine environments should be surveyed for invasive species. Standard protocols, such as PVC settling plates as passive collectors in subtidal marine environments (Ruiz et al. 1997), should be used whenever possible to survey invasive species. Freshwater streams should be monitored for the presence of potential invasive species such as Northern pike or Atlantic salmon. As part of the Vital Signs Monitoring Plan, invasive/exotic species surveys are planned with a strong focus on vegetative invasive species. We recommend that invasive/exotic species surveys are sure to include not only areas of relatively dense human use, but also the more remote, inaccessible areas of LACL.

Planning for natural hazards: Future tectonic activity is inevitable in and near LACL, and the likely effects of a large eruption, earthquake, tsunami, and/or catastrophic flood may have devastating short-term consequences to its resources despite some long-term benefits (e.g. nutrients in volcanic ash). While the timing and magnitude of such natural events cannot be manipulated by resource managers, certain measures can be taken to minimize secondary damage incurred by the destruction of human-related infrastructure. Most importantly, the NPS should be a proponent of moving the oil storage facility at the Drift River from its current location, which is in an active earthquake zone and within the pathway of water flooding and lahar flows from the regularly active Redoubt Volcano. Structural compromise or destruction of this facility may result in tremendous deleterious effects on water and biological resources not only for the lower Drift River area, but for an extensive part of the adjacent coastal region of LACL. Other actions that could minimize or prevent secondary damage to LACL resources from volcanic eruptions and tsunamis include the rerouting of marine and air traffic away from the area, so that these vessels and any hazardous materials they may contain will not injure LACL resources in the event of their destruction. In particular, the NPS should continue to work with the AVO on effective communication regarding volcanic hazards and development and maintenance of response strategies.

Hydrology/Oceanography

Physical scientist hire for LACL: LACL should consider hiring a physical scientist to oversee monitoring of hydrologic and oceanographic resources as well as park climatology.

Climate/weather stations: Climate change is one of the major threats to water resources in Alaskan parks. Streamflow in coastal parks such as LACL is particularly sensitive to climate change because during the winter the air temperature near sea level in southwestern Alaska is close to the freezing point of water. As a result, a relatively small increase in temperature can shift precipitation from snow to rain which, in turn, shifts the annual pattern of streamflow in coastal watersheds. Basic climate parameters in LACL should be monitored, ideally at both a coastal and an interior location because of the strong climate gradients within the park. Data collection should be automated, continuous, and archived with transmittal of information to national databases (i.e. NOAA, USGS). Physical parameters that should be monitored include air temperature, precipitation, wind speed, wind direction, and other weather and oceanographic factors. To this end, it will be critical to ensure ongoing funding for the SWAN I&M remote weather stations at Hickerson Lake and in the Chigmit Mountains.

Glacier monitoring: The SWAN I&M program is currently working to map glaciers within LACL using LANDSAT imagery and repeat photography. We recommend that LACL also investigate the possibility of using newly developed methods to predict and visualize future changes in glacial extent (Paul et al., 2007). These methods are automated and require only digital glacier outlines (available from satellite images) and a digital elevation model (DEM) and can be used to calculate new glacier geometries from given shifts of the steady-state equilibrium line altitude for LACL glaciers. These visualizations of glacier change would be useful for resource managers and also represent an excellent outreach product that can be used to communicate research results on glacier changes to the general public.

Streamflow gaging: There are currently no streamflow gaging stations operating within LACL, although streamflow is a key parameter in any water quality monitoring effort. Information on seasonal discharge patterns, as well as longer-term variations in streamflow along one or more LACL coastal streams, would be highly useful for evaluating the effects of climate change on surface water hydrology. If possible, gages should be established on one glacial and one non-glacial stream.

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Appendix A. Southwest Alaska Network vital signs in the context of the program-wide vital signs organization framework of the National Park Service (Table 3-1 in SWAN Vital Signs Monitoring Plan, Bennett et al., 2006).

Level 1	Level 2	Level 3	SWAN Vital Sign	ALAG	ANIA	KATM	KEFJ	LACL
Air and Climate	Air Quality	Visibility and particulate matter	Visibility and particulate matter	-	●	-	-	●
	Weather and Climate	Weather and Climate	**Weather and Climate**	-	-	X	X	X
Geology and Soils	Geomorphology	Glacial features and processes	**Glacier Extent**	-	-	X	X	X
		Coastal / oceanographic features and processes	**Geomorphic coastal change**	-	-	X	X	X
	Subsurface Geologic Processes	Volcanic and Seismic Activity	Volcanic and Earthquake activity	●	●	●	●	●
Water	Hydrology	Surface water dynamics	**Surface hydrology**	X	X	X	X	X
	Water Quality	Water chemistry	Marine Water Chemistry			X	X	X
			Freshwater Chemistry	X	X	X	X	X
Biological Integrity	Invasive Species	Invasive/Exotic plants and animals	Invasive/Exotic plants	●	●	●	●	●
	Infestations and Disease	Insect pests	Insect outbreaks	-	-	●	●	●
	Focal Species or Communities	Marine communities	Kelp and eelgrass	-	-	X	X	X
		Marine invertebrates	Marine intertidal invertebrates	-	-	X	X	X
		Fishes	**Resident Lake Fish**	X	X	X	X	X
			Salmon	●	●	●	●	●
		Birds	**Black oystercatcher**	-	-	X	X	-
			Bald eagle	X	X	X	X	X
			Seabirds	-	-	X	X	X
		Mammals	**River otter (coastal)**	-	-	X	X	X
			Brown bear	X	X	X	-	X
			Wolf	X	X	X	X	X
			Wolverine	X	X	X	X	X

Level 1	Level 2	Level 3	SWAN Vital Sign	ALAG	ANIA	KATM	KEFJ	LACL
			Moose	X	X	X	-	X
			Caribou	●	●	●	-	●
			Sea otter	-	-	X	X	X
			Harbor seal	-	-	●	●	●
		Vegetation complex	**Vegetation Composition and Structure**	X	X	X	X	X
			Sensitive Vegetation Communities	X	X	X	X	X
Human use	Consumptive Use	Consumptive use	Resource harvest for subsistence and sport	●	●	●	-	●
	Visitor and Recreation Use	Visitor usage	Visitor use	●	●	●	●	●
Landscapes (Ecosystem Pattern and Processes)	Landscape Dynamics	Land cover and use	**Land Cover/Land Use**	X	X	X	X	X
			Landscape Processes	X	X	X	X	X

X = Vital signs that the SWAN is working independently or jointly with a Network park, federal, state, or private partner to develop and implement monitoring protocols using funding from the vital signs or water quality monitoring programs
● Vital signs that are monitored independently of SWAN by a Network park, another NPS program, or another federal, state, or private agency. (category 2, information is obtained and used by SWAN)
- Vital sign will not be monitored in that park

Appendix B. Non-indigenous invasive species that have invaded or could soon invade Alaska. The species listed are all highly invasive, have caused severe impact in areas they have spread to, and are capable of living in Alaska's climate. Many of these species have already spread to the Pacific Northwest and are a risk to Alaska. From ADFG (2002a) and with updates from Amy Miller (NPS-Anchorage, personal communication, 2008).

Species	**Originally from…**	**Now located in…**	**Why it is a concern**
Fish:			
Northern Pike	Alaska	Spreading to other areas of Alaska; found i lakes on Kenai Peninsula and Susitna River drainage	Highest priority threat to Southcentral Alaska. They eliminate or greatly reduce the native species. Cause damage to resident spec (rainbow trout and grayling). Potential impact to coho salmon stocks.
Atlantic Salmon	Escape from Fish farms in BC and Washington	Cordova Ketchikan Yakutat Bering Sea	Serious threat to native species due to competition in stream habitat. Displace native fish by out-competing for food and spawning habitat.
Yellow perch		Kenai Peninsula	Compete with all resident fish species and salmon fry. This population has been eradicated.
Ornamental aquarium fish			Compete with and may feed on native species.
Invertebrates:			
Green crab	N. Europe	California to Vancouver Island	Out-competes resident species for shoreline habitat. Very aggressive.
New Zealand mud snail	New Zealand	Europe Asia Idaho Montana Wyoming California Arizona	May impact the food chain for native trout and the physical characteristics of streams themselves. A serious threat to Alaska's sport fisheries.
Chinese mitten crab	China	San Francisco Bay/delta Possible it is in Oregon' Columbia River	Similar life history to American eel and can move upriver hundreds of miles displacing native species. Feeds on salmonid eggs.
Zebra mussel	Europe	Great Lakes	Out-compete resident mussels, clog water inta lines, sequester nutrients for primary producti
Signal crayfish	W. Canada	Kodiak Island	Out-compete stream fauna, eat everything, can survive extended periods of drought and famine.
Spiny water flea	Europe	Great Lakes California	Displaces existing zooplankton communities, but is unpalatable to fish resulting in lower fish numbers.
Parasites:			
Whirling disease	Eurasian continent	Present in 22 states. Found in all western states excep Arizona and Alaska.	Parasitic infection that attacks juvenile trout a salmon. Causes fish to swim erratically and in severe cases, to die.
Plants:			
Hydrilla or water thyme	Originally from S. India and Korea.	Present in 15 states including Califor and Washington	Hydrilla is a noxious water weed that can quickly spread to become an impenetrable mat. Fills lakes and rivers completely until it "tops out" at the surface. Native plants are out-competed. Greatly slows water flow and

			clogs the area. Can alter water chemistry and oxygen levels. Hinders fish development.
Dotted duckweed	Australia and Southeast Asia	Present in 22 states including Oregon	This small floating plant grows rapidly into dense masses in still water covering the entire surface in a green "bloom".
Purple loosestrife	Eurasia	Present in all states except Hawaii. Also found in Canada. Found in Anchorage in 2005	Loosestrife is able to rapidly establish and replace native vegetation with a dense, homogeneous stand that reduces local biodiversity, endangers rare species and provides little value to wildlife.
Eurasian water-milfoil	Europe and North Africa	Present in 46 states including Alaska	Found in a variety of habits, becoming established in both impoundments and natural waters, sometimes brackish water or in clear, cool, spring-fed rivers. Problems include displacement of native vegetation, disruption of navigation and recreation by the formation of impenetrable mats, and decreased water flow.
Reed Canary grass	Eurasia	All but the southeastern portion of the US including Alaska. Also found in Canada. Widespread in the lowe Kenai Peninsula	Is invading freshwater wetlands and in some places choking channels of small streams. Its creeping rhizomes out-compete native grasses leading to less biodiversity.
Japanese knotweed	Great Britain	Sitka Juneau Other Southeast Alaska areas	Spreads rapidly, choking out native plants. Can spread along streambanks, shorelines, and estuaries. Loss of springtime cover and woody streamside vegetation causes destabili stream banks and less woody debris in stream
Foxtail barley	Western North America	Juneau Interior Alaska	Invades salt marsh habitats
Salt marsh cordgrass	Eastern seaboard of the US from Maine to Texas	Has spread to Canada and western US including Washington, Oregon, and California.	Able to trap sediment leading to higher deposition rates. Changes water circulation patterns. Competitive replacement of native plants and impacts native flora and fauna in intertidal zone. Also, decreases production of bottom-dwelling algae, changes bottom-dwelling invertebrate populations, and loss of shorebird foraging areas.
Dense-flowered cordgrass	Chile South America	California	Outcompetes native flora and impacts native fauna. Eliminates foraging habitat for shorebi and waterfowl. Dense clusters slow the flow c water and increase sedimentation (raising the wetland).
Swollen bladderwort	Southeastern US	Western Washington	Grows in still or slow-moving water and forms dense beds of floating plants. Impacts native plants and animals and water quality.

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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