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# The transport and retention of dissolved silicate by rivers in Sweden and Finland

*Abstract*—Here we report on the role of natural (lakes) and artificial barriers (dams) in regulating dissolved silicate (DSi) concentrations in rivers from Sweden and Finland. Concentrations of DSi and total phosphorus in rivers were strongly affected by the presence of lakes and reservoirs along the aquatic continuum, with riverine DSi concentrations decreasing as the percentage of area occupied by lakes and reservoirs increased. Rivers with <2% lake and reservoir area in their watershed averaged 164 $\mu$M, whereas DSi in rivers containing greater than 10% lake and reservoir area averaged 46 $\mu$M. The relationship between percentage lake area and DSi concentration was best fit by an exponential function ($r^2 = 0.79, P < 0.001$), because once lake and reservoir area exceeds 10%, minimum DSi concentrations are reached. Because lakes and reservoirs act to reduce watershed DSi concentrations through diatom growth and sedimentation, our results support the hypothesis that further declines in the delivery of DSi to the coastal ocean should be expected as new dams are constructed on rivers. These reductions in DSi transport to the coastal zone with dam construction will have important repercussions on diatom growth and coastal food webs.

Rivers contribute significantly to the worldwide increase in the delivery of nutrients to the coastal zone causing overenrichment and subsequent severe eutrophication problems (Nixon et al. 1996). However, before reaching the coastal ocean, nutrients from land sources transit though the continuum formed by wetlands, rivers, lakes, and estuaries where intense biological and physiochemical processes occur, leading to transformation, immobilization, or elimination of nutrients before they reach the ocean (Billen et al. 1991). In addition, human modification of river system morphology has considerably altered the functioning of nutrient retention along the aquatic continuum (Billen and Garnier 1997).

Although our knowledge concerning how processes along the aquatic continuum affects the transport of N and P is considerable (Howarth et al. 1996; Nixon et al. 1996), we know significantly less about the production and transport of dissolved silicate (DSi). DSi originates from the weathering and breakdown of silicate-containing minerals. Variations in the average global delivery of DSi by rivers from continents to the ocean have been shown to be influenced by lithology, continental weathering intensity, climatic variation, and diatom production (Conley 1997). Significant reductions in the transport of DSi have also been reported after construction of dams, with severe consequences for food web structure in the coastal zone as diatoms are replaced by species not requiring DSi for growth (Turner et al. 1998; Humborg et al. 2000).

Here we evaluate DSi from rivers in Sweden and Finland and examine relationships between DSi concentrations and land-use patterns in the watershed. In addition, the effect of land-use patterns on total phosphorus (TP) concentrations will be presented. We demonstrate that the presence of lakes and reservoirs along the aquatic continuum leads to the enhanced retention of DSi and TP.

Regular monitoring of discharge and nutrients was begun in the mid-1960s in rivers from Sweden and Finland, and the core of the program has remained practically unchanged (Pitkänen 1986; National Swedish Environmental Protection Board 1985). The present study was based on data from the national monitoring programs from 61 sites in Sweden and 30 sites in Finland. All sites in Finland and 39 of the sites in Sweden were located near the river mouth. Annual flow-weighted nutrient concentrations (long-term arithmetic means) were calculated from monthly samples taken over the period 1971–1994 for Sweden and 1970–1993 for Finland. Land-use statistics for river basins were obtained from Statistics Sweden and the Finnish Environmental Institute (Helsinki, Finland). Land use was divided into different categories, including percentage of arable land, forested land, urban area, and other land in the watershed.

Sweden has approximately 96,000 lakes with an area of more than 1 ha and Finland, roughly 56,000 lakes. Lakes cover 8.5% and 10% of the total area of Sweden and Finland, respectively (Statistics Sweden 1987). The forested lakes in Sweden and Finland generally receive a sizable input of humic substances from the surrounding forested land, as well as losses from the numerous bogs and mires. The rivers drain a variety of catchments, ranging from almost pristine areas in northwestern Sweden and Finland to intensively farmed areas in southern Sweden and southwest Finland. During the post-WWII period, the nutrient supply has been further enriched by agricultural runoff. Dams and reservoirs are primarily found in northern and central Sweden and Finland and were constructed for hydropower production and protection from floodwaters, especially during spring when the highest annual discharges after snow melt usually take place.

There is a clear climatic gradient from south to north in Sweden and Finland. The annual average temperature in southern Sweden is 7.5°C in comparison with 1°C in northern Sweden and Finland. The gradient in precipitation is particularly accentuated in Sweden, with 500–600 mm yr$^{-1}$ along the eastern coast and up to 1,600 mm yr$^{-1}$ in the mountain areas in the northwest. In Finland, the mean annual precipitation varies between 400 and 650 mm yr$^{-1}$, with the highest values in the southern and central parts of the country and the lowest in northern Lapland. Snow cover averages only a couple of weeks in southern Sweden and 7 months in northern Finland and Sweden.

Finland and almost the whole of Sweden rest on one of the oldest, most stable and resistant rock masses on earth—the Precambrian Fennoscandina Shield (Koljonen 1992). However, small remnants of younger, sedimentary rocks from the Precambrian can still be found in parts of southern and central Sweden. In addition, the Scandinavian mountain chain in northern Sweden and Norway consists largely of

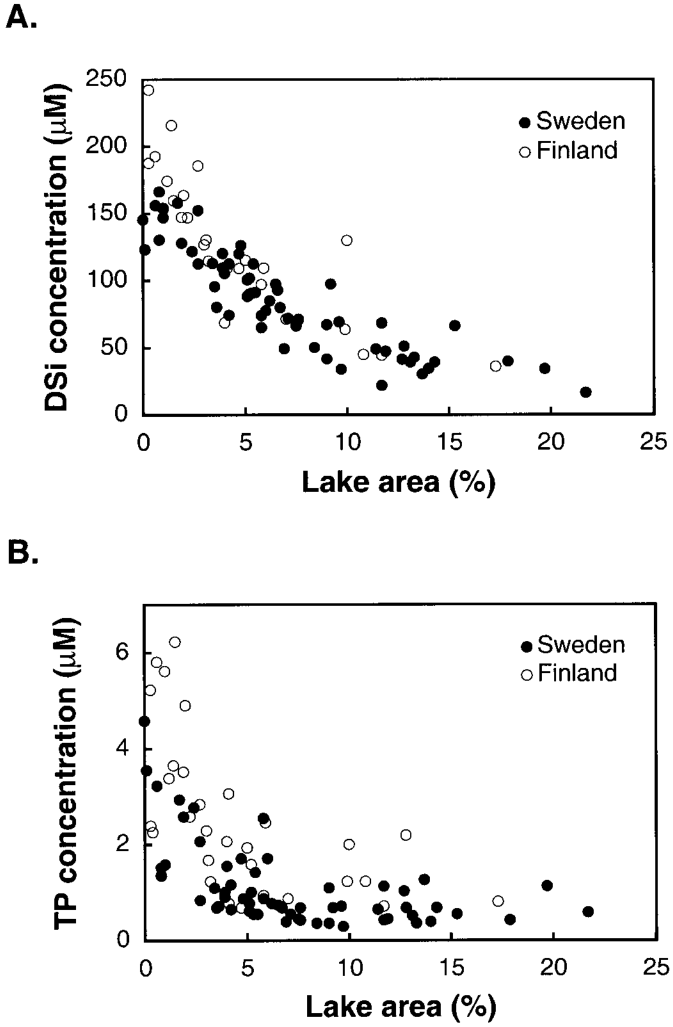


Fig. 1. Mean flow-weighted DSi concentration (A) and mean flow-weighted TP concentration (B) as a percentage of lakes and reservoirs in a watershed from 61 sites located throughout Sweden for the period 1971–1994 and from 30 watersheds located throughout Finland for the period 1971–1993. Two outliers from Finnish rivers with DSi concentrations greater than 250 $\mu$M DSi have been removed (see text).

sedimentary rocks. Glacial deposits from the last ice age are scattered over Sweden and Finland.

Maximum and minimum DSi concentrations in rivers from Sweden and Finland were very similar although somewhat higher in Finland (Fig. 1A). No apparent differences in DSi concentrations were found between rivers that drain into different basins of the Baltic Sea, and no north–south gradient in DSi concentration existed. This suggests that the regional differences in climate and geology cannot explain the observed variation in DSi concentrations in rivers. Two outliers from Finnish rivers with high DSi concentrations (292 and 319 $\mu$M) were removed from Fig. 1A. These two outliers from the rivers Laihianjoki and Sirppujoki have large areas of pyritic soils in their catchment (Koljonen 1992), releasing high amounts of sulfuric acid and perhaps affecting the weathering rate. Similarly high DSi concentrations ($>300$ $\mu$M) have been reported in a tributary to Lake Hjälmaren in Sweden with acid pyritic soils.

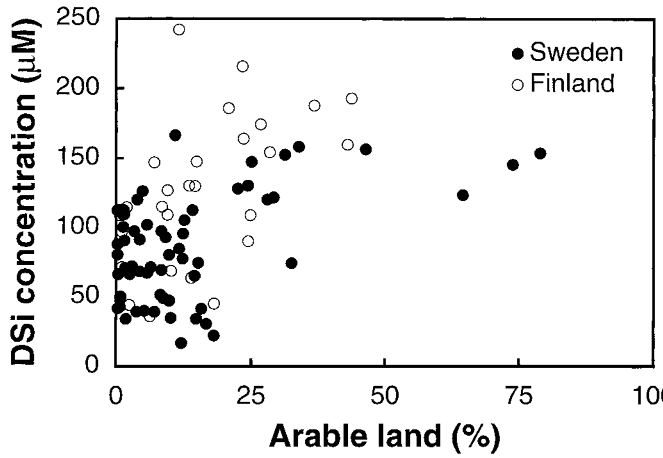


Fig. 2. Mean flow-weighted DSi concentration as a percentage arable land in a watershed from 61 sites located throughout Sweden for the period 1971–1994 and from 30 watersheds located throughout Finland for the period 1971–1993.

DSi concentrations, however, were strongly affected by the presence of lakes and reservoirs along the aquatic continuum. Rivers with $<2\%$ lake and reservoir area in their watershed averaged 164 $\mu$M, whereas DSi in rivers containing greater than 10% lake area averaged 46 $\mu$M. The relationship between percentage lake area and DSi concentration was best fit by an exponential function ($y = 166e^{-0.098x}$, $r^2 = 0.67$, $P < 0.05$), because once lake and reservoir area exceeds 10%, minimum DSi concentrations are reached. Significant relationships were not found between DSi and many of the other variables considered, e.g., forested land, urban area, other land use, and population in the watershed (only Sweden).

The TP concentrations in rivers were also strongly affected by the presence of lakes and reservoirs along the aquatic continuum (Fig. 1B), although no such relationships were found for nitrate concentrations or total-nitrogen concentrations (data not shown). The relationship between percentage lake area and TP concentration was also best fit by an exponential function ($y = 2.18e^{-0.096x}$, $r^2 = 0.37$, $P < 0.05$). Strong negative relationships between the percentage of lake area and specific transport rates of TP have been previously reported in Finnish rivers (Pitkänen 1986).

Strong relationships have been established between landscape structure and nitrate concentrations, with nitrate concentrations increasing with higher percentages of agricultural land in Swedish and Finnish watersheds (Pitkänen 1986) and watersheds in general (Jordan et al. 1997). No such relationships have been established for DSi, although a weak negative relationship ($r^2 = 0.44$, $P = 0.038$) was found by Jordan et al. (1997) between the percentage of cropland and DSi concentrations from Piedmont watersheds of Chesapeake Bay. By contrast, we found that DSi concentrations were generally higher at greater percentages of arable land (Fig. 2), and a weak but significant correlation was found between DSi concentration and arable land ($r^2 = 18$, $P < 0.05$).

Table 1. Dissolved silicate (DSi) concentrations in the inflow and the outflow of lakes and their hydraulic residence times. When there were more than one measurement of inflow concentration, the range in values was presented.

| Lake | Inflow DSi (μM) | Outflow DSi (μM) | Residence time (yr) | Reference |
|---|---|---|---|---|
| Mälaren | 43–207* | 21 | 3 | This study |
| Vänern | 28–164† | 18 | 9 | This study |
| Vättern | 46–296‡ | 11 | 58 | This study |
| Laurel | 57 | 10 | 0.56 | Soukoup 1974 |
| Malawi | 220 | 8 | 140 | Hecky et al. 1996 |
| Michigan | 73 | 13 | 100 | Schelske 1985 |
| Mirror | 145 | 64 | 1.02 | Likens et al. 1985 |

* 70% of watershed monitored.
† 87% of watershed monitored.
‡ 48% of watershed monitored.

Table 2. The loss of dissolved silicate (DSi) with construction of reservoirs on some of the world's major rivers.

| River | Before construction (μM) | After construction (μM) | Reference |
|---|---|---|---|
| Colorado | 225 | 133 | Mayer and Gloss 1980 |
| Danube | 140 | 58 | Humborg et al. 1997 |
| Nile | 210 | 10 | Wahby and Bishara 1980 |

The reasons for the observed correlation between DSi concentration and arable land are unknown. Important factors might include the local geology or climatology. A weak but significant correlation was observed between the arable land and the percentage of lake and reservoir area in watersheds ($r^2 = 0.17$, $P < 0.01$), suggesting that a covariance may be responsible for the DSi–arable land relationship. DSi is not generally considered to be altered by agriculture, although one might expect soil tilling to enhance weathering rates, compared with forested areas. However, additional processes exist, such as changes in water storage and transport, differences in the Si content of plants, and the ability of plants to enhance weathering, that could affect weathering rates in agricultural areas (Drever 1994). Clear-cutting of forests has been shown to increase the export of DSi by a factor of 2–3 for the first few years after clear-cutting, with DSi declining and approaching normal levels within 5 yr (Likens et al. 1970). There is, however, a very incomplete understanding of the effects of land use on variations in DSi discharge, with more investigations required to determine the governing factors affecting DSi transport by rivers.

The direct effect of lakes on DSi can be seen by comparing DSi concentrations in rivers with lake outflow. For our stations, this occurs at only three locations (lakes Mälaren, Vänern, and Vättern), and we observed substantial declines in DSi (Table 1). These decreases in DSi concentrations are likely caused by in-lake processes associated with diatom growth and sedimentation, as has been commonly seen in other studies as well (Table 1). This phenomena is most pronounced in lakes that have experienced cultural eutrophication, with the best-known case being the North American Great Lakes (Schelske et al. 1983). Eutrophication-associated nutrient enrichment stimulates diatom growth, sedimentation, and subsequent burial of diatoms in sediments, causing declines in DSi concentrations in both freshwater and marine ecosystems with long residence times (Conley et al. 1993).

The creation of artificial lakes (reservoirs) has allowed for Si in diatom frustules to be deposited and preserved in sediments behind dams. In addition, improved light conditions and increased water residence time provide the preconditions for enhanced algal growth. This process has been termed the artificial lake effect (van Bennekom and Salomons 1981). Spectacular examples of declines in DSi concentrations have been reported with the building of dams (Table 2), and more modest reductions have been observed in northern Sweden with dams built for hydroelectric power (Brydsten et al. 1990).

Owing to their long residence times and the resulting higher biological activity, the presence of lakes and reservoirs in a watershed strongly increases the overall nutrient retention in river systems. The presence of lakes is thus important to consider when evaluating the transfer of nutrients from the land to the sea. In addition, many rivers in Sweden and the Baltic are currently regulated by dams. With the number of dams projected to increase globally in the coming decades (Vörösmarty et al. 1997), further decreases in DSi delivery to the coastal zone should be expected (Humborg et al. 2000). The impact of DSi decreases in the coastal zone may result in food web effects, including reductions in diatoms with potentially disruptive harmful algal blooms becoming more prevalent (Turner et al. 1998).

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