The influence of landscape position on lake chemical responses to drought in northern Wisconsin

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Abstract
Climatic shifts to drier conditions during drought alter the hydrologic pathways of water and solute flow to aquatic ecosystems. We examined differences in drought-induced trends in the semiconservative cations, Ca+Mg, in seven northern Wisconsin lakes. These spanned the range of hydrologic settings in the region, including hydraulically mounded, groundwater flowthrough, and groundwater-discharge lakes. Parallel increases in concentration across the seven lakes during drought were attributable to evapoconcentration. However, we observed divergent trends for mass, which better reflects altered solute flux by accounting for changes in lake volume. Ca+Mg mass increased in three groundwater-dominated lakes as precipitation inputs were low and groundwater discharging from longer flowpaths became proportionately more important. In contrast, decreases in Ca+Mg mass for two precipitation-dominated lakes reflected diminished inputs of solute-rich groundwater. Landscape position, defined by the spatial position of a lake within a hydrologic flow system, accounted for the divergence in chemical responses to drought.

Changes in climate to wetter or drier conditions alter the hydraulic properties of individual lakes and the hydrologic flowpaths connecting lakes to the landscape. Such hydrologic shifts can disrupt the biogeochemical fluxes and cycling of major ions and nutrients and can lead to changes in other lake properties, such as thermal structure and light regime, which directly influence aquatic organisms (Carpenter et al. 1992; Schindler et al. 1990). Short-term climatic fluctuations, such as the recent and widespread drought during the 1980s in the upper Midwest (Krug and Simon 1992), provide an opportunity to examine lake responses to climatically mediated changes in hydrology.

Shifts in hydrology during warmer and drier climatic periods can generate contrasting signals in lake chemistry that depend on the net response to changes in the major pathways of water and solute supply. For example, higher evaporation rates and decreased precipitation can cause conservative solutes to accumulate in the water column. This pattern was documented for Lake 239, a drainage lake in the Experimental Lakes Area, Ontario, during a 20-yr period of continuous warming (Schindler et al. 1990). In contrast, if the net effect of a hydrologic shift is to diminish the supply of solutes into a lake, solute concentration can decrease. This occurred in Nevis Lake, a soft-water seepage lake in upper Michigan, where diminished inputs of solute-rich groundwater during a drought led to a substantial decrease in major cation concentration (Webster et al. 1990; Krabbenhof and Webster 1995).

Our objective here is to determine whether these contrasting chemical responses to drought can be explained by the position of a lake in the landscape. For lakes in northern Wisconsin, we define landscape position as the relative location of a lake in a local hydrologic flow system, quantified by the percentage of water inflow supplied by groundwater. The end members defining the flow system are hydraulically mounded lakes that receive virtually all their water from direct precipitation and terminal groundwater-discharge lakes that receive substantial inputs of groundwater (Fig. 1). Groundwater flowthrough lakes lie across a gradient intermediate to these two extremes. Because landscape position dictates the relative importance of the different pathways of water and solute flow (i.e., precipitation, groundwater, and surface water), we predict it also determines the magnitude and direction of changes that occur in solute chemistry during climatic shifts.

We evaluated this predicted heterogeneity in chemical response by examining temporal patterns in calcium plus magnesium during a 4-yr drought in a set of northern Wisconsin lakes that range broadly in landscape position. We chose these cations because their concentration in this region’s lakes is closely tied to annual groundwater

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Methods

**Description of study lakes**—The seven lakes we discuss are in northern Wisconsin. Six of the lakes are in Vilas Co., within a 12-km radius; Morgan Lake is 120 km east in Florence Co. All are glacially formed lakes situated over thick drift typically low in carbonate minerals, such as calcite and dolomite (Attig 1985; Kenoyer and Bowser 1992). The lakes cover a range of hydrologic types (Born et al. 1979), with two drainage lakes (Allequash and Trout) and five seepage lakes (Table 1). These seepage lakes, which differ in the amount of groundwater they receive, include one hydraulically mounded lake (Morgan) and four groundwater flowthrough lakes (Vandercook, Crystal, Big Muskellunge, and Sparkling). Except for Morgan and Vandercook, the lakes lie within the same groundwater flow system that culminates in a terminal discharge point at Trout Lake. Landscape position is reflected by the mean in-lake concentrations of calcium, magnesium, alkalinity, and silica (Table 1)—constituents whose concentrations are largely controlled by groundwater inflow (Eilers et al. 1983; Hurley et al. 1985; Kenoyer and Anderson 1989; Wentz et al. 1995).

The lakes are relatively unproductive, ranging from ultra-oligotrophic (Crystal and Morgan) to meso-oligotrophic (Trout, Sparkling, and Allequash) and are not strongly influenced by wetlands, as reflected in the low dissolved organic C (DOC) concentrations. All lakes are in state or national forests, four have campgrounds (Morgan, Trout, Big Muskellunge, and Crystal), and three have low-to-moderate levels of cottage development (Sparkling, Trout, and Vandercook). Data have been collected on these lakes as part of two ongoing programs: the North-Temperate Lakes, Long Term Ecological Research (LTER) Program (Allequash, Big Muskellunge, Crystal, Sparkling, and Trout) and the EPA Regional Long Term Monitoring (RLTM) Program (Morgan and Vandercook).

**Climate, hydrology, and chemistry data**—Monthly precipitation data were obtained from a weather station at Minocqua Dam, 18 km from Trout Lake (NOAA 1993). One-year running means for precipitation were calculated in quarterly time steps. We divided the 10-yr period of record for lake chemistry (1984–1993) into three time intervals: predrought (1984–1986), drought (1987–1990) and postdrought (1991–1993) (Krug and Simon 1992).

We estimated lake volume for each sampling date using hypsometric relationships for Vandercook from Wentz and Rose (1991), for the LTER lakes from D. M. Robertson (unpubl. doc.), and from a bathymetric map for Morgan Lake. Levels for Morgan Lake before fall 1987, when measurements began, were estimated with a regression between lake levels measured between 1987 and 1993 and the corresponding water level in a U.S. Geological Survey long-term water-table monitoring well 10 km northwest. The regression variables—lake level (dependent) and well level (predictor)—were means for April, July, and October, months when water chemistry samples were collected. The regression equation had a significant

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Fig. 1. Relationship between the direction and magnitude of Ca and Mg response during drought to landscape position, defined by the location of a lake in a groundwater flow system.

inflow rates (Kenoyer and Anderson 1989; Wentz et al. 1995) and because they can be considered semi-conservative (Krabbenhoft et al. 1994). To distinguish between the effects of altered groundwater inflow and evapoconcentration, we transformed the Ca + Mg concentration time series into mass by calculating for changes in lake volume. We assumed the resultant trends in mass represent changes in the supply or flux from altered groundwater inputs.

We found that evapoconcentration could explain the increased cation concentration observed in all lakes during the drought. However, trends in cation mass differed across lakes in a pattern related to landscape position. The chemical response to drought along the hydrologic gradient was anchored by hydraulically mounded lakes that did not respond to drought (Fig. 1). The response trajectory was defined further by precipitation-dominated lakes whose cation mass declined as solute inputs from groundwater diminished during drought. Finally, in lakes receiving substantial groundwater inputs, solute mass increased as increased evaporation and decreased dilution by precipitation were compensated by contributions from solute-rich groundwater discharging from longer flowpaths. These results suggest that prolonged climatic shifts from average conditions may influence steady-state concentrations in a heterogeneous pattern across lakes that is related to position in the landscape.
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$R^2 (0.89, \ n = 30)$ and the residuals were not autocorrelated.

The percentage of water inflow from groundwater and water residence time (lake volume divided by inputs) were available from water budgets for Morgan (W. J. Rose unpubl. data), Vandercook (Wentz et al. 1995), Sparkling, Crystal, and Big Muskellunge (Krabbendam et al. 1994). Because hydrologic budgets were not available for the drainage lakes (Trout and Allequash), we calculated water residence time as lake volume divided by stream outflow using data provided by J. Elder; we assume that groundwater outflow from these lakes was small relative to surface-water outflow. We estimated percent groundwater inflow for Trout and Allequash Lakes from a regression between percent groundwater input and the mean concentration of Ca+Mg ($R^2 = 0.97$) from the other five study lakes. We consider these to be coarse estimates of groundwater inputs because we extrapolated beyond the range of cation data used to developed the regression and applied a relationship developed for seepage lakes to drainage systems whose hydrology is complicated by surface-water inflow. However, these estimates are adequate for establishing relative hydrologic ranking of lakes within the flow systems discussed here.

Samples for major ion chemistry were collected after ice-out in late April or May, in midsummer (July–August), and in fall after the water column was mixed (October–November). The LTER database consists of hypsometrically weighted water-column averages from three to six discrete-depth samples. The hypsometric weighting yields an estimate of concentration that would be observed if the lake were completely mixed. Data for the RLTM lakes were from epilimnetic samples collected 1 m from the surface. Because the two RLTM lakes are relatively shallow and do not stratify strongly or routinely, epilimnetic samples from these lakes are considered comparable to the water-column means. Dissolved Ca and Mg were determined with atomic absorption (LTER lakes and RLTM lakes before 1992) and inductively coupled plasma spectroscopy (RLTM, 1992–1993) on samples passed through 0.4-μm polycarbonate filters and preserved with acid. Details on methodology for these and other variables are given by Morrison et al. (1991) for the RLTM lakes. Outliers identified from examination of ion balances, calculated conductance, and interquartile ranges for a given lake were not included in the analysis.

In the text we use the notation [Ca+Mg] to represent the sum of the concentration of Ca+Mg, in μeq liter$^{-1}$. We computed the mass of Ca+Mg (in units of eq) by multiplying the hypsometrically weighted or epilimnion values for concentration by the lake volume on that particular sampling date. Because mass is not affected by the concentrating effect of declining lake volume, we assume the resultant temporal patterns reflect changes in the flux of cations from altered groundwater inflow to the lakes.

Statistical analysis—We used regression models to quantify slopes in Ca+Mg concentration and mass for each lake during the drought. The models, which included the entire time series for a given lake ($n = 29$ or 30),

<table>
<thead>
<tr>
<th>Lake</th>
<th>Concentration (μeq liter$^{-1}$)</th>
<th>Residence Time (days)</th>
<th>Groundwater Input (%)</th>
<th>Groundwater Type</th>
<th>Groundwater Volume (m$^3$)</th>
<th>Groundwater Depth (m)</th>
<th>Groundwater Mean (μeq liter$^{-1}$)</th>
<th>Groundwater Max (μeq liter$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morgan</td>
<td>45.46, 89.37</td>
<td>0.5</td>
<td>Calculated</td>
<td>M</td>
<td>3.4</td>
<td>3.8</td>
<td>3.4</td>
<td>3.8</td>
</tr>
<tr>
<td>Vandercook</td>
<td>45.59, 89.41</td>
<td>0.5</td>
<td>Calculated</td>
<td>G</td>
<td>3.5</td>
<td>4.4</td>
<td>3.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Crystal</td>
<td>46.00, 89.37</td>
<td>0.5</td>
<td>Calculated</td>
<td>G</td>
<td>3.6</td>
<td>4.4</td>
<td>3.6</td>
<td>4.4</td>
</tr>
<tr>
<td>Big Muskellunge</td>
<td>46.03, 89.32</td>
<td>0.5</td>
<td>Calculated</td>
<td>G</td>
<td>3.7</td>
<td>4.4</td>
<td>3.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Allequash</td>
<td>46.02, 89.37</td>
<td>0.5</td>
<td>Calculated</td>
<td>G</td>
<td>3.8</td>
<td>4.4</td>
<td>3.8</td>
<td>4.4</td>
</tr>
<tr>
<td>Trout</td>
<td>46.02, 89.40</td>
<td>0.5</td>
<td>Calculated</td>
<td>G</td>
<td>3.9</td>
<td>4.4</td>
<td>3.9</td>
<td>4.4</td>
</tr>
</tbody>
</table>
provided estimates of slopes and intercepts for each time period (predrought, postdrought, and drought) through the use of dummy variables (Draper and Smith 1981). Each slope was tested for its difference from zero with $t$-tests (significance level at $P = 0.10$). Through visual examination of time-series plots of the residuals and the Durbin-Watson statistic, we found no evidence for strong autocorrelation. All statistical analyses were run using SAS, version 6.08.

Results

Hydrologic responses to drought — The late 1980s drought was initiated by one of the lowest snow seasons on record in winter 1986–1987 (Wentz et al. 1995) followed by 3 yr of continued lower-than-normal precipitation (Fig. 2a). As a result, the groundwater table and the water level in many of the region’s lakes declined substantially (Anderson and Cheng 1993; Rose 1993; Wentz et al. 1995).

The magnitude of lake level fluctuation induced by the drought was related to hydrologic type (Fig. 2b,c). Declines in lake level were most dramatic for the five seepage lakes, ranging from 0.7 m for Morgan to between 0.9 and 1.0 m for Vandercook, Big Muskellunge, Crystal, and Sparkling. These water level declines represented a loss of volume ranging from 9% for the deeper Crystal Lake to 25% for the shallow Morgan Lake. Of these lakes, only Morgan had recovered to predrought water levels by 1993 following a reversal of lake-level decline in 1990; the other four lakes had recovered to only $\sim 50\%$ of their predrought level. Vandercook, Big Muskellunge, and Crystal showed remarkably similar temporal patterns; the latter two are separated by a narrow isthmus, so it was not surprising that their lake levels were relatively coherent (Magnuson et al. 1990). In contrast, the lake levels of the two drainage lakes did not show a strong response to the drought, declining only slightly (Trout) or showing strong seasonal fluctuations over time (Allequash) (Fig. 2c).

Chemical responses to drought — $[\text{Ca} + \text{Mg}]$ increased in all seven lakes during the 1987–1990 drought (Fig. 3). Only two lakes had slopes that were not significantly different from zero (Table 2). These trends correspond to a total change in $[\text{Ca} + \text{Mg}]$ over the 4-yr drought ranging from $\sim 10 \mu\text{eq liter}^{-1}$ at Crystal and Morgan to $\sim 100 \mu\text{eq liter}^{-1}$ at Trout and Sparkling. These changes were directly proportional to the mean $[\text{Ca} + \text{Mg}]$ of each lake, translating into an increase of $\sim 10\%$ in concentration from pre- to postdrought means across lakes. Only two nondrought slopes showed significant trends, both in the postdrought interval (Morgan, slope $= -7.5 \mu\text{eq liter}^{-1} \text{yr}^{-1}$; Crystal, slope $= -1.5 \mu\text{eq liter}^{-1} \text{yr}^{-1}$).

The drought response for $\text{Ca} + \text{Mg}$ mass did not show the consistent pattern across lakes that typified the concentration data (Fig. 4; Table 2). In Sparkling, Allequash, and Trout, the three lakes receiving the largest inputs of groundwater, significant increasing trends for mass paralleled those described above for cation concentration. These increases were on the order of 10 (Trout and Sparkling) to 20% (Allequash) of the mean cation mass. Slopes for mass in Morgan and Crystal were likewise positive, but small and nonsignificant. However, $\text{Ca} + \text{Mg}$ mass decreased in both Vandercook and Big Muskellunge (slope not significant at $P = 0.129$) even though concentrations increased (Table 2). These declines were 6 and 10% of mean mass for Big Muskellunge and Vandercook. Only two nondrought slopes showed trends in $\text{Ca} + \text{Mg}$ mass, Big Muskellunge postdrought (slope $= 310 \times 10^6 \text{eq yr}^{-1}$) and Vandercook predrought (slope $= 0.087 \times 10^6 \text{eq yr}^{-1}$).

Discussion

The 4-yr drought in northern Wisconsin had a significant impact on lake hydrology and chemistry. Higher evaporation rates combined with decreased precipitation caused substantial declines in lake volume in many of the
seepage lakes and led to increased cation concentrations in all lakes—significant in five cases (Fig. 5a). This suggests that evapoconcentration was a major mechanism influencing the concentrations of more conservative solutes such as Ca and Mg during the drought, confirming the results of Schindler et al. (1990).

Further analysis suggested that evapoconcentration was not the only mechanism influencing major cations. If it were, we would expect mass to be unresponsive to drought. However, when we accounted for the evaporative concentration of Ca + Mg by converting concentration to mass, significant trends emerged. Furthermore, the response patterns included both positive and negative changes in lake mass, suggesting not only that there was a change in the supply of base cations, but that the underlying mechanisms driving lake chemical responses to drought differed among the lakes.

Indeed, the magnitude of groundwater inflow, determined by position in the landscape, separated the lakes into two groups reflecting differing responses to drought (Fig. 5b). The three lakes with the largest groundwater contributions (Trout, Allequash, and Sparkling) showed substantial increases in cation mass during the drought. In these lakes, deviations from normal hydraulic inputs during periods of higher evaporation and lower precipitation were compensated by a higher percentage contribution from surface- and groundwater sources enriched with cations. During dry periods, streams are often dominated by base flow, and groundwater inflow to lakes consists of proportionately more water discharging from long flowpaths having more contact time with glacial drift.

In contrast to this pattern of increasing cation mass, we detected decreases in mass for Vandercook and Big Muskellunge that could be attributed to diminished groundwater input during the drought. Detailed hydrologic studies of lakes in the region have documented drought-induced cessation of groundwater inflow at Vandercook (Wentz et al. 1995), Crystal (Anderson and Cheng 1993), and nearby Little Rock Lake (Rose 1993). At Vandercook, annual groundwater inflow declined from 1 to 9% of the total hydrologic input between 1980 and 1986 to zero in 1987. Predrought (1984–1986) groundwater

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Table 2. Slope and standard error (in parentheses) for Ca + Mg concentration and mass during the drought period (1987–1990). The level of significance for the test of the slope not equal to zero was $P = 0.10$; asterisks: * = significant slopes. Lakes are listed in order of percent groundwater input (see Table 1).

<table>
<thead>
<tr>
<th>Lake</th>
<th>[Ca + Mg] (μeq liter$^{-1}$ yr$^{-1}$)</th>
<th>Ca + Mg mass (10$^6$ eq yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morgan</td>
<td>$3.8^* (2.0)$</td>
<td>$-0.00 (0.10)$</td>
</tr>
<tr>
<td>Vandercook</td>
<td>$1.9 (1.2)$</td>
<td>$-0.042^* (0.021)$</td>
</tr>
<tr>
<td>Crystal</td>
<td>$1.2^* (0.5)$</td>
<td>$1.1 (1.8)$</td>
</tr>
<tr>
<td>Big Muskellunge</td>
<td>$2.7 (3.8)$</td>
<td>$-170 (110)$</td>
</tr>
<tr>
<td>Sparkling</td>
<td>$14.1^* (4.0)$</td>
<td>$96^* (38)$</td>
</tr>
<tr>
<td>Allequash</td>
<td>$17.3^* (9.4)$</td>
<td>$120^* (40)$</td>
</tr>
<tr>
<td>Trout</td>
<td>$18.8^* (5.8)$</td>
<td>$3,100^* (920)$</td>
</tr>
</tbody>
</table>

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inputs averaged just 1%, yet supplied ~50% of the total Ca and Mg flux to the lake (Wentz et al. 1995). A similar decline in groundwater inflow was documented for Crystal Lake from a high of 10% in 1982–1983 (Kenoyer and Anderson 1989) to zero during the drought (Anderson and Cheng 1993). Presumably, Big Muskeg Lake underwent a comparable decline in groundwater inflow although its higher groundwater inflow rate (16%) suggests that a total reversal in flow direction from discharge to recharge, such as observed for Vandercook and Crystal, was unlikely.

Morgan and Crystal Lakes showed no drought-related declines in cation mass. The lack of response of Morgan Lake can be explained by its general isolation from the groundwater flow system (W. J. Rose unpubl. data). Because Morgan receives virtually no groundwater even during nondondrought periods, it would not be expected to show a drought-related signal with respect to mass. The lack of response of Crystal Lake, despite documented reductions in groundwater inflow, may reflect its long water residence time compared to Vandercook and Big Muskeg Lake. Ranked by increasing water residence times, we detected a significant negative trend in Ca+Mg mass for Vandercook, a nonsignificant negative trend for Big Muskeg Lake, and no trend for Crystal. This pattern suggests that water residence time is an important factor influencing the base cation response for this group of lakes; if water residence time is too long in relation to the drought extent, there is inadequate time for a chemical response to occur.

None of the lakes showed as strong a chemical response to the drought as did Nevins Lake, where Ca+Mg concentration declined at a rate of $-23 \mu$eq liter$^{-1}$ yr$^{-1}$ (Webster et al. 1990). With a relatively fast water residence time for a seepage lake (1.6 yr) and a major cation chemistry that closely tracks transient seasonal and annual groundwater inflow (Krabbenhoft and Webster 1995), both the concentration and, presumably, mass of cations declined in Nevins Lake during the drought. In contrast, Vandercook and Big Muskeg Lake, with longer water residence times, did not show consistent trend direction for concentration and mass. Thus, despite apparent declines in the supply of Ca and Mg from groundwater inflow during this 4-yr drought, evapoconcentration prevented detectable decreases in major cation concentration in these two lakes.

Although we focused our analysis on the major cations Ca and Mg as indicators of altered interactions between lakes and groundwater, the responses of these semiconservative ions have implications for less conservative, but more biologically active substances supplied to lakes by groundwater. For example, concentrations of silica, a key element for diatom populations, are closely tied to groundwater inputs (Hurlay et al. 1985). In addition, other hydrologic connections between lakes and the landscape can be altered by drought. Decoupling of surface connections between lakes and wetlands can generate large shifts in transparency, light, and thermal characteristics of lakes related to decreased loading of DOC (Schindler et al. 1990; Urban et al. 1989).
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Fig. 5. Annual percent change (with standard error bars) in concentration and mass of Ca+Mg during the drought. Percent change was determined from the slopes in Table 2 divided by the mean Ca+Mg concentration (a) or the average Ca+Mg mass (b) measured during the study period. Abbreviations as Fig. 2.

One final consideration is that these hydrologically mediated shifts in the biogeochemical properties of lakes resulting from climatic change can interact with and exacerbate the effects of other anthropogenic stresses. Climatically induced declines in groundwater inputs reduces the supply of key acid-neutralizing substances to soft-water lakes, making them more sensitive to acid deposition (Anderson and Bowser 1986; Webster et al. 1990). Increased transparency of lakes related to declines in DOC inputs may increase the exposure of aquatic organisms to ultraviolet radiation (Williamson et al. 1996).

Conclusions

Our results suggest that position within a hydrologic flow system can strongly influence the biogeochemical responses of individual lakes to climatic shifts, leading to divergence in chemical response patterns across a region. Landscape position, thus, may provide a framework for predicting biogeochemical responses in lakes ranked along other types of hydrologic gradients in addition to the lake-groundwater system discussed here. Response to climate change can also be attenuated by lake-water residence times. We observed a lack of chemical response to diminished groundwater inputs in lakes with long residence times relative to the duration of the drought. We focused our study on chemical responses across a gradient in the interaction strength between lakes and groundwater, a key factor influencing both the static and dynamic properties of northern Wisconsin lakes.

References


Born, S. M., S. A. Smith, and D. A. Stephenson. 1979. The hydrogeologic regime of glacial-terrain lakes, with management and planning implications. J. Hydrol. 43: 7–44.


