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Temporal coherence of two alpine lake basins of the Colorado Front Range, U.S.A.

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SUMMARY

1. Knowledge of synchrony in trends is important to determining regional responses of lakes to disturbances such as atmospheric deposition and climate change. We explored the temporal coherence of physical and chemical characteristics of two series of mostly alpine lakes in nearby basins of the Colorado Rocky Mountains. Using year-to-year variation over a 10-year period, we asked whether lakes more similar in exposure to the atmosphere behaved more similarly than those with greater influence of catchment or in-lake processes.
2. The Green Lakes Valley and Loch Vale Watershed are steeply incised basins with strong altitudinal gradients. There are glaciers at the heads of each catchment. The eight lakes studied are small, shallow and typically ice-covered for more than half the year. Snowmelt is the dominant hydrological event each year, flushing about 70% of the annual discharge from each lake between April and mid-July. The lakes do not thermally stratify during the period of open water. Data from these lakes included surface water temperature, sulphate, nitrate, calcium, silica, bicarbonate alkalinity and conductivity.
3. Coherence was estimated by Pearson's correlation coefficient between lake pairs for each of the different variables. Despite close geographical proximity, there was not a strong direct signal from climatic or atmospheric conditions across all lakes in the study. Individual lake characteristics overwhelmed regional responses. Temporal coherence was higher for lakes within each basin than between basins and was highest for nearest neighbours.
4. Among the Green Lakes, conductivity, alkalinity and temperature were temporally coherent, suggesting that these lakes were sensitive to climate fluctuations. Water temperature is indicative of air temperature, and conductivity and alkalinity concentrations are indicative of dilution from the amount of precipitation flushed through by snowmelt.
5. In Loch Vale, calcium, conductivity, nitrate, sulphate and alkalinity were temporally coherent, while silica and temperature were not. This suggests that external influences are attenuated by internal catchment and lake processes in Loch Vale lakes. Calcium and sulphate are primarily weathering products, but sulphate derives both from deposition and from mineral weathering. Different proportions of snowmelt versus groundwater in different years could influence summer lake concentrations. Nitrate is elevated in lake waters from atmospheric deposition, but the internal dynamics of nitrate and silica may be controlled by lake food webs. Temperature is attenuated by inconsistently different climates across altitude and glacial meltwaters.

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6. It appears that, while the lakes in the two basins are topographically close, geologically and morphologically similar, and often connected by streams, only some attributes are temporally coherent. Catchment and in-lake processes influenced temporal patterns, especially for temperature, alkalinity and silica. Montane lakes with high altitudinal gradients may be particularly prone to local controls compared to systems where coherence is more obvious.

Keywords: alpine lake basins, Colorado front range, temporal coherence

Introduction

'A group of lakes confronts the investigator as a series of very complex physicochemical and biological systems, each member of which has its own characteristics and yet also has much in common with the other members of the group. It is this diversity in unity that gives the peculiar fascination to limnology.'

– G. Evelyn Hutchinson (1957).

Hutchinson (1957) defined a lake district as a geographically distinct cluster of lakes of similar origins and general characteristics. By this definition, all lakes from the southern Yukon territory of Canada to northern New Mexico are part of the Rocky Mountain lake district. The Rocky Mountains of North America contain thousands of alpine and sub-alpine lakes which are similar in their genesis through montane glacial activity. All of these lakes are ice-covered for some, if not most, of the year, and spring snowmelt is the dominant hydrologic event. Despite these similarities, the lakes differ in their climate, bedrock chemistry, biotic history and degree to which their basins have been disturbed by human activity (Hauer *et al.*, 1997). From Hutchinson (1957) to the present, there has been a continued interest in the relative magnitude of natural versus human-driven and intrinsic versus extrinsic controls on lake dynamics (Magnuson, Benson & Kratz, 1990). This interest is driven by intellectual curiosity, but also by the need for better understanding on the part of resource managers charged with protecting these lakes. What constitutes change away from a natural condition? Do externally imposed changes, such as acid deposition or climate change, influence all lakes within a district similarly? Can changes be predicted for a lake district by knowing the dynamics of one or two well-studied lakes?

In this paper, we explore the spatial and temporal dynamics of physical and chemical characteristics of two series of lakes in nearby basins of the Colorado Rocky Mountains. Our exploration addresses the concept of temporal coherence by looking at the year-to-year variation of a number of parameters over a 10-year period (Magnuson *et al.*, 1990). Among the questions asked by Magnuson *et al.* (1990) were whether lakes which were more similar in exposure to the atmosphere behaved more similarly than those which were less similar. Lakes with the smallest drainage areas, i.e. lakes with proportionately more of their inputs derived from precipitation and deposition than from groundwater, were less buffered from climatic variability, or more temporally coherent, than lakes with more basin area and less direct atmospheric influence. In Rocky Mountain lakes, headwater lakes tend to have the smallest drainage areas, allowing landscape position (sequence in the lake chain) to serve as a surrogate for drainage area.

Since the 1950s, air temperatures at the higher altitudes of the Colorado Front Range have decreased, while precipitation has increased in the Front Range (Williams *et al.*, 1996; Stohlgren *et al.*, 1998). Other regional scale changes include increased atmospheric nitrogen deposition and decreased atmospheric sulphur deposition (Baron, Allstott & Newkirk, 1995; Lynch, Grimm & Bowersox, 1995). We use these changes in climate and deposition as regional drivers to ask: (1) How similarly do Front Range lakes respond to external changes? and (2) Are some lakes or some physicochemical parameters more susceptible to external forcing than others?

Methods

Study sites

Our study sites were located in the Front Range of Colorado, a north–south-trending massif located directly west of Denver, CO, U.S.A. The Front Range

is predominantly Precambrian granite, schist and gneiss. A narrow belt of intrusive rocks containing productive, or once-productive, mineral deposits extends south-west at the southern end of the range (Lovering & Goddard, 1959). The Front Range contains over 400 small alpine and sub-alpine lakes.

Lakes in the Rocky Mountains are commonly arranged in series down steeply incised, glaciated valleys. We compared two such series of lakes in the Front Range, including five from the Green Lakes Valley and three from the Loch Vale Watershed (Fig. 1). The Green Lakes Valley is a 700-ha, east-facing catchment ranging in altitude from 4000 to 3345 m. Green Lakes 4 and 5 are above treeline, while Green Lakes 3, 2 and 1 are at treeline. About two hectares of sub-alpine forest occupy the north valley slope above Lake Albion. Green Lake 1 is a seepage lake, tributary to the main drainage from the north. The outlets to Green Lake 2 and Lake Albion are controlled, and the water levels of these water bodies fluctuate greatly in some years. The 660-ha Loch Vale Watershed is 25 km north of the Green Lakes Valley and is a north-east facing catchment in Rocky Mountain National Park. Within its altitudinal range of 4000 to 3100 m, there are four lakes: Andrews Tarn, Sky Pond and Glass Lake in the alpine zone, and The Loch in the sub-alpine forest. There are glaciers at the headwaters of the Green Lakes Valley (above Green Lake 5) and at the headwaters of the Loch Vale Watershed (above Sky Pond and also above Andrews Tarn). Green Lake 3 and Andrews Tarn were not included in our analyses because these are rarely sampled.

The study lakes are small and shallow, with average depths of between 1.5 and 8.6 m (Table 1). The lakes are typically ice-covered for more than half of the year. The open-water period for Green Lakes 5 and 4 is typically 3–3.5 months long, while the lower lakes can have 5–5.5 months of open water. Snowmelt is the dominant hydrologic event each year, flushing about 70% of the annual discharge from each lake between mid-April and 15 July (Baron & Bricker, 1987). After snowmelt, glacial melting and groundwater seepage continue to supply cold water. None of the lakes stratify thermally during the open-water period. The lakes are dilute and oligotrophic. Conductivity ranges from 8 to 40 μS cm^{-1} and dissolved silica from 10 to 40 μmols L^{-1}. Sulphate ranges from 20 to 130 μeq L^{-1} and nitrate averages about 16 μeq L^{-1}. In Loch Vale, except during midwinter algal blooms under lake ice, nitrate concentrations do not go below 5 μeq L^{-1}. All lakes except Green Lake 1 have circumneutral pH, and alkalinities range between 40 and 250 μeq L^{-1} (Caine & Thurman, 1990; Baron, 1992).

Data have been collected from the Green Lakes and from Loch Vale since the early 1980s as part of long-term ecological research programmes supported by the U.S. National Science Foundation and the U.S. Department of Interior, respectively. Samples have been taken twice monthly or weekly during the open water season since 1982 in the Green Lakes Valley (Caine & Thurman, 1990). Weekly sampling of surface waters in Loch Vale Watershed during the open water season occurred from 1983 to 1989. Since 1989, lake sampling currently occurs weekly at The Loch outlet year-round and twice monthly at other lake sites during the open water season (Newkirk, Allstott & Baron, 1995).

The climate of the Green Lakes Valley and the Loch Vale Watershed is windy and harsh, characterized by long cold winters and short, cool summers. Temperature is inversely related to altitude. The 40-year mean annual air temperature at 3750 m on Niwot Ridge above the Green Lakes is –3.8 °C. At 3048 m, the mean 1953–1994 air temperature is 1.3 °C (Williams *et al.*, 1996). The mean 1984–1990 temperature at 3160 m in the Loch Vale Watershed is 1.5 °C (Baron, 1992). Both basins receive an average of slightly more than 1000 mm of precipitation per year, of which 65–80% of occurs as snow. Precipitation is quite variable from year to year; for instance, a range of 890 mm to 1420 mm has been recorded in Loch Vale since 1984 (Newkirk, Baron & Allstott, 1996).

Lake data

The lake data used for this analysis included mean surface water temperature for the open water season, several chemical variables thought to be representative of atmospheric deposition (sulphate and nitrate), and mineral weathering and groundwater inputs (calcium, silica, bicarbonate alkalinity and conductivity). Nitrate and silica are also biologically mediated, leaving open the possibility that uptake could confound results. Consistent long-term biological records are missing from these lakes. Sampling and analysis methodologies, including quality control procedures, have been described elsewhere (Baron &

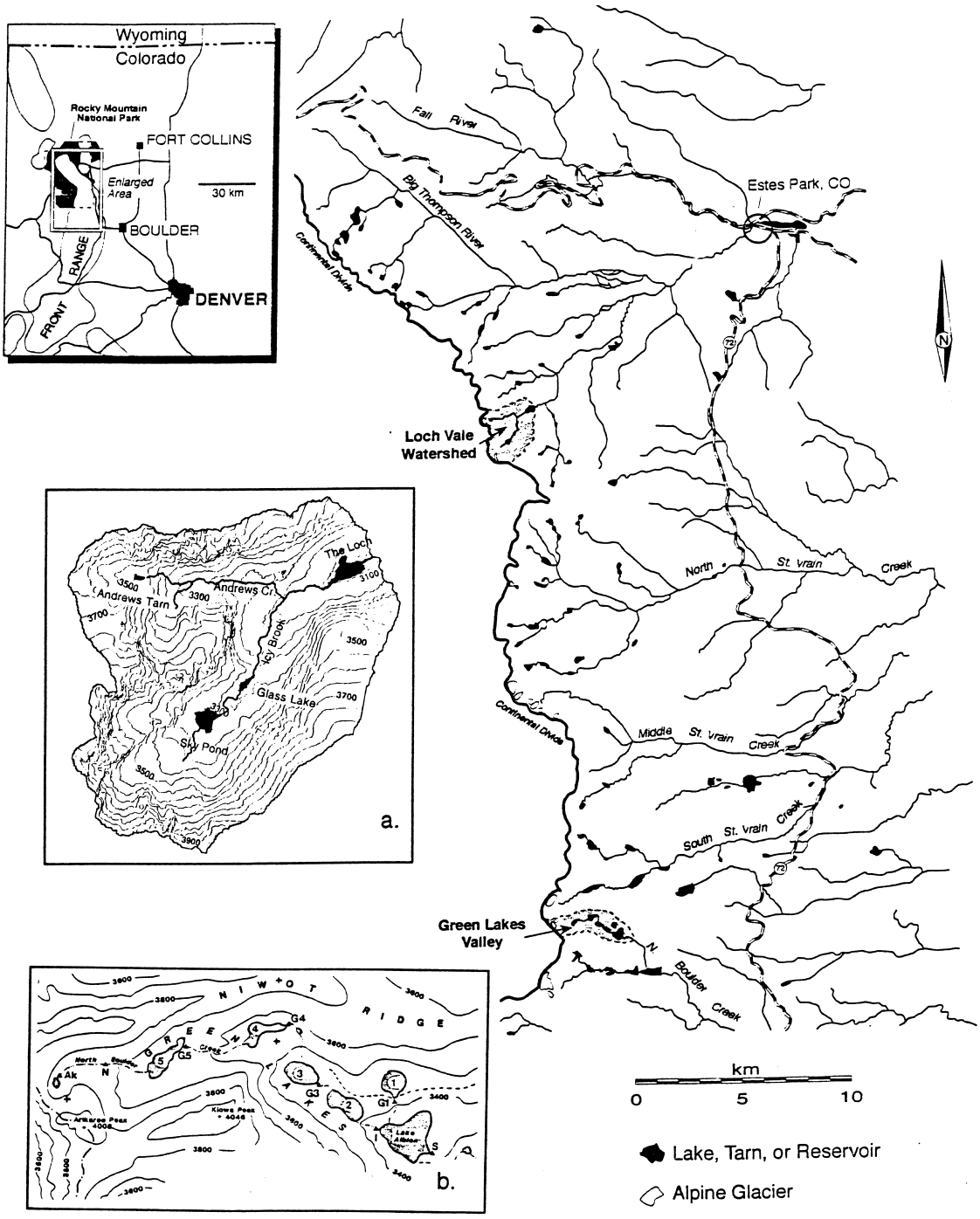

Fig. 1 Locations of the Loch Vale Watershed and the Green Lakes Valley (shaded) in the Front Range Mountains of Colorado, U.S.A. Note many other similar headwater catchments with lake chains. The upper inset shows the location of the Front Range Mountains within the larger region of northern Colorado and southern Wyoming. Inset (a) shows lakes within the Loch Vale Watershed and inset (b) shows lakes within the Green Lakes Valley.

Bricker, 1987; Caine & Thurman, 1990; Newkirk *et al.*, 1995).

We calculated the mean open water concentrations for each lake, as measured from the lake outlet. Open water periods varied from year to year, but were generally between June and October. Ten years of lake data from 1985 to 1995 were used; 1989 data were excluded because of poor data quality and a small

Table 1 Characteristics of the Loch Vale and Green Lakes Valley lakes of Colorado. Landscape position refers to the sequence in the lake chain, where position 1 is the highest lake in the chain, position 2 is the second highest lake in the chain and so on

		Area (ha)			Depth (m)				
Lake	Altitude (m)	Basin	Lake	Volume (10^6 m^3)	Mean	Maximum	Landscape position	Basin area/ volume	Lake area/ volume
Green Lake 5	3620	135	4.5	0.18	4.0	8.0	1	750	25
Green Lake 4	3550	221	5.3	0.21	4.1	13.0	2	1052	25
Green Lake 2	3400	≈ 400	6.8	0.52	7.7	16.0	4	769	13
Green Lake 1	3425	47	4.1	0.18	3.7	7.0	1	261	23
Lake Albion	3345	546	21.6	1.30	6.0	15.0	5	420	17
Sky Pond	3322	204	3.0	0.12	4.5	7.3	1	170	2.5
Glass Lake	3292	257	1.0	0.03	2.8	4.7	2	857	3.3
The Loch	3048	660	5.0	0.06	1.5	4.7	3	1100	3.3

number of samples. Sample sizes varied between years and sites. There were between nine and twenty-two samples per year for each of the Green lakes, and between three and twenty-two for each of the Loch Vale lakes. The Green lakes were sampled weekly to every other week, so that analyses are spread through the open water season. Daily to weekly sampling year-round between 1983 and 1987 in the Loch Vale watershed showed remarkably similar chemical concentrations during summer periods (Baron, 1992; Baron *et al*., 1998). Therefore, sampling frequency was reduced after 1987 without compromising our ability to characterize open water season chemistry.

We followed the methods described by Magnuson *et al*. (1990) for assessing temporal coherence. All possible combinations of lake pairs were rank ordered according to similarities in their altitude, morphometric characteristics and landscape position. These characteristics, enumerated in Table 1, included altitude, basin area (a rough measure of groundwater contribution), lake area, lake volume, mean lake depth and landscape position (i.e. position in the lake chain).

Statistics for estimating temporal coherence

The Pearson product-moment correlation was calculated for the 10 years of data for each lake pair and each variable using SAS (SAS Institute, 1988). As in Magnuson *et al*. (1990), the mean correlation, ρ (rho), was calculated for each lake pair and for each variable. For each lake pair, the arithmetic mean of all variable correlation coefficients was used to determine temporal coherence between lakes. For each variable, the arithmetic mean of the twenty-eight lake-pair correlation coefficients was used to examine temporal coherence of the variables. The percentage of strong correlations was also calculated for each variable and lake pair. A Bonferroni correction was applied to the significance level used to assign a strong correlation. Magnuson *et al*. (1990) defined strong correlation as correlation values greater than or equal to the critical value for a one-tail test of the correlation coefficient for significance at the $\alpha = 0.05$ level (since we are only concerned with positive correlations that indicate in-phase responses). The percentage of strong correlations was derived from the number of correlation coefficients that were significant at the 0.05 level. With 10 years of data, the $\alpha = 0.05$ critical value of rho in a one-tail test is +0.602.

Spearman rank correlation coefficients were used to estimate the relationship between the temporal coherence of lake pairs and their ranked similarity in morphometric characteristics. The Spearman rank correlation is a good metric because it is non-parametric and allows interpretation of the degree of association between two random variables.

Results

Temporal coherence across lake pairs

There were twenty-eight possible lake pairs from eight lakes. The mean rho for all variables and all lakes was +0.33; only 18% of the lake pairs were strongly correlated. Magnuson *et al*. (1990) found that one lake in their set from northern Wisconsin stood out as most

often dissimilar to the others. Our lakes were more variable, in that six out of the eight lakes were unique for at least one characteristic. The Loch, Glass Lake and Albion were at extreme ends of a rank order for four, three and three characteristics, respectively.

The mean rho for the twenty-eight lake pairs ranged from –0.02 to +0.74 (Table 2). The slight negative correlation occurred when Green Lake 1 was paired with Green Lakes 4 and 5. Green Lake 1 also showed very low correlation (+0.09 to +0.14) with the three lakes from Loch Vale, but was somewhat temporally coherent with Green Lake 2 and Albion (mean rho = +0.36).

The Loch was temporally coherent with Glass Lake and with Sky Pond, with mean rho values of +0.71 and +0.54, respectively, but there was less coherence between Sky Pond and its nearest neighbour, Glass Lake (mean rho = +0.36). Other lake pairs that were temporally coherent were the mainstem lakes from Green Lakes Valley: Green Lakes 5, 4 and 2, with mean rho values between +0.52 and +0.74. Albion and Green Lake 2 were temporally correlated (mean rho = +0.68), and this may not be surprising, considering that lake levels are sometimes manipulated together for water supply. Albion showed little temporal coherence with the other Green Lakes, and even less with the Loch Vale lakes.

No lake pair showed strong correlation for all variables, but the Green Lake 4–Green Lake 5 lake pair came close, with six out of seven variables, or 86%, having strong correlations (Table 2). All physicochemical variables except NO_3 had correlation coefficients greater than +0.60 between these two lakes. The lake pairs Albion–Green Lake 2 and The Loch–Glass Lake both showed five out of seven, or 71%, strong correlations, indicating that these lakes were synchronous for nearly all variables tested. Silica and

Table 2 Comparison of the lake pair mean correlation (rho) and strong correlations (%) with lake rank difference by altitude, morphometric characteristics and landscape position. Lake ranks were developed by the absolute difference in values between lakes; those lakes with identical landscape position were assigned the rank of 0

Lake pair	Mean rho	$r > 0.60$ (%)	Rank altitude	Rank basin area	Rank volume	Rank basin area/volume	Rank lake area/volume	Rank landscape position
Albion Glass	0.32	0.14	2	2	5	3	3	3
Albion Loch	0.28	0.14	3	1	4	5	3	2
Albion Sky	0.31	0.14	1	4	1	2	4	4
Albion GL1	0.36	0.29	2	6	3	1	2	4
Albion GL2	0.68	0.71	1	1	4	3	1	1
Albion GL4	0.31	0.43	3	3	1	4	2	3
Albion GL5	0.45	0.29	4	5	7	2	2	4
Glass Loch	0.71	0.71	1	3	2	2	1	1
Glass Sky	0.36	0.29	1	2	5	5	1	1
Glass GL1	0.13	0	4	4	2	4	4	1
Glass GL2	0.22	0	3	2	2	1	2	2
Glass GL4	0.37	0.43	5	1	1	1	5	0
Glass GL5	0.38	0.29	6	3	2	1	5	1
Loch Sky	0.54	0.43	2	5	4	7	1	2
Loch GL1	0.14	0.14	5	7	2	6	4	2
Loch GL2	0.19	0.14	4	2	1	2	2	1
Loch GL4	0.25	0.43	6	4	3	1	5	1
Loch GL5	0.25	0.14	7	6	2	3	5	2
Sky GL1	0.09	0	3	2	6	1	4	0
Sky GL2	0.19	0	2	3	4	4	3	3
Sky GL4	0.29	0.14	4	1	5	6	6	1
Sky GL5	0.15	0.14	5	1	6	4	6	0
GL1 GL2	0.36	0.43	1	5	3	3	2	3
GL1 GL4	–0.02	0.14	1	3	1	5	1	1
GL1 GL5	–0.02	0	2	1	1	3	1	0
GL2 GL4	0.52	0.43	2	2	3	2	3	2
GL2 GL5	0.53	0.57	3	4	3	1	3	3
GL4 GL5	0.74	0.86	1	2	1	2	1	1

temperature were not strongly correlated for Albion–Green Lake 2, while alkalinity and temperature were not strongly correlated for The Loch–Glass Lake. Five lake pairs showed no strong correlation at all, including Sky Pond and Glass Lakes with Green Lakes 1 and 2, and Green Lake 1 with Green Lake 5.

Rank landscape position did not appear to be a deciding characteristic for explaining temporal coherency, or lack thereof, between lakes (Tables 2 & 3). The lake pairs that were least similar, such as Green Lake 1 with Green Lake 5 and Sky Pond, had identical rank landscape position. These are all headwater lakes, although their catchments are quite different, especially with regard to the extent and nature of surficial deposits. The extreme topographic complexity of the Front Range allows lakes of identical landscape position to have very different basin characteristics, so that some lakes of identical landscape position had high rho values, while others had low rho values. Lake pairs which were most temporally similar had a range of landscape position ranks of 1–3. Similarity of lake basin area was also unrelated to temporal coherence; lake pairs with both low and high temporal coherence were found among all ranks of basin area similarity. The relation of temporal coherence to lake volume appeared mostly random. The rank lake area/lake volume ratio, which could be construed as a measure of the strength of in-lake processes (low area to volume ratio) or the strength of hydrologic processes (high area to volume ratio), captured lake pairs with the highest temporal coherence, but also the pairs with the lowest coherence. Lakes with small area to volume ratios will be deeper than lakes with large area to volume ratios.

Table 3 Spearman rank correlation coefficients (P = 0.05) showing the relationship of lake pair temporal coherence with the ranked morphometric characteristics of the lake basins

	Correlation	
Lake characteristic	Mean	Strong
Lake volume	0.11	–0.07
Altitude	–0.32	–0.25
Altitude excluding Green Lake 1	–0.51	–0.29
Basin area	0.07	0.11
Landscape position	0.26	0.09
Landscape position excluding Green Lake 1	0.00	–0.25
Basin area/lake volume	–0.25	–0.21
Lake area/lake volume	–0.30	–0.30

Our observations in the Rocky Mountains are that deeper lakes have slower flushing rates during spring snowmelt and that the longer residence time allows for manifestation of lake processes. In shallow lakes, internal processes are obscured by hydrologic flushing of upstream waters. A large basin area to lake volume ratio implies strong hydrologic control over lake flushing rates during the spring snowmelt which dominates the hydrology of alpine lakes. Inputs from the catchment overwhelm lake processes when lake water is replaced every 2–3 days.

Altitude appeared to be the morphometric characteristic that explained the most temporal coherence among lake pairs, although the correlations were not very strong (Table 3, Fig. 2). The lake area/lake volume ratio also explained a similar amount of temporal coherence (Fig. 3). Spearman rank correlation coefficients improved when Green Lake 1 was removed from the altitude data set. Green Lake 1 is an outlier, being the only seepage lake in the study. Water quality was quite different from other lakes; for instance, bicarbonate alkalinity, silica and conductance were up to twice the concentrations of any other lake (Caine & Thurman, 1990). Dissimilar lake pairs were found among a range of rank altitudes from 1 to 5, although the three lake pairs with the highest percentage of strong correlations all had rank altitudes of 1 (Fig. 2). Because these lake pairs were also nearest neighbours, proximity and cascading flow-through effects, rather than altitude, may have had more to do with their strong temporal coherence.

Temporal coherence by individual variables

With all eight lakes considered together, the coherence across variables was moderate (Table 4). Specific conductance had the highest temporal coherence, with a mean rho of +0.49. Calcium and sulphate had similar, but slightly lower mean rho values of +0.46. Of all variables considered, silica was the least coherent across all lakes, with a mean rho of +0.06. Conductivity was again the variable with the greatest percentage of strong correlations, 50%, across lake pairs. Nitrate and silica had the lowest percentage of strong correlations, with values of 7% and 10%, respectively.

Different patterns of temporal coherence were evident when each of the two basins, Green Lakes

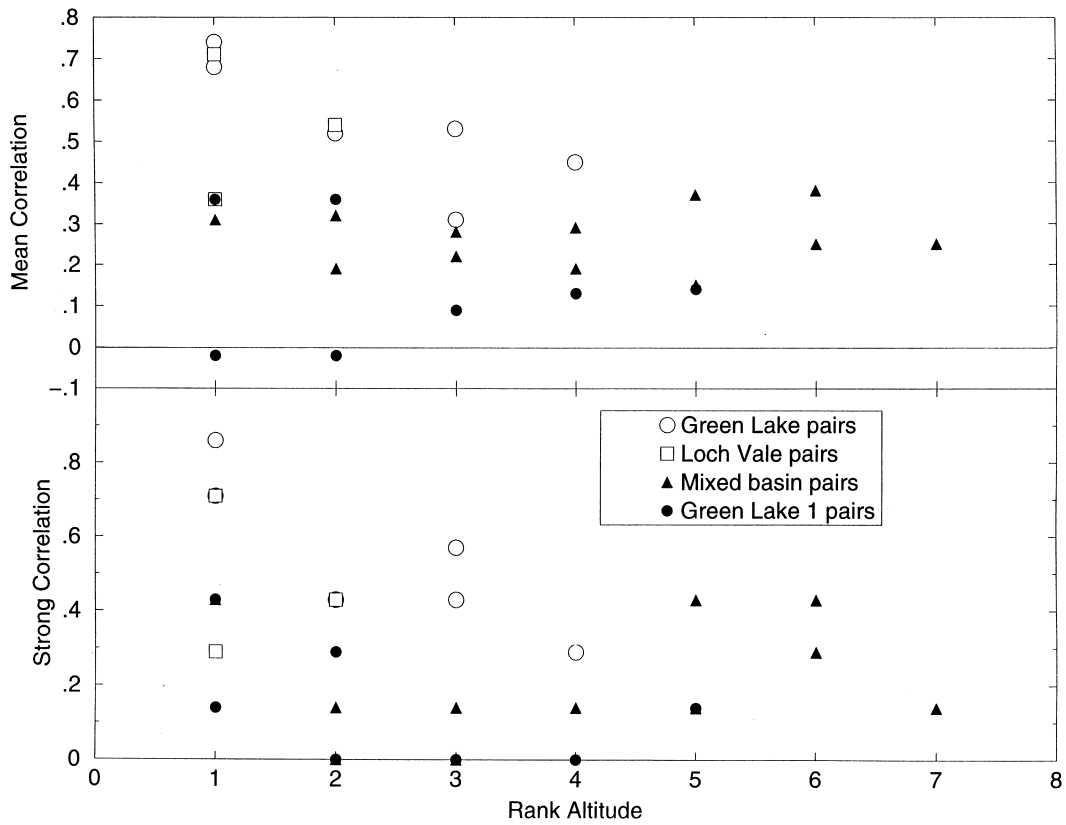

Fig. 2 Mean and strong correlations by rank elevation for lake pairs of the Green Lakes Valley and the Loch Vale Watershed. Mean and strong correlations were calculated using the methods of Magnuson *et al.* (1990) which are also described in the 'Methods' section of the present paper. Rank altitude was developed by ranking the absolute difference in values between lakes. Lake pairs within the same basin showed higher correlations than lake pairs from different basins: (○) Green Lake pairs; (□) Loch Vale pairs; (▲) mixed basin pairs; and (●) Green Lake 1 pairs.

Valley and Loch Vale, was considered separately (Table 4, Fig. 4). The mean correlation for individual variables ranged from +0.70 to 0 for the Green Lakes lake pairs and from +0.76 to +0.28 for the Loch Vale lake pairs (Table 4). The percentage of lake pairs that were strongly correlated ranged from 60% to 0% for the Green Lakes, and from 100% to 0% for lake pairs of Loch Vale.

Among the Green Lakes, alkalinity showed the greatest temporal coherence across lake pairs and all lake pairs except those including Green Lake 1 were strongly correlated (Fig. 4). Temperature and conductivity were other variables that showed high mean correlations between lake pairs. Calcium and sulphate showed moderate mean correlations. Nitrate was weakly coherent in temporal patterns. Temporal trends in silica ranged from weak to negative coherence in Green Lakes. When the Green Lake pairs included Green Lake 1, it either increased the range of observed coherence or greatly reduced coherence across the Green Lakes (Fig. 4).

Temporal coherence across variables for Loch Vale lake pairs revealed some interesting patterns (Table 4, Fig. 4). Calcium and sulphate had the highest mean correlation coefficients of +0.76. All lake pairs were strongly correlated. Alkalinity, conductivity, nitrate and silica were moderately correlated across lake pairs, and only one lake pair was strongly correlated for each variable. Glass Lake and The Loch were strongly correlated for conductivity, nitrate and silica, but not for alkalinity. The Loch was strongly correlated with Sky Pond for alkalinity, even though Glass Lake is located between these two lakes. Temperature behaved independently across all lakes; correlation coefficients were moderate for all lake pairs.

Mixed basin pairs (excluding the outlier Green Lake 1) showed moderate to strong coherence for calcium, conductivity and nitrate, but weak to negative

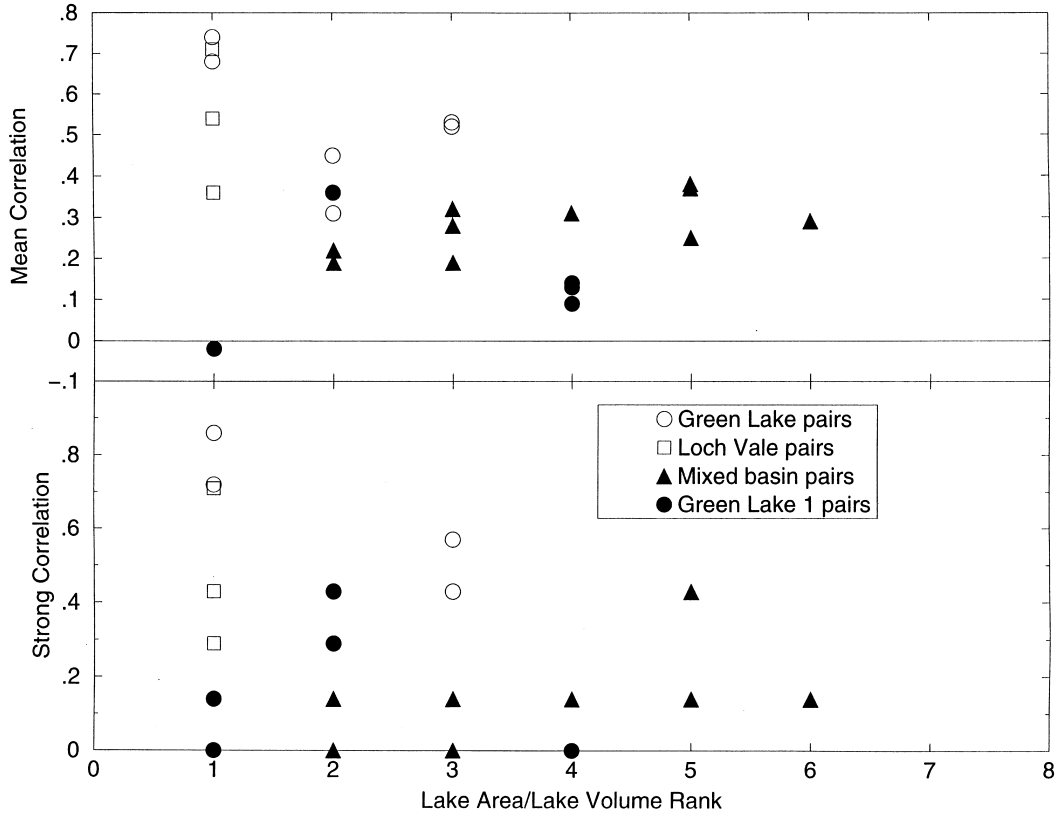

Fig. 3 Mean and strong correlations by rank lake area/lake volume for lake pairs of the Green Lakes Valley and the Loch Vale watershed. Mean and strong correlations were calculated using the methods of Magnuson *et al.* (1990) which are also described in the 'Methods' section of the present paper. Rank lake area/lake volume was developed by ranking the absolute difference in values between lakes. Lake pairs within the same basin showed higher correlations than lake pairs from different basins: : (○) Green Lake pairs; (□) Loch Vale pairs; (▲) mixed basin pairs; and (●) Green Lake 1 pairs.

coherence for sulphate, alkalinity, dissolved silica and temperature (Fig. 4).

Discussion

Catchment influence, defined as the ratio of basin area/lake volume, explained a small amount of overall temporal coherence. The ratio of lake area/lake volume had more explanatory power (Table 3, Fig. 3). Magnuson *et al.* (1990) hypothesized that the ratio of surface area to mean depth was a index of the exposure of a lake to the atmosphere (Kratz *et al.*,

Table 4 Comparison of lake variable mean correlations and percentage strong correlations by lake pair for all lakes and for individual lake basins

	All lakes		Green lakes		Loch Vale lakes	
Variable	Mean rho	$r > 60$ (%)	Mean rho	$r > 60$ (%)	Mean rho	$r > 60$ (%)
Conductivity	0.49	50	0.51	50	0.48	33
Alkalinity	0.18	25	0.70	60	0.50	33
Temperature	0.34	29	0.53	60	0.28	0
Calcium	0.46	32	0.46	50	0.76	100
Nitrate	0.25	7	0.09	0	0.57	33
Sulphate	0.46	36	0.46	50	0.76	100
Silica	0.06	10	0.00	10	0.38	33

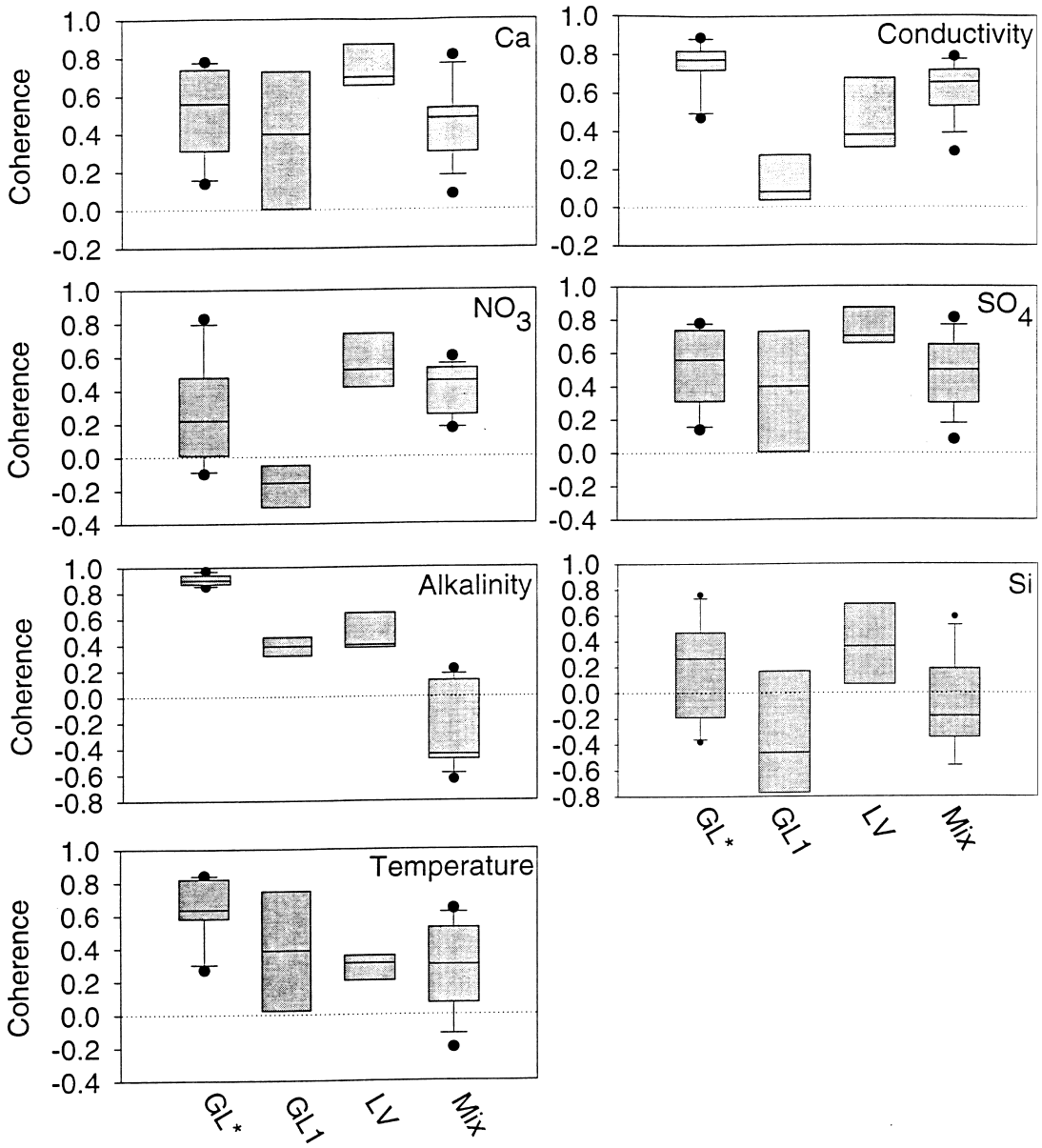

Fig. 4 Distribution of coherence values for the Green Lakes and the Loch Vale catchments: (GL*) Green Lake pairs exclusive of Green Lake 1; (GL1) all Green Lake pairs; (LV) all Loch Vale pairs; and (Mix) all lake pairs exclusive of Green Lake 1.

1998). Lakes with similar ratios respond similarly to atmospheric forcing. This was found for the Front Range lakes, with the exception of lake pairs including the outlier, Green Lake 1 (Table 2). Rather than similarity in exposure to the atmosphere, similar lake area/volume ratios in mountainous terrain may indicate similarity in hydrologic processes because snowmelt directly influences lake retention times to a greater or lesser degree depending on this ratio (Baron, 1992). Kratz *et al.* (1998) noted that climate-driven synchrony should be most apparent in lake districts without large altitudinal gradients; our results concur.

Altitude combines more than one morphometric characteristic and that may be one reason for its explanatory power (Fig. 2). Basin area generally decreases with altitude, as does percentage vegetated area and soil development (Caine & Thurman, 1990; Drever & Zobrist, 1992). In addition, relative relief generally increases with altitude, suggesting steeper slopes and quicker hydrologic responses. Another reason may actually be altitudinal. In areas of extreme

topographic relief, such as the Colorado Front Range, lakes may experience different climate at different altitudes as a result of adiabatic cooling, upslope weather versus frontal systems and orographic precipitation (Barry, 1973; Hansen, Chronic & Matelock, 1978; Baron & Denning, 1993). The different number of weeks of open water season for the upper and lower Green Lakes attests to different climatic influences. Finally, the presence of headwater glaciers at the top of each catchment moderates the immediate climate adjacent to headwater lakes and continuous glacial melt during the open water season certainly dampens the response of these water bodies to air temperature fluctuations.

We hypothesized that lakes at the heads of their basins should be most responsive to climate signals because there would be less buffering of the signal by catchment or within-lake influences (e.g. Caine, 1995). This was refuted for the variables we examined. Hydrologic influences, including glacial meltwater, tended to overwhelm a climate signal and explained some of the observed temporal coherence. All lake volumes are slight compared with flushing rates through mid-July, amounting to only 5–10 days of peak season flow (Baron, 1992; Caine, 1995).

The altitudinal differences in response to a climate signal have been noted by Denning *et al*. (1991) with reference to streamwater chemistry during snowmelt. Many authors have noted a solute pulse related to preferential elution of solutes from snowpacks in spring, but the lag in the onset of snowmelt with increasing altitude in Loch Vale led instead to a snowmelt 'smear' or sustained elevated levels of snowpack solutes in streamwater (Johannessen & Henriksen, 1978; Semkin & Jeffries, 1988; Denning *et al*., 1991).

There was greater temporal coherence within the Green Lakes Valley and within Loch Vale than there was at similar landscape position regardless of location (Table 4, Fig. 4). The two basins were more internally consistent than they were with each other when the south-facing seepage lake, Green Lake 1, was excluded from analyses. All lakes that were strongly coherent were pairs within either Green Lakes Valley or Loch Vale, and lake pairs which were the least temporally coherent were pairs between basins, with a few exceptions. Temporal coherence of individual variables was also greater for within-basin lake pairs for nearly all variables.

Variables that were highly coherent in one basin were not in the other, so that conductivity, alkalinity and temperature were temporally coherent among the Green Lakes, while calcium, nitrate and sulphate were strongly synchronous for Loch Vale (Table 4, Fig. 4). This implies a differential influence of catchment and in-lake processes across basins and lakes that masks climate signals, as described above.

The most coherent variables across all lake pairs were calcium, conductivity, nitrate and sulphate. Calcium, sulphate and many of the solutes that contribute to conductivity have both atmospheric deposition and mineral weathering sources. These have been shown to covary spatially and temporally in our lakes and others of the Front Range as a result of hydrologic dilution during snowmelt (Caine & Thurman, 1990; Turk & Spahr, 1991; Baron, 1992; Campbell *et al*., 1995). Within-year sulphate and calcium dynamics in Loch Vale have been shown to follow a flow-dilution pattern with high concentrations from snowmelt followed by lower concentrations from weathering products (Campbell *et al*., 1995). Cosmogenic ^{35}S analyses, used as a measure of S residence time because of its 87-day half-life, in a wetland in Loch Vale showed rapid flushing of atmospherically deposited SO_4 during snowmelt and no indication of multiyear storage (Brock, 1997). However, there was no among-year variability in total sulphate flux, regardless of trends in precipitation in a study of yearly input–output budgets (Baron *et al*., 1995). Even although the regional sulphate concentrations in precipitation have decreased 33–45% since 1980, we saw no concurrent trend in lake concentration response (Baron *et al*., 1995; Lynch *et al*., 1995). This is because the mineral S source in the basin is large relative to that from atmospheric deposition (Baron, 1992; Brock, 1997). Sulphate adsorption capacities of soils were very low compared with capacities described for older soils with more clay content (Baron, 1992).

Both lake catchments receive elevated N deposition from the atmosphere. The moderate coherence of nitrate is probably a result of concentrations in excess of that needed for biological productivity (Williams *et al*., 1996; Baron & Campbell, 1997; Fenn *et al*., 1998).

Alkalinity was strongly temporally coherent among lake pairs from the Green Lakes Valley when Green Lake 1 was excluded, but displayed low to negative correlations when Green Lakes were paired with Loch

Vale lakes (Fig. 4). Loch Vale lakes were moderately coherent among themselves. Turk & Spahr (1991) regressed alkalinity against a number of minerals derived from weathering products across mountain ranges of the Rocky Mountains. Only 73% of the spatial variance in alkalinity was explained by calcium mineral weathering (compared with 92% for the Bitteroot Mountains of Idaho), and the above authors suggested differential mineral composition could account for the unexplained variability in alkalinity across different lakes. If timing differences in the onset of snowmelt with increasing altitude also add to differences in concentrations, this could explain why these lakes do not covary in time.

Temperature was only moderately coherent across all lakes, but strongly coherent within lake pairs of the Green Lakes. Although the altitudinal range between highest and lowest lakes in both basins is identical, at 275 m, Loch Vale lakes are situated lower in their basin than the Green Lakes. Sky Pond, the highest lake of Loch Vale, is 23 m lower than Albion, the lowest lake of the Green Lakes Valley. By itself, an offset caused by altitudinal lapse rate should not affect correlations so long as it is consistent. It would amount to no more than addition or subtraction of a constant and so would be removed in standardizing that occurs in calculation of the correlation. However, other things than lapse rate (which is atmospheric) can introduce variability, including volume/area ratios of different lakes and the fact that water discharge from the lower Green Lakes was not always from the surface.

There are several reasons why temperature is less temporally coherent within Loch Vale. The length of time after snowmelt flushing ends and winter ice formation begins is 10–12 weeks per year. It is sufficient for the lakes to develop their own temperature signatures. Sky Pond is large and deep, Glass Lake is small and shallow, and The Loch is very shallow but has the largest surface area. During late summer, after snowmelt has ended, the different morphometries should contribute to different thermal properties. However, a continuous supply of glacial melt water (0 °C) to Sky Pond and The Loch via Andrews Glacier, Tarn and Creek would obscure a logical warming sequence expected with altitude loss.

Silica and nitrate could be biologically controlled, and were the only two variables that we measured that could be used to address in-lake processes affecting temporal coherence. Silica behaved independently across all lake pairs and both basins. Silica can be taken up by diatoms: its depletion from Sky Pond and The Loch during the winter has been documented (Spaulding, Ward & Baron, 1993; Baron, 1992; Campbell *et al.*, 1995) and a consistent decrease in its concentration across Lake Albion was noted by Caine & Thurman (1990). Diatom and other algal abundances change from year to year as a result of many factors. These include persistence of a stable water column, temperature, predation and parasitism. Toetz & Windell (1993) also reported large spatial variability among diatom flora of high altitude Rocky Mountain lakes, with only 33% and 41% overlap between the flora of Lake Albion, and that of Sky Pond and The Loch, respectively. Spatial and temporal variability of diatom communities could influence the amount of silica consumed from the water column. Magnuson *et al.* (1990) also found that biological variables lacked temporal coherence as a result of individual lake food web complexities.

Nitrate is elevated in waters of both basins because of atmospheric deposition (Caine & Thurman, 1990; Williams *et al.*, 1996; Baron & Campbell, 1997). It is moderately coherent in Loch Vale (Table 4, Fig. 4). The nitrogen budget for Loch Vale suggests that phytoplankton are a significant reservoir for N, and given the variability in algal populations and species from year to year, it is not surprising that there is limited coherence for this variable. Nutrient budgets and plankton communities are altered when fish are introduced to previously barren alpine lakes (Leavitt *et al.*, 1994). Trout were introduced into Sky Pond and other Loch Vale lakes in the 1930s, and trout populations persist today. The highest of the Green Lakes are fishless, and therefore, it is not surprising that there are differences in nitrogen dynamics which lessen temporal coherence.

Two lakes stood out as unusual, and were either not coherent or only moderately so when compared with other lakes. Green Lake 1 was an outlier even within its own basin, a point that has been made by Caine & Thurman (1990). There is little surface drainage into this lake, and solutes are two to four times more concentrated in Green Lake 1 than the other Green Lakes (Caine & Thurman, 1990). Sky Pond also displayed only low to moderate coherence with all other lakes, including the two others within Loch Vale. It was most synchronous with The Loch, with a mean rho of +0.54 and 43% strong correlations, for all

variables. Sky Pond was completely synchronous with Glass Lake and The Loch for calcium and sulphate, two solutes derived from mineral weathering (Baron *et al*., 1995).

In summary, although Front Range lakes are topographically close, geologically and morphologically similar, and often connected by streams, there was only partial temporal coherence among these water bodies. Regional trends in deposition chemistry, such as increasing deposition of nitrogen compounds and decreasing sulphate, are not uniformly reflected in lake solute chemistry. Similarly, regional trends in climate are attenuated by topographic variation, the presence of headwater glaciers and the rapid hydrologic flushing that overwhelms each lake with meltwater every spring, regardless of long-term climatic variation. For the two basins that we explored, lakes were most similar to their nearest neighbours and least similar to lakes of the other basin. Out of the morphometric characteristics we looked at, lakes at similar altitudes within their basins were most coherent, and we attribute this to a combination of factors, including similar basin characteristics at similar altitudes, and also climatic differences associated with altitude and topography.

The moderate annual temporal coherence does not imply that Rocky Mountain lakes respond independently to each disturbance, but rather that (1) internal processes ameliorate responses on different time scales and (2) the external influences are below a threshold that will elicit a regional response. A large enough disturbance, over a long enough period of time, will influence a lake district. Certainly entire lake districts have responded to large regional inputs of strong acid anions (Charles, 1991) and to regional warming trends (Schindler *et al*., 1990). The fact that lakes in both Green Lakes Valley and Loch Vale are moderately temporally coherent for several parameters, and strongly coherent for others within their basins, suggests to us that these water bodies will respond similarly to a large enough change in climate and deposition.

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