

COMMENT

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Toward improving comparisons of alkalinity generation in lake basins

In his article "Alkalinity dynamics in an unacidified alpine lake, Sierra Nevada, California," Stoddard (1987) suggests (p. 838) "that Sierran lakes represent very different systems from those observed in ELA" (the Experimental Lakes Area, Canada). He also states (p. 838) that his Gem Lake data "support the conventional view that the alkalinity of unacidified lakes can result largely from mineral weathering within watersheds." I am writing to comment on these two points.

First, I think clarification is necessary to evaluate whether alkalinity generation in Gem Lake is truly different from ELA lakes. In-lake, alkalinity-generating processes have been extensively studied at ELA (e.g. Kelly and Rudd 1984; Rudd et al. 1986) and are significant contributors to total alkalinity generation there (e.g. Schindler et al. 1980; Cook et al. 1986; Schindler 1986). In Gem Lake, in-lake alkalinity production is a minor component of the lake-watershed alkalinity budget. This observation should not be interpreted to mean, however, that alkalinity is not being generated in this lake, or that little in-lake generation is generally associated with unacidified lakes. In acidified lakes, in-lake alkalinity generation is dominated by biological reactions, such as denitrification and sulfate reduction (Cook et al. 1986), with a smaller but still significant contribution to internal alkalinity generation in unacidified lakes (Schindler 1986). Sulfate reduction and denitrification have been measured in a wide geographic distribution of acidified lakes, including oligotrophic Crystal Lake in Wisconsin and unacidified ELA lakes (Kelly and Rudd 1984; Rudd et al. 1986; Kelly et al. 1987).

In discussing Gem Lake, Stoddard states (p. 838) that "it seems unlikely that redox reactions will prove to be substantial contributors to alkalinity in this lake." While

true with respect to the overall alkalinity budget, the unstated reason is that the water residence time of Gem Lake is so short (7–135 d) that there is little chance for sedimentary reactions to have much effect on the chemistry of the overlying water. Stoddard points out this fast flushing time, but perhaps did not realize that the water residence time of the ELA lakes for which alkalinity budgets have been measured is 5–8 yr. In Gem Lake, during periods of lower flow, measured alkalinities were higher than values predicted from water inputs (his figure 7) and alkalinity increased under the ice (his figure 3). During most of the year, however, flow rates were too high for such reactions to have a measurable effect on the water chemistry. Thus, biological alkalinity generation could be occurring in Gem Lake at similar rates as in unacidified ELA lakes, but would not be detectable by a water-column budget approach in any fast-flushing lake. The way to determine this would be with pore-water studies and direct rate measurements such as those of Rudd et al. (1986).

My main purpose in addressing this point is to prevent the impression that an alkalinity budget which shows no significant internal alkalinity generation is evidence that sulfate reduction and denitrification are not operating within that lake. For example, in Dart's Lake in the Adirondacks (water residence time, 0.06 yr), losses of sulfate and nitrate from the water are not easily detectable in the budget (Kelly et al. 1987), but are easily measured directly at rates similar to those at ELA (Rudd et al. 1986).

The effect of biological alkalinity generation on water chemistry has been modeled successfully for acidified lakes, assuming sulfate reduction (Baker et al. 1986; Kelly et al. 1987) and denitrification (Kelly et al.

Table 1. Estimates of terrestrial and within-lake alkalinity generation rates on a per unit area basis. Data for Lake 239 are from Schindler (1986) and for Gem Lake from Stoddard (1987) and from Stoddard's reply to this comment, assuming Gem Lake precipitation to have ~ 0 alkalinity.

Lake	Terrest. area (10^4 m ²)	Lake area	Alk. gen. terrest.	Alk. yield terrest. (meq m ⁻² yr ⁻¹)	Alk. gen. in-lake	Water residence time (yr)	Total gen. in-lake (%)
239	340	56	26	16	74	6.2	30
Gem	123	2.77	104	104	<49	0.02–0.36	<1

1987) to be first-order reactions, and using water residence time and mean depth in the model. The application of these models to unacidified lakes is probably straightforward for sulfate, because the range of concentrations for which models have been tested is so wide (62–210 $\mu\text{eq liter}^{-1}$). Use of a model developed for nitrate removal in acidified lakes for predicting nitrate removal in unacidified lakes is more complex because algal uptake will dominate nitrate uptake at lower nitrate concentrations (common in unacidified lakes) and denitrification will dominate at higher concentrations (common in some acidified lakes) (Kelly et al. 1987). The amount of phosphorous input will probably also affect the degree of dominance of algal uptake (e.g. Schindler et al. 1985). These models, however, do predict correctly that in-lake processes will be relatively unimportant in the overall alkalinity budget of the unacidified Gem Lake basin. Thus, the way in which Gem Lake is apparently "different" from the ELA lakes is in its morphometry, i.e. the large watershed coupled with a small lake volume, and the predominance of watershed processes in its alkalinity generation is consistent with general principles developed from the study of ELA and other lakes.

I believe that a weakness in the approach of Stoddard and many others in comparing terrestrial and in-lake alkalinity generation within and between lake-watershed systems is that total terrestrial and total in-lake quantities have been emphasized. Although this approach is informative for each particular system, it does not promote understanding of the underlying mechanisms of alkalinity generation. In order to promote clearer analyses, I propose the *minimum* scheme of components shown in Table 1. For the terrestrial area, it is important to

include both alkalinity generation and yield (the amount of alkalinity leaving the watershed and entering the lake). As acidification increases, terrestrial alkalinity generation might increase and yield might decrease at the same time, with important consequences for the lake. This approach is similar to that of Schindler (1986) in comparing different systems as to alkalinity-generating activities, except that water residence time was not quantitatively examined in his data set. This scheme fosters direct comparisons of areal rates, which might elucidate fundamental differences in different types of watersheds or sediments, or differences that occur over time, and these differences could then be studied for their underlying causes. It would also show that the "conventional view" (that in-lake alkalinity generation is insignificant) developed because many workers happened to be studying lakes with large drainage basins and very short water residence times, i.e. the type of lake common in the Adirondacks where so much acidification research has been done.

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Confusion over the origin of alkalinity in lakes

Stoddard's (1987) description of the alkalinity budget of Gem Lake in the Sierra Nevada represents a significant contribution to the neglected limnology of western and alpine regions. In conversations with many limnologists, however, I sense that this and other recent works may be causing an unnecessary dichotomy of viewpoints on the subject of sources of lake alkalinity and perhaps some confusion over the roles of external and internal factors that control alkalinity. I use alkalinity here to refer to carbonate alkalinity, which is the sense used by Stoddard and in traditional works. More recently, the term acid-neutralizing capacity (ANC) has been used to denote the total suite of organic and inorganic phenomena that cause a lake to resist acidification. This comment illustrates that the alkalinity balances of lakes can be predicted from simple geological, biological, geomorphological, and hydrological information. The same processes occur in all basins, differing only in magnitude and relative importance.

Stoddard (p. 838) states that his studies of Gem Lake in the Sierras "support the conventional view that the alkalinity of unacidified lakes can result largely from min-

eral weathering within watersheds." However, the limnological literature suggests that the notion that lakes produce alkalinity *in situ* is at least as "conventional" as that envisioning it to originate from external sources. For example, Hutchinson (1941) illustrated internal alkalinity generation in Linsley Pond, Connecticut. The works of Yoshimura (1931), Mortimer (1941-1942), and Ohle (1952) also clearly show internal sources of alkalinity in lakes. Scientists studying acid rain seem to be generally unaware of these classical works.

The relative contribution of internal alkalinity generation to the total can easily be deduced by comparing the measured alkalinity of lakes with the theoretical alkalinity based on external sources, i.e. terrestrial runoff, precipitation and inflow from other lakes, and water outflows. Where groundwater is insignificant, the theoretical alkalinity would be equal to the sum of alkalinity entering the lake, divided by the outflow volume of the lake (using outflow rather than inflow automatically corrects for concentration of ions by evapotranspiration). In acid-sensitive lakes with small watersheds, this value is typically much lower than the observed alkalinity (Schindler 1986).

For lakes of equal morphometry in similar geological settings and similar climates, the relative importance of internal alkalinity generation will be inversely related to the size of the lake's terrestrial watershed.

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