Hydrological alterations with river damming in northern Sweden: Implications for weathering and river biogeochemistry

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Received 30 October 2000; revised 25 February 2002; accepted 26 February 2002; published 27 July 2002.

[1] This case study tests the hypothesis that damming leads to a depletion of major elements in river systems. It determines the effect of river dams on the weathering regime, and thus on dissolved silicate (DSi) fluxes from land to the Sea by comparing two headwater areas in northern Sweden. In the pristine River Kalixälven, major dissolved elements are enriched within a few kilometers downstream from a high mountainous provenance, coming from an area low in vegetation and a thin active soil layer to a forested landscape. Also, alkalinity increased from 30 μeq L^{-1} to 110 μeq L^{-1}, compared to 240 μeq L^{-1} measured at the river mouth. In the headwater of the River Luleälven, regulations led to inundation of the river valley and associated loss in vegetated soils. In reaches between the reservoirs, underground channeling of water and a reduction of water level fluctuations result in further decrease in soil-water contact, and consequently diminishing weathering rates. The ratio of forest area to lentic area in the headwater was reduced dramatically with damming, from 2.65 to 0.84. As a consequence, geochemical variables in the river water show uniformity in space and in time. Alkalinity values at the River Luleälven mouth (155 μeq L^{-1}) remained unchanged from the two main mountainous storage reservoirs (161 μeq L^{-1} and 166 μeq L^{-1}). These results indicate that loss of vegetated soils through damming in river headwater critically reduces weathering fluxes and also suggest that changes in vegetation coverage in the Quaternary have altered DSi inputs significantly to the global Ocean. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; 4885 Oceanography: Biological and Chemical: Weathering; *KEYWORDS:* damming, weathering, headwaters, dissolved silicate, vegetation, land-ocean interactions

1. Introduction

[2] River systems are perturbed by man mainly through pollution and river regulation, which occurred simultaneously in the twentieth century. Thus, the effect of damming alone is often difficult to disentangle by other anthropogenic impacts, and much less studied. Today, more than 25% of the global river flow is dammed or diverted [*Vörösmarty et al.*, 1997]. Some 40,000 large dams (defined as more than 15 m in height) and more than 800,000 smaller ones are in operation, and more are still being constructed [*Nilsson and Berggren*, 2000; *Vörösmarty and Sahagian*, 2000]. It now appears that nutrient fluxes to rivers and coastal water bodies are being increasingly perturbed by dam constructions, with adverse impact on the quality and structure of aquatic ecosystems [*Humborg et al.*, 2000; *Ittekkot et al.*, 2000a], even on a global scale [*Rosenberg et al.*, 2000]. Decreasing nutrient fluxes to coastal seas through damming are most obvious for dissolved silicate (DSi) [*Wahby and Bishara*, 1979; *Mayer and Gloss*, 1980; *Humborg et al.*, 1997; *Garnier et al.*, 1999], whereas the impact on nitrogen (N) and phosphorus (P) are often overweighed by cultural eutrophication downstream. In Figure 1 the relation between the river DSi concentrations versus reservoir live storage is given, based on measurements in 12 Swedish rivers draining the Scandinavian mountain chain (the Scandes). An inverse relationship is apparent between the degree of damming and the DSi concentration.

[3] Silica (Si) is the second most abundant element on Earth and is a major element in most bedrocks of the crust [*Wedepohl*, 1969]. Chemical weathering of such rocks is the natural source of DSi in water bodies [*Wollast and Mackenzie*, 1983]. Along with N and P, Si is an essential nutrient for diatoms and silicoflagellates. Diatoms form a major part of the aquatic food chain [*Treguer et al.*, 1995] and play a critical role in marine biogeochemical cycles, especially in the sequestration of carbon dioxide from the atmosphere via

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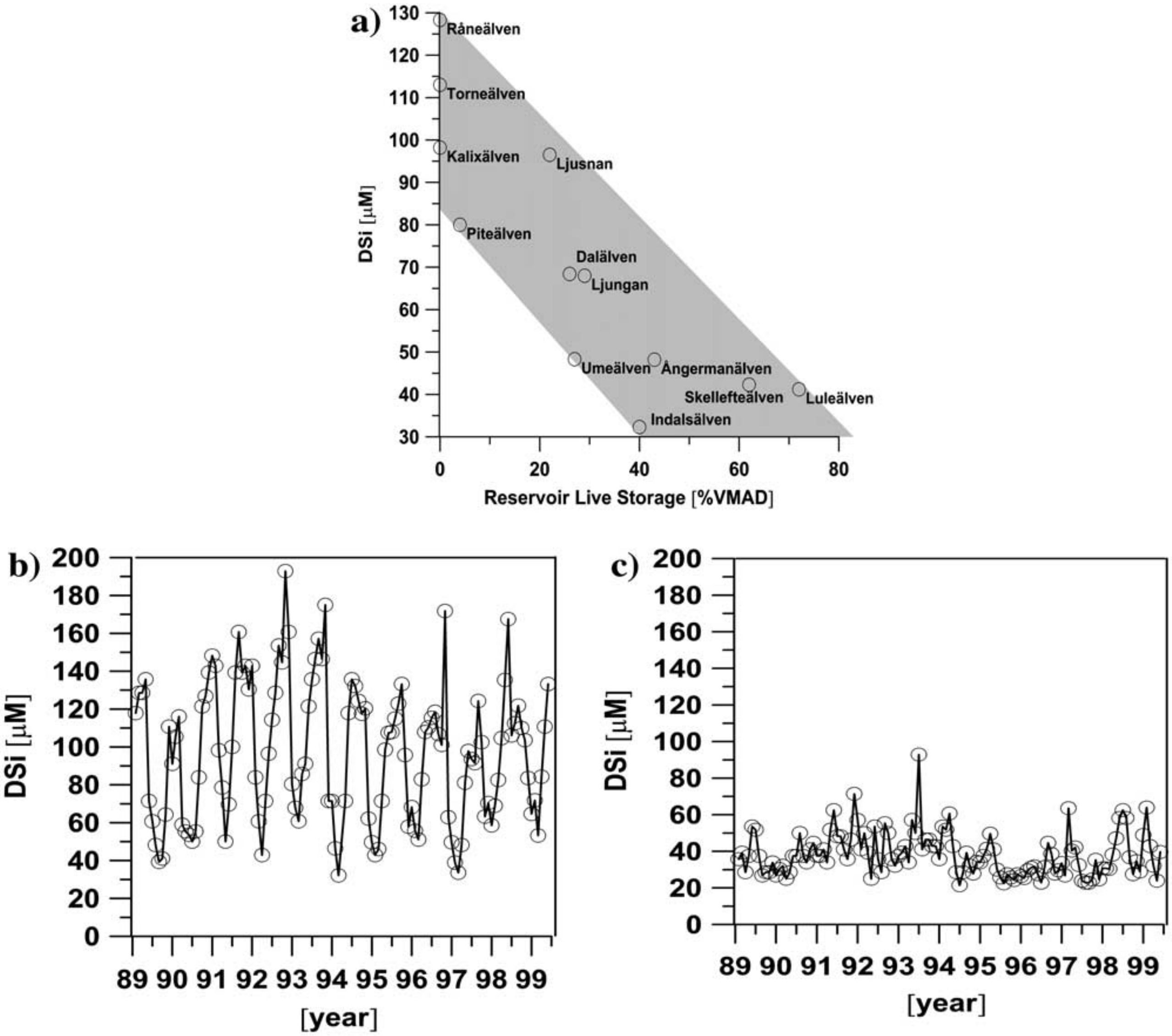

Figure 1. (a) Dissolved silicate (DSi) concentrations versus reservoir live storage of 12 Swedish rivers, draining the Scandinavian mountain chain. The reservoir live storage is expressed as the percentage of the virgin mean annual discharge [%VMAD] of the river system that can be contained in reservoirs and, thus, is a measure for the degree of damming of a river; the "live" storage refers to the volume that can be withheld in, and subsequently released from, the reservoir. (b) Dissolved silicate (DSi) concentrations versus time at the river mouth of the Kalixälven (nonregulated) and (c) versus time at the river mouth of the River Luleälven (regulated); data from monthly measurements were monitored at the river mouths by the Swedish University of Agricultural Sciences, Uppsala, Sweden.

the "biological pump" [*Dugdale et al.*, 1995; *Ittekkot et al.*, 2000b]. However, it is not fully understood how damming affects the Si cycle, since damming effects have been observed in eutrophic [*Humborg et al.*, 1997] as well as oligotrophic parts of rivers [*Garnier et al.*, 1999]. For example, all rivers shown in Figure 1a can be classified as oligotrophic. Thus, there must be factors other than flourishing diatoms in the reservoirs [cf. *Mayer and Gloss*, 1980] causing the low DSi concentrations in these rivers.

[4] The two northern Swedish river systems of Kalixälven and Luleälven are ideal test systems for a case study, with sufficient background data on the effect of damming as such on coastal biogeochemistry. The headwaters are rather close to each other (Figure 2a), and while River Kalixälven is nonregulated, River Luleälven represents the most intensively dammed river in Eurasia, with 72% recorded live storage [*Dynesius and Nilsson*, 1994]. Apparent changes with damming are the much lower and all-the-year-round uniform DSi concentrations in the River Luleälven compared to the high seasonal variations in the River Kalixälven, as measured at the river mouths (Figures 1b and 1c). Lower concentrations in the River Luleälven are likewise observed for other major cations, for nutrients as well as for total organic carbon (TOC) (Table 1).

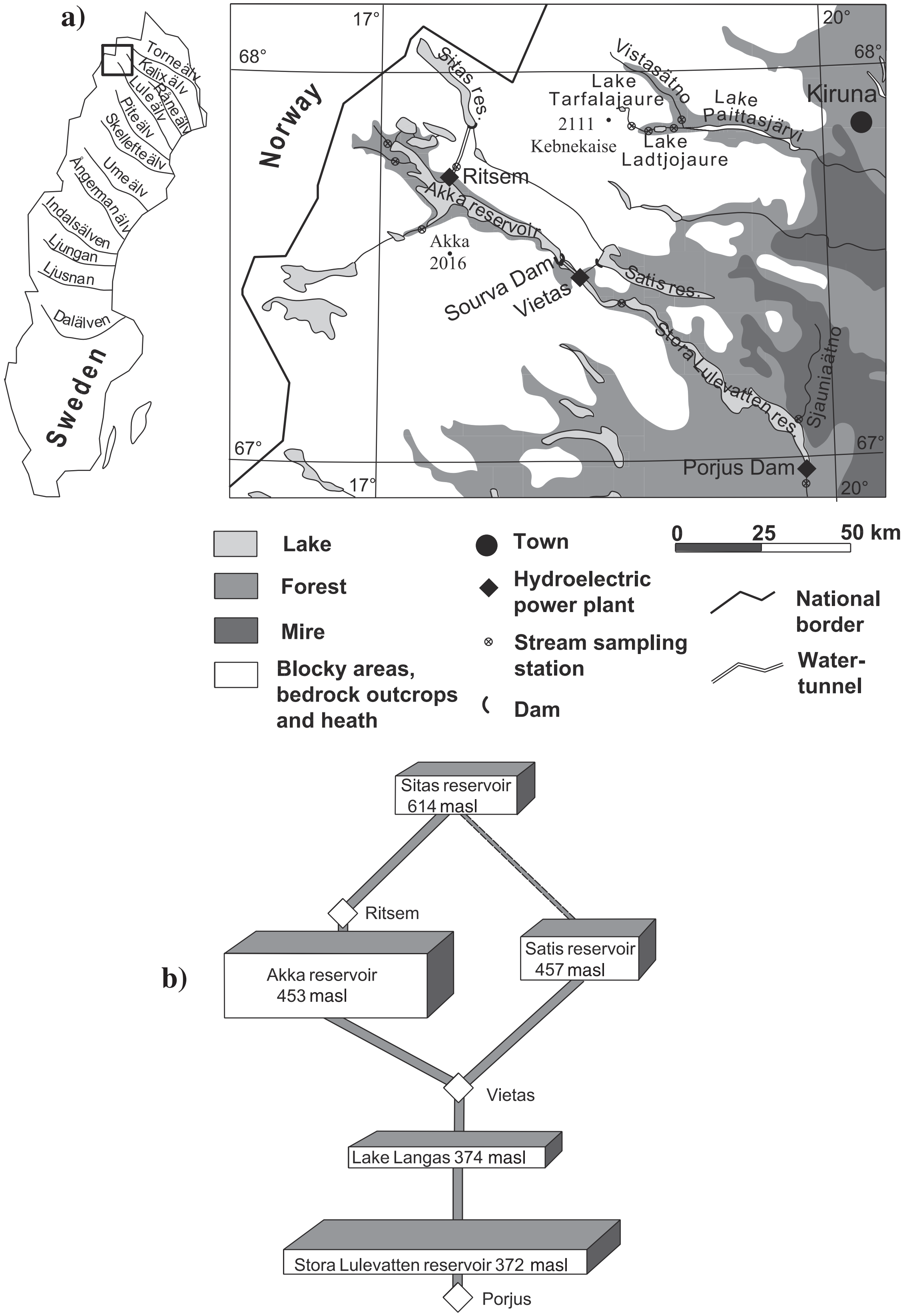

Figure 2. (a) Investigation area with location of water sampling sites. (b) Scheme over the major reservoirs (boxes, including Lake Langas), headrace tunnels (tubes), and power plants (diamonds) in the upper River Luleälven. (c) Changes in vegetation cover in the upper River Luleälven (nowadays, Akka reservoir) with damming.

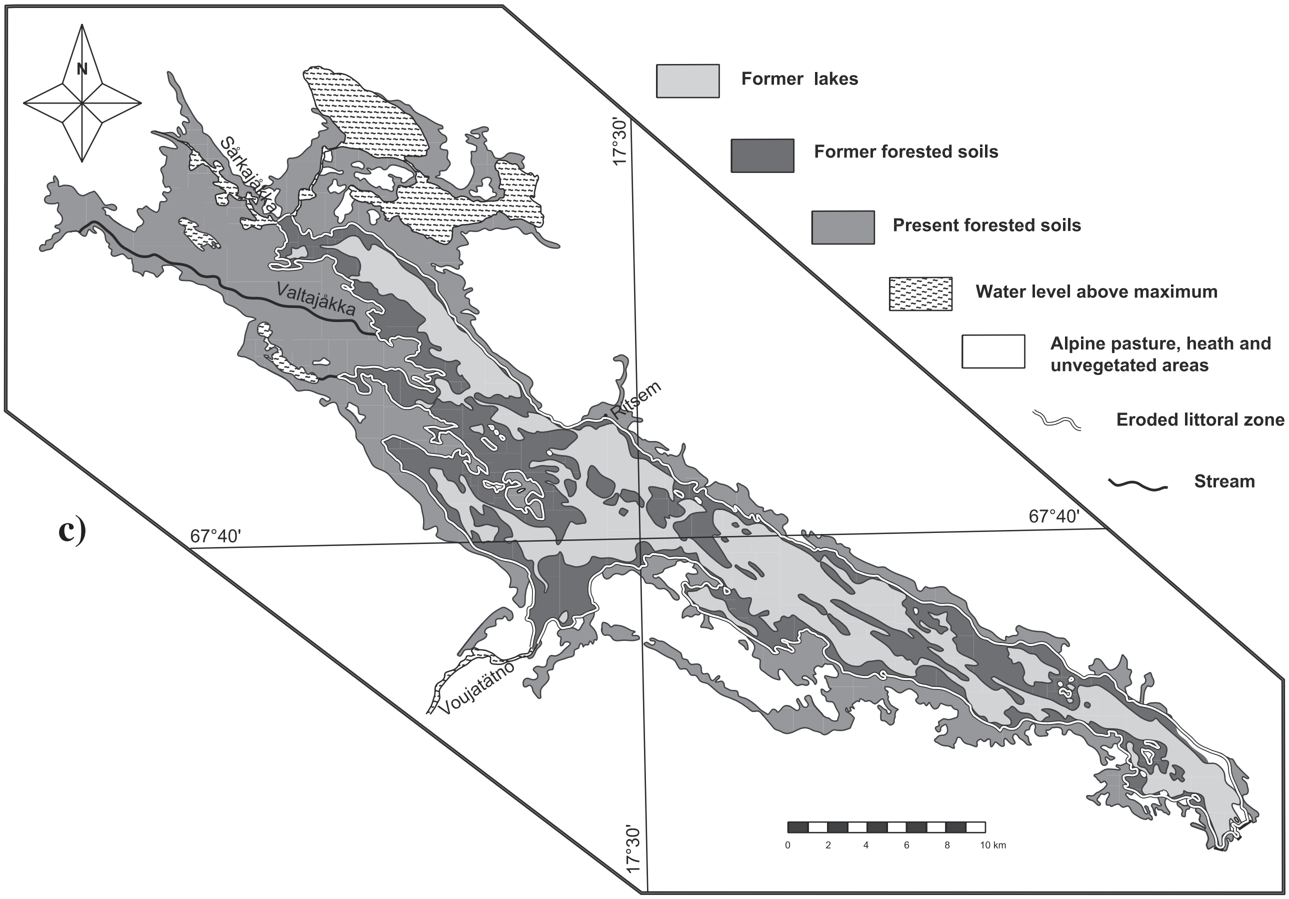

Figure 2. (continued)

[5] Since high capacity reservoirs are often built in headwater areas, where river elevation drops steeply, it appears rational to investigate this area in more detail. Furthermore, natural weathering processes that enrich the water with dissolved constituents as it runs downstream from its high mountainous (including glacier) provenance, as well as potential perturbations of biogeochemical fluxes through damming, can here be studied in close proximity. In this paper, we compare two dammed and three undammed headwater lakes in an area otherwise unexploited by human activities, in order to get a better understanding of the changes in biogeochemical processes that are responsible for the apparent depletion of dissolved constituents in dammed rivers.

2. Methods

2.1. Investigation Area

[6] The catchment areas of the rivers Kalixälven (23,846 km^2) and Luleälven (25,237 km^2) are situated in Swedish Lapland, between 65°N and 68°N (Figure 2a). These areas are sparsely populated and might, apart from the regulation in the River Luleälven, be classified as pristine. The headwaters of the rivers investigated are situated in the Scandinavian Caledonides, above the Arctic Circle, in a mountainous area close to the Norwegian border. The rivers flow southeastward in parallel, and empty into the Bothnian Bay. Two of the highest mountains in Sweden are sited within the headwater areas; the ice-capped summit of Kebnekaise reaches about 2114 ± 5 m above sea level (asl) [*Holmlund and Jansson*, 1999] in the River Kalixälven system, whereas in the River Luleälven system the somewhat lower massif of Akka is about 2010 m asl.

[7] The climate of the area is typical subarctic, with continuous frost from mid-October to May [*Swedish Meteorological and Hydrological Institute*, 1991; *Grudd and Schneider*, 1996]. Dominating westerly winds deliver high precipitation to the headwater areas; in amounts between 1000 and 2000 mm yr^{-1} [*Carlsson and Sanner*, 1994]. The mean water discharge of the River Kalixälven and River Luleälven is about 300 and 500 m^3 s^{-1}, respectively.

2.2. Geology and Vegetation

[8] In the investigated area, crystalline bedrock predominates. Common rocks are dolerite, amphibolites, granite, syenite, gneisses and schists. Around the reservoir of Akka (River Luleälven) intercalations of marble occur [*Kulling*, 1964, 1982]. The Kebnekaise massif (River Kalixälven) is dominated by sheeted dolerite complexes, amphibolites, gneisses and schists [*Andréasson and Gee*, 1989]. Along the easterly marginal zone of the Caledonian thrust (nappe) succession, Phanerozoic sediments (sandstone and shale) are found [*Kulling*, 1964, 1982]. Farther eastward in the studied

Table 1. Mean Dissolved Concentrations of Major Cations, Nutrients and Total Organic Carbon (TOC) in River Kalixälven (Nonregulated) and River Luleälven (Regulated) Systems

Location	Altitude, m asl	Volume, 10^6 m^3	Catchment Area, km^2	Percent Lentic	Percent Forest	Discharge, m^3 s^{-1}	Ca, µM	K, µM	Mg, µM	Na, µM	DSi, µM	DIN, µM	PO_4, µM	Alk, µeq L^{-1}	TOC, µM
						River Kalixälven									
Lake Tarfalajaure	1168	13	20.6	3	0	–	24.5	2.1	9.9	9.2	23.4	3.6	0.01	45.8	–
Tarfalajåkka	580	–	200.5	1	7	–	61.3	7.9	18.2	28.4	63.1	6.75	0.02	89.2	–
Lake Ladtjojaure	513	11	215.7	2	9	–	68.2	9.3	19.0	27.6	67.0	4.2	0.01	117.5	–
Ladtjojåkka	500	–	298.9	2	12	–	59.9	8.4	20.0	28.0	71.0	2.1	0.02	111.1	–
Lake Paittasjärvi	465	910	1065.3	5	22	–	57.0	9.8	17.5	27.3	57.5	3.1	0.01	106.6	–
River mouth[a]	0	–	23846.0	5	35	294	123.4	18.2	49.7	91.9	96.5	11.4	0.16	242.6	367.5
						River Luleälven									
Vuojatätno	453	–	2846.6	13	2	>50	99.6	11.0	34.6	47.3	15.6	2.83	0.01	234.8	–
Akka Reservoir	453	8000	4650.6	16	4	–	71.3	10.9	24.4	41.7	12.3	2.38	0.01	161.3	–
Sourva Dam	453	–	4650.6	16	4	168	74.8	11.4	24.6	44.3	12.3	2.59	0.01	201.3	–
Jaurekaska Riffle	374	–	7716.6	15	10	–	69.1	10.1	22.7	42.0	20.0	0.82	0.01	150.0	–
Stora Lulevatten Reservoir	372	1300	9793.1	14	18	–	68.6	10.1	22.8	41.5	15.5	0.79	0.01	166.0	–
Porjus Dam	372	–	9876.3	14	18	220	67.3	10.3	23.4	42.3	19.6	1.32	0.01	140.3	–
River mouth[a]	0	–	25327.0	10	44	496	73.5	11.5	27.8	64.5	38.5	3.2	0.08	155.0	199.2

[a] Data from monthly measurements (1988–1999) monitored at the river mouths (Karlsborg and Luleå) by the Swedish University of Agricultural Sciences, Uppsala, Sweden.

areas, the underlying older (Svecokarelian) basement is dominated by volcanic and sedimentary (quartzitic) rocks, and plutonic rocks of granite, syenite and gabbro [*Ödman*, 1957].

[9] In the northern Caledonides, the forests are mainly deciduous shrub predominated by birch (*Betula* spp.), and in wet habitats willow (*Salix* spp.) is also frequent. Eastward, coniferous vegetation, essentially Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), is also found. Above the tree line, i.e., at about 800 m asl, alpine heath is the leading biotope. In other words, all main tributaries of both river systems have their origin in sparsely vegetated or unvegetated areas, with thinner soil thickness compared with the forested landscape downstream.

2.3. Regulation of River Luleälven

[10] The River Luleälven was first regulated at Porjus (Figure 2a) in 1910–1915 [*Forsgren*, 1982]. Later, in 1923, the Suorva Dam was erected [*Forsgren*, 1987]. Up to the late 1970s, three additional regulations of the Akka reservoir have been conducted [*Nilsson*, 1972]. Today, one fifth of the hydroelectric power in Sweden is produced by 15 hydroelectric power plants in the River Luleälven [*Carlsson and Sanner*, 1994]. Three of these plants (Porjus, Vietas, and Ritsem) are situated in the sampling area (Figure 2a). There are also four reservoirs permitting storage of runoff water for more than 1 year, namely the reservoirs of Sitas, Akka, Satis, and Stora Lulevatten. The active storage volumes in the magazines are estimated as about 640, 5900, 1240, and 1310 $\times$ 10^6 m^3, with a regulated magnitude of 10, 30, 19, and 6 m, respectively [*Swedish Power Association/Swedish State Power Board*, 1981; *Forsgren*, 1989; *Swedish Meteorological and Hydrological Institute*, 1996]. The water from the three upper reservoirs is transported via headrace tunnels into the lower reservoir of Stora Lulevatten (Figure 2b). The spring flood runoff water is stored in the reservoirs and tapped whenever electricity production is required. On a yearly basis, there is a balanced distribution of the water discharges to the Gulf of Bothnia. This is in sharp contrast to the unregulated rivers in Northern Sweden, such as the River Kalixälven, which show a clear seasonal variation in water discharge, peaking in June–July [*Bergström and Carlsson*, 1994].

[11] Different geological and vegetation maps were used to compile the changes in landscape with damming. Information on vegetation type and coverage, margin zones of former and present lakes was digitized, using OCAD®.

2.4. Sampling Strategy

[12] Since the hydrological winter period in the study area normally extends from October to May, we chose to sample early winter conditions in November and December, late winter conditions in March to May, spring conditions in June, and summer conditions in August. All samplings were conducted in 1999–2000. The sampling stations are indicated in Figure 2a.

[13] In the River Kalixälven, the sampled lakes were Lake Tarfalajaure, Lake Ladtjojaure, and Lake Paittasjärvi (-jaure and -järvi mean "lake"). The streams connecting the lakes, named Tarfalajåkka and Ladtjojåkka (-jåkka means

"stream"), were sampled seasonally at the inlet to Lake Ladtjojaure (Tarfalajåkka) and at the inlet to Lake Paittasjärvi (Ladtjojåkka). In May 2000, the connecting streams were sampled in more detail during base flow at the following stations: Tarfalajåkka 1 and 2 (two stations 580 m asl and 530 m asl, downstream Lake Tarfalajaure); Ladtjojåkka, at the inlet of Lake Ladtjojaure and Lake Paittasjärvi; Vistasätno (-ätno means "river"), which is an additional tributary to Lake Paittasjärvi.

[14] Sampling of the River Luleälven was in a way more complicated because former consecutive lakes, such as in the River Kalixälven headwater, are now converted into two huge lake systems (the reservoirs of Akka and Stora Lulevatten) ranging over 170 km, thus stretching over different biotopes and geochemical provinces. In the River Luleälven the two largest reservoirs (Akka and Stora Lulevatten) were sampled. Several watercourses drain into the Akka reservoir. The stream of Voujatätno, the main tributary to the Akka reservoir, and the water of the Ritsem Power Plant, coming through a headrace tunnel from the Sitas reservoir, were sampled seasonally. The other larger inflows, Valtajåkka and Sårkajåkka were sampled during base flow and spring flood. Water leaving the Akka reservoir at the Suorva Dam was sampled seasonally. Water entering the reservoir of Stora Lulevatten was also sampled seasonally in the running stream Jaurekaska Riffle, and water leaving Stora Lulevatten was sampled at the Porjus Power Plant. The stream of Sjaunjaätno, entering Stora Lulevatten 16 km above the Porjus Dam, was sampled during base flow.

2.5. Analytical Methods

[15] Temperature, conductivity, dissolved oxygen, and pH were measured in situ using a Hydrolab® Multiprobe 4 water quality probe. The probe was equipped with a low ionic strength electrode for the pH and conductivity determinations.

[16] Water samples in duplicate were provided from all depths and stations. Shallow watercourses were sampled directly at the surface by syringes, whereas samplings of water columns were conducted by means of a Teflon-coated Ruttner-type sampler (Limnos®), prewashed in 0.1 *M* hydrochloric acid and carefully rinsed. The water samples were pressed directly through prewashed cellulose membrane filters (0.45 μm Millipore®), and the filtrates were collected in polypropylene tubes for nutrient analysis, and in acid-washed polyethylene bottles for IC (ion chromatography) and ICP (inductively coupled plasma spectrometry) analysis. For the latter analysis, 1 mL of suprapure HNO_3 was added (in the field) for every 100 mL of water to conserve the samples. The syringes, tubes and bottles were precleaned and stored filled with ultraclean (18.2 $M\Omega\ cm^{-1}$) water of an ELGA® spectrum RO1 system.

[17] The concentration of dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorus (DIP) was determined with a flow injection analysis (FIA) system [*Ranger*, 1993]. Major dissolved elements, including dissolved silicate (DSi), were determined by means of an inductively coupled plasma-atomic emission spectrometer (ICP-AES, Varian Vista®). Alkalinity was determined by back titration [*Almgren et al.*, 1983]. Total organic carbon (TOC) was determined on unfiltered water samples using a Shimadzu® TOC-5000-analyzer (catalytic combustion).

3. Results

3.1. Changes in Riparian Zone With Damming in Akka Reservoir

[18] The Akka reservoir covers five former, now submerged major lakes (Figure 2c) as well as 148 ponds and tarns [*Curry-Lindahl*, 1971]; by the final regulation the lentic area was approximately doubled. In the southeastern part of the valley the slopes are much steeper, and consequently area loss after inundation was less than in the northwestern part of the valley, where the slopes are more flat and the lotic-lentic marginal zone was much wider. Here, the three major natural inflows (Vuojatätno, Valtajåkka, and Sårkajåkka) enter. As indicated in Figure 2c, this area was previously covered mainly by birch forest, which nowadays is left mainly in the Valtajåkka catchment. The birch forest of the former Vuojatätno delta is completely lost. The estimated loss of forested soils is 127 km^2, with 217 km^2 still remaining. Before damming 7% of the catchment of the former lakes was forested, similar to the headwater of the Kalixälven (Table 1). The former lake area was about 130 km^2, compared to the 257 km^2 of the full reservoir today. In other words, the ratio of forest area to lentic area was reduced dramatically with damming, from 2.65 to 0.84.

[19] The most obvious alteration with the damming is the completely eroded marginal zone of the reservoir, which is caused by the seasonal amplitude in water level of up to 30 m. The upper active soil layers and lag gravel are completely lost, and basically only blocks and boulders are left. Thus, in contrast to the predammed situation, the water that once entered the reservoir in the northwestern part of the valley, today no longer has contact with soils and/or vegetation. Although the lentic area is much larger than before damming, the length of the marginal zone decreased from about 235 to 215 km.

3.2. Seasonal Variations of Dissolved Constituents

[20] The headwater of both River Kalixälven and River Luleälven are extremely oligotrophic. In the River Luleälven system, DIP values were mostly under or just above the detection limit (0.016 μM P), while DIN values ranged from 0.2 to 4 μM. In the River Kalixälven system, slightly higher DIP values up to 0.04 μM were measured, and the DIN values were also slightly higher than in the Luleälven, 1–7 μM.

[21] The seasonal dynamics of nutrient and major cations in the River Kalixälven headwater were clearly dominated by the hydrological cycle. In Figure 3a the annual variation of DSi in Lake Paittasjärvi is shown, which is consistent with that of Lake Ladtjojaure. Highest concentrations were found during base flow in April and May, whereas lowest values were recorded at the time of the snowmelt in spring (June). All other major cations indicating weathering, such as Ca (Figure 3c) as well as Mg and K (not shown), follow similar patterns. The seasonal dynamics of nutrient and major cations in Lake Paittasjärvi and Lake Ladtjojaure

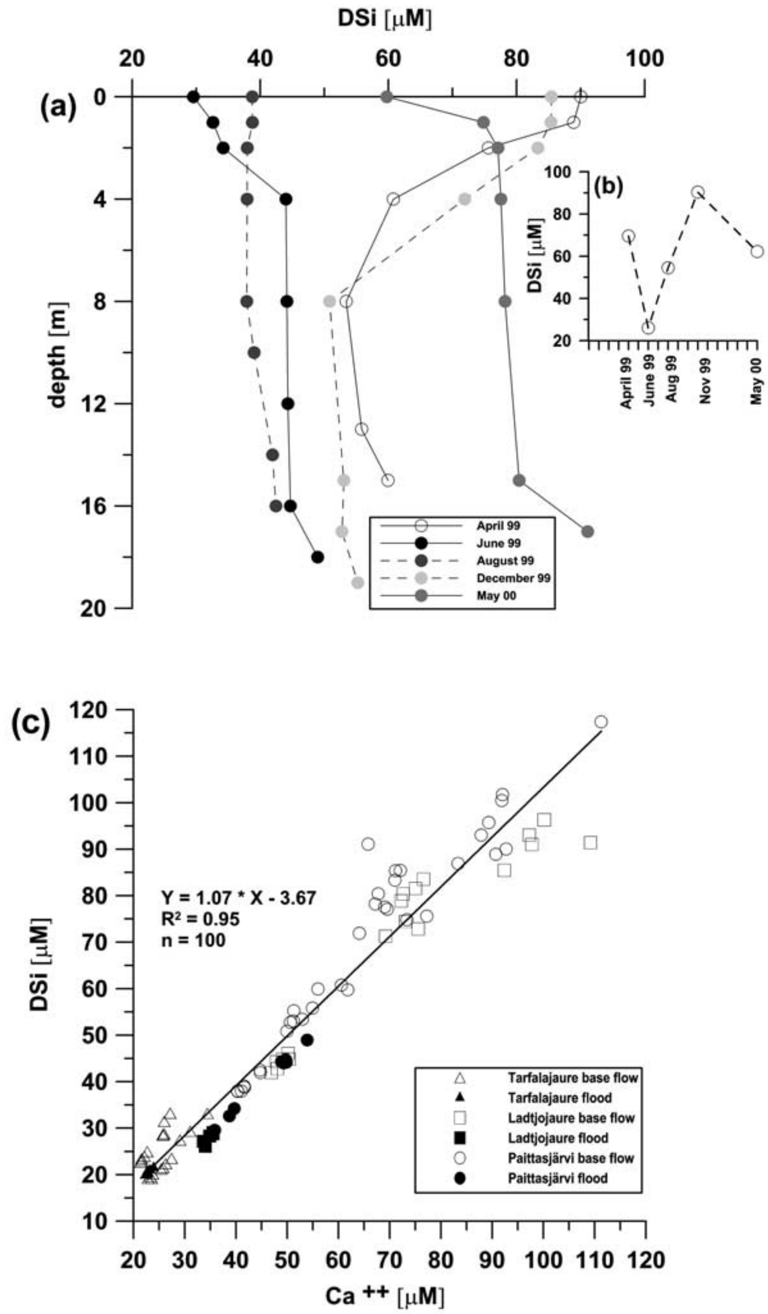

Figure 3. Dissolved silicate (DSi) concentrations in the River Kalixälven (nonregulated) headwaters (a) versus depth in Lake Paittasjarvi, (b) versus time in the Tarfalajakka, and (c) versus calcium (Ca) concentrations in the three headwater lakes Tarfalajaure, Ladtjojaure, and Paittasjarvi.

were also observed in all tributaries below the tree line (Figure 3b).

[22] Throughout the year a remarkable constant ratio of about 1 between DSi and Ca appears in all three headwater lakes (Figure 3c). The lowest DSi and Ca concentration were detected in Lake Tarfalajaure. In contrast to the two downstream lakes Ladtjojaure and Paittasjärvi, Lake Tarfalajaure showed almost no seasonal variations. Changes in major cations and nutrients were only a few micromoles. Tarfalajaure, located at 1 160 m asl near the glacier terminus of the Kebnepakteglaciären, is ice-free only between the end of July and September, and water temperatures recorded in this study did not exceed 2.5°C. Hence, wind induced mixing occurred frequently when the lake was ice-free. Measurements from two glacier termini (Isfallsglaciären and Storglaciären in September 1999) also showed very low concentrations of all dissolved constituents; these are in the same order of magnitude as the

Table 2. Dissolved Concentrations of Major Cations, Nutrients, and Total Organ Carbon (TOC) as Well as pH and Conductivity in River Kalixälven (Nonregulated) and River Luleälven (Regulated) Headwaters During Base Flow (March 2000)[a]

Location	Altitude, m asl	Date, month-year	Ca, µM	Mg, µM	Na, µM	K, µM	DSi, µM	Ca/DSi	TOC µM	DIN, µM	PO_4, µM	Alk, µeq L^{-1}	pH	Cond, µS cm^{-1}
River Kalixälven														
Wet deposition[b]	–		2.4	1.1	4.5	2.2	–	–	–	–	–	–	4.5	2.0
Isfallsglaciären (0 km)	1200	09-1999	6.8	1.7	4.3	0.5	3.5	1.9	–	6.8	0.16	28.1	–	–
Storglaciären (0 km)	1100	09-1999	16.8	6.8	8.7	2.1	17.0	1.0	–	1.32	0.07	39.6	–	–
Lake Tarfalajaure (0 km)	1168	05-1999	24.0	10.9	9.5	2.2	26.9	0.9	≤42	3.28	0.01	52.1	7.13	7.3
Tarfalajåkka 1 (3 km)	580	05-1999	74.3	27.5	36.1	7.2	95.8	0.8	75	3.50	0.03	232.2	7.31	23.8
Tarfalajåkka 2 (5 km)	530	05-1999	76.1	19.3	26.7	10.1	62.2	1.2	108	4.46	0.01	112	7.48	21.6
Lake Ladtjojaure (10 km)	513	05-1999	92.6	27.8	32.7	12.7	99.2	1.0	100	4.94	0.01	164.3	7.16	26.2
Ladtjojåkka (15 km)	500	05-1999	71.1	26.9	29.6	11.9	90.2	0.8	192	1.45	0.03	146.6	6.80	20.8
Vistasätno	465	05-1999	64.5	23.0	28.1	20.9	62.5	1.0	308	1.46	0.04	123.5	7.07	19.7
Lake Paittasjärvi (21 km)	465	05-1999	67.8	22.6	27.7	11.9	77.0	0.9	92	2.9	0.01	165.4	7.08	22.4
River Luleälven														
Särkajåkka	453	03-2000	30.9	1.9	33.2	7.0	15.4	2.0	58	2.74	0.01	69.2	6.57	13.1
Valtajåkka	453	03-2000	53.8	25.0	66.4	19.6	59.6	0.9	83	3.84	0.01	150.3	6.51	22.0
Vuojatätno	453	03-2000	109.1	37.8	53.8	11.4	18.3	2.1	58	4.03	0.01	262.2	7.17	33.8
Ritsem Tunnel	453	03-2000	68.6	18.4	41.0	11.6	13.4	5.1	58	3.30	0.02	145.4	6.96	21.2
Akka Reservoir	453	03-2000	68.2	22.8	42.6	10.8	13.1	5.2	67	3.15	0.01	186.6	6.87	23.1
Sjaunjaätno	372	03-2000	110.4	51.3	75.3	11.6	180.0	0.6	217	9.89	0.02	297.5	6.93	38.9

[a] Kilometer values (within parentheses) after station names of River Kalixälven give distance from glacier termini.
[b] Average yearly composition of wet deposition in River Kalixälven area during period 1983–1989 [*Granat*, 1990].

measured wet deposition in the headwater of the River Kalixälven (Table 2).

[23] In summary, during base flow, the water running down the Tarfala Valley, passing an area initially sparsely vegetated to a forested biotope, has been substantially enriched with DSi and all major cations, and has been increased in alkalinity within only a few kilometers. In contrast, during the period of snowmelt and peak discharge, all three lakes (Tarfalajaure, Ladtjojaure, and Paittasjärvi) have concentrations similar to the water leaving the glaciers (Isfallsglaciären and Storglaciären) and to wet deposition. The annual mean DSi concentration detected in Lake Ladtjojaure and Lake Paittasjärvi is already 60% of the concentration measured at the river mouth. Ca and K concentrations were about 50% of the river mouth, and Mg and Na reached 40 and 30%, respectively (Table 1).

[24] Almost no seasonal variations of dissolved constituents could be observed in the headwater of River Luleälven. Except for the stream of Valtajåkka, which showed higher values during base flow (Figure 4b, Table 2), all other main tributaries to the Akka reservoir showed only minor variation in time. During all samplings in the Akka reservoir, physical variables (temperature and conductivity) as well as chemical variables (major cations as well as nutrients) showed only minor variations in time and with depth. For example, plots of DSi, Ca, Mg, and K concentrations against depth revealed almost no variations throughout the year (Figure 4a). Only once in June was a thermocline recorded (at about 7 m depth), separating an upper layer with about 7°C from a lower water column of about 5°C. This is the time when the Suorva Dam discharge is set to a minimum and the spring flood fills the Akka reservoir. On all other sampling dates the water column was homogeneous, even when it was ice-covered. This pattern is also reflected in the DSi/Ca relationship (Figure 4c). Only during the reservoir filling stage in June is a correlation between DSi and Ca visible; at all other samplings the values in the DSi/Ca plot lie in a close spot, indicating strong mixing of the water column, especially in November (note the difference in scales between Figures 3c and 4c). The same patterns can be observed in the Stora Lulevatten reservoir (Figure 4c), where about the same concentrations in major cations and nutrients were found. At the Porjus Dam, the concentrations of Ca, Mg, K, Na, and alkalinity are still unchanged from the two major reservoirs upstream (Akka and Stora Lulevatten), whereas DSi is slightly enriched. This can be attributed to water coming from the tributary Sjaunjaätno (Figure 2a), where DSi concentrations up to 180 µM were measured during base flow (Table 2). However, down to the Porjus Dam, which comprises about half the drainage area and water discharge of the River Luleälven (Table 1), the water is frequently mixed and, compared with the River Kalixälven, has been only slightly enriched with DSi and major cations.

3.3. TOC and DSi During Base Flow

[25] In March and May 2000, we conducted a more detailed field sampling in both headwaters, in order to investigate the possible effect of organic matter on

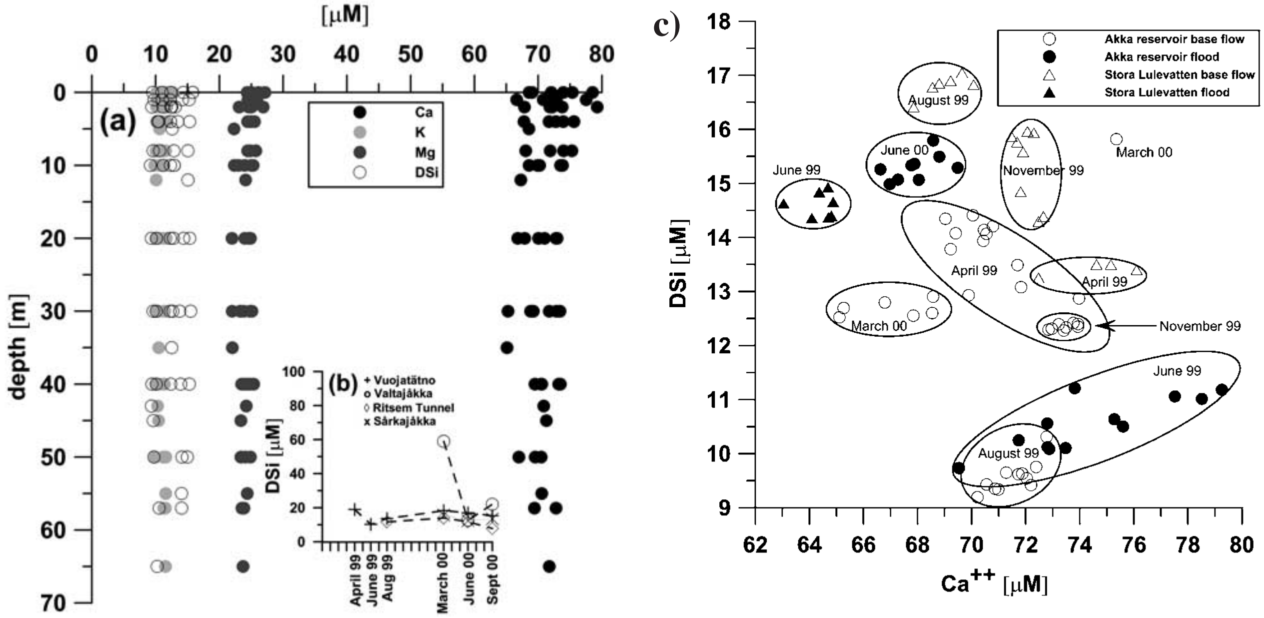

Figure 4. Dissolved silicate (DSi) concentrations in the River Luleälven (regulated) headwaters (a) versus depth in Akka Reservoir (for sampling occasions, see section 2), (b) versus time in the main tributaries to the Akka reservoir, and (c) versus calcium (Ca) concentrations in the two major reservoirs of Akka and Stora Lulevatten; envelopes are drawn around single sampling occasions in 1999–2000.

weathering (Table 2). A clear positive correlation between TOC and DSi was apparent from monitoring measurements at the river mouth of the five northernmost rivers in Sweden, where all, except the River Luleälven, can be characterized as pristine (Figure 5b). This relationship is not found in the other more southern rivers marked in Figure 1a, possibly because massive wood and fiber deposits are found at their river mouths. However, a similar positive relationship holds for both headwater areas in the rivers of Kalixälven and Luleälven (Figure 5a). In the River Kalixälven headwater, the lowest TOC concentrations were detected in proglacial areas, which are barren in vegetation. In Lake Tarfalajaure, the TOC concentration was often below the detection limit, and measurable TOC concentrations were found only in a few samples. Running down the Tarfala Valley, the water was substantially enriched in both DSi and TOC. In fact, where the riparian zone of Tarfalajåkka and Ladtjojåkka became vegetated by birch shrub, the concentration of DSi and TOC was similar to the lakes of Ladtjojaure and Paittasjärvi. The tributary Vistasätno also showed DSi levels comparable to those found in the other tributaries below the tree line, but had even higher TOC values than Tarfalajåkka and Ladtjojåkka.

[26] Low concentrations of DSi and TOC were also recorded in the Akka reservoir and in three of its main tributaries. In contrast, the stream of Valtajåkka, which today still drains an extended birch forest (Figure 2c), had higher values, similar to those from the vegetated headwater of the River Kalixälven. Highest DSi and TOC levels were found in the Sjaunjaätno, which drains a large mire area and flows into the Stora Lulevatten reservoir (Figure 2a). Due to its low water discharge, the overall contribution of this tributary remains small. However, it may explain the somewhat higher DSi values at the Porjus Dam compared with the reservoirs of Akka and Stora Lulevatten.

4. Discussion

[27] Chemical weathering of silica minerals is mainly a function of temperature [*Berner and Berner*, 1995] and electrolyte composition, with pH regarded as the single most crucial factor [*Busenberg and Clemency*, 1976; *Chou and Wollast*, 1985; *Brantley and Stillings*, 1996]. Also, increased dissolution in natural systems can result from ligand-forming ions, such as organic acids [*Amrhein and Suarez*, 1988; *Lundström and Öhman*, 1990; *Drever and Zobrist*, 1992; *Franklin et al.*, 1994; *Stillings and Brantley*, 1995; *Stillings et al.*, 1996; *Berner and Cochran*, 1998; *Oliva et al.*, 1999], exudated directly from plants, or formed during biomass degradation [*Berner and Berner*, 1995].

[28] As a result, the DSi content in river waters commonly varies between 110 µM in arctic regions and 710 µM in the tropics [*Meybeck*, 1979]. The former value conforms well to the end-member concentration observed in the nonregulated Swedish rivers (Figure 1). From studies in a series of small catchments in the Swiss Alps, *Drever and Zobrist* [1992] stressed the significance of the combined effect of temperature and vegetation on silicate weathering. They observed an exponential decrease in major cations and DSi in surface waters with elevation (ranging from 220 to 2400 m). This was related to a change in vegetation from deciduous forest in the foothill area, through coniferous forest to alpine pasture and essentially unvegetated rocks at the top elevation. They found that HCO_3^- stream flux from silicate weathering was about 25 times higher at the lowest elevation than at the highest. A three-fold increase in silica fluxes

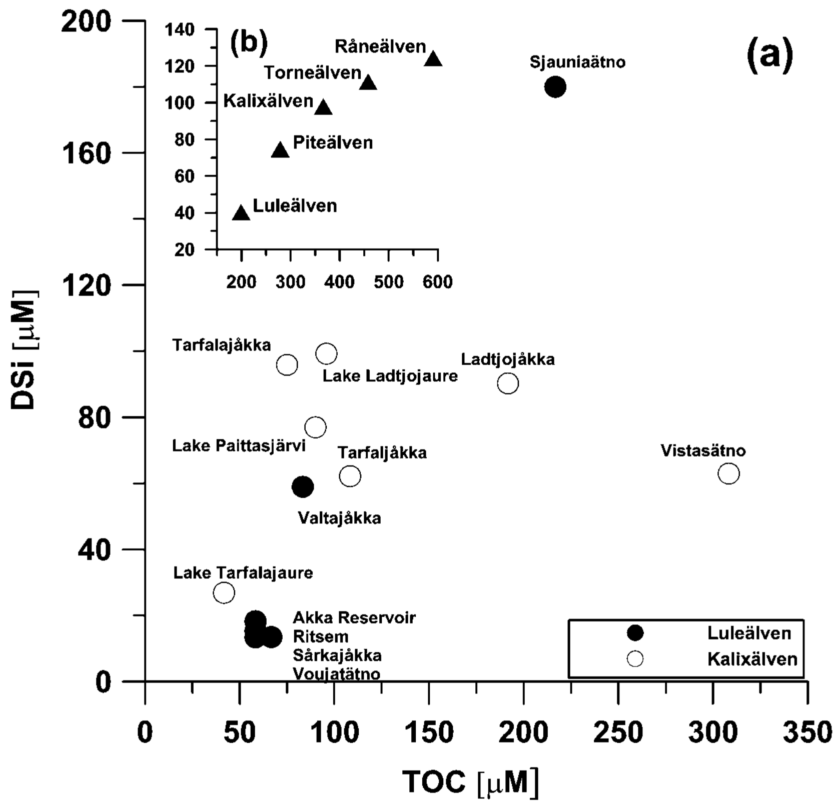

Figure 5. Dissolved silicate (DSi) concentrations versus total organic carbon (TOC) concentration (a) in the River Kalixälven (nonregulated) and River Luleälven (regulated) headwater tributaries, lakes, and reservoirs during base flow (March 2000) and (b) in the northernmost Swedish rivers (long-term mean values; see also Table 1), which are not influenced by wood and fiber deposits; data from monthly measurement were monitored at the river mouths by the Swedish University of Agricultural Sciences, Uppsala, Sweden.

was related to temperature. In other words, in this area, deciduous vegetation was ascribed to an eight-fold increase in silicate weathering [*Berner and Berner*, 1995]. Also relating to the headwater of the rivers Kalixälven and Luleälven, the impact of vegetation on silicate weathering has been reported for a glacier-dominated environment [*Anderson et al.*, 2000]. From chemical denudation measurements in the foreland of a retreating glacier in south central Alaska, it was concluded that silicate weathering reactions become significant only after vegetation coverage is established.

[29] Similar to what is reported from the Swiss Alps [*Drever and Zobrist*, 1992], a decrease in all major cations and DSi with altitude could be observed in the headwater of the River Kalixälven. As reported in Figure 2a and Table 1, in the catchment of the alpine Lake Tarfalajaure, higher vegetation is lacking, and the active soil layer is thin due to natural erosion and permafrost. Thus, the ionic composition of water resembles that of precipitation and of the water from the glacier termini. As soon as the water runs down the Tarfala Valley, with its 7% forest coverage, high DSi concentrations during base flow were recorded. That vegetated soils are mainly responsible for the DSi increase is indicated also by the positive correlation between DSi and TOC found for the base flow in the headwater of the rivers Kalixälven and Luleälven, as well as for the long-term measurements at the river mouths (Figure 5). In contrast, the spring flood water in the studied streams and lakes of the River Kalixälven system is dominated by the meltwater from high mountain areas and glaciers and are, thus, low in ionic strength. These patterns, with dilution during snowmelt and high concentrations during base flow, are consistent with measurements at the river mouth [*Land and Öhlander*, 1997]. However, the present study shows that an enrichment of river water with major elements happens, to a large extent, already in the headwater area, which certainly affects the biogeochemistry of the downstream river system.

[30] The headwater of the River Luleälven down to the Suorva Dam is less vegetated than the River Kalixälven headwater (Figure 2a, Table 1), which appears to result in low seasonal variations in major components, especially in DSi and TOC concentrations. The streams of Vuojatätno and Sårkajåkka drain an alpine heath area. The same is true for the catchments of the Sitas reservoir (upstream of the Akka reservoir). Part of the water drains today via the Ritsem Power Plant into the Akka reservoir and has low ionic strength throughout the year at the outlet of the headrace tunnel. The background values for Ca, Mg, and K in the main tributary to the Akka reservoir (Vuojatätno)

are somewhat higher than in the River Kalixälven headwater, which is probably caused, at least partly, by the presence of carbonate rock in the Padjelanta National Park [*Kulling*, 1982]. However, today the reservoirs of Akka and Stora Lulevatten are similar in much of their chemical characteristics to these high alpine streams, with almost no seasonal dynamics in concentrations of dissolved constituents. Prior to the damming, this water passed through extended areas of birch forest, before entering the former lakes. The stream of Valtajåkka, where at least parts of the former vegetated soil remain, demonstrates the significance of such areas in enriching the water with major elements. This tributary shows similar seasonal variation in dissolved constituents to the streams in the River Kalixälven headwater, with high concentrations during base flow (Table 2). Nowadays, the reservoir area is even larger than the borderline forest, whereas before damming the riparian zone was almost 3 times as large as the former lakes. Thus, the headwater of the River Luleälven has lost much of its potential for biogeochemical enrichment.

[31] Although the percentage in forest coverage of the river catchment down to the Porjus Power Plant increases in comparison to the River Kalixälven; why is there no further DSi enrichment in the River Luleälven downstream of the Suorva Dam? In high-capacity storage reservoirs, such as Akka and Stora Lulevatten, the water level is at its lowest in early spring and rises to its maximum in late summer. The operation of the reservoirs, with periods of tapping and filling, might result in a strong mixing and a homogeneous water column, as reflected in the DSi/Ca plot (Figure 4c). However, most of the river margins that become inundated during the growing season are barren in vegetation [*Jansson et al.*, 2000] and completely washed out [*Nilsson and Berggren*, 2000] from soil (O-E-B-horizons) and underlying till. From studies in the River Kalixälven catchment, the significance of soil water from till in the riparian zone as a source for elevated DSi concentrations has been emphasized [*Land and Öhlander*, 1997], but such infiltration of lentic water into soil does not happens in the regulated River Luleälven.

[32] Within the reservoirs of Akka and Stora Lulevatten, which are between 60 and 80 km long, respectively, water has not the contact with vegetated soils as it had before damming, even though the percentage of forest coverage is increasing comparable to the headwater of the River Kalixälven. In some sections of the river, downstream of the Suorva Dam, as well as downstream of the Sitas and Satis reservoirs (Figure 2a), the river channel is dry or has very low discharge, due to underground conveyance of water through 10- to 18-km long headrace tunnels. Water simply bypasses parts of the former riverbed where it could potentially have been enriched, which additionally prevents soil-water contact and consequently decreases weathering fluxes. Thus, water (220 $km^3\ yr^{-1}$) running down the River Luleälven to the Porjus Power Plant has lost most of its opportunity to be enriched in DSi. From Porjus downstream to the river mouth, there are further nine major dams located along the River Luleälven [*Forsgren*, 1989]. Also, the major tributary, the River Lilla Luleälven, which drains a contiguous southern mountainous area (including the Sarek National Park) and contributes with about one third (170 $km^3\ yr^{-1}$) of the total water discharge (496 $km^3\ yr^{-1}$), is heavily dammed. This tributary hosts sixteen dams, with similar hydrological characteristics and effects on the riparian zone surrounding the reservoirs [*Swedish Environmental Protection Agency*, 2001]. Between all reservoirs, the river flow is regulated either by headrace tunnels (see above) or by the balanced distribution of water discharges from the power plants, which reduces water level fluctuations in height [*Jansson et al.*, 2000] along the river stretches of the entire system; both prevent soil infiltration. To conclude, almost the entire River Luleälven system is affected by hydrological alterations, which explains why even the concentrations found at the river mouth are similar to the mountainous headwater areas.

[33] What other factors may reduce DSi loads of dammed rivers and explain the unexpected uniformity in dissolved constituents over extended river stretches? Dams essentially convert rivers into lentic ecosystems, increasing water residence times and often improves light conditions in the water column, providing favorable preconditions for algal growth, including diatoms, as reported from eutrophied river systems, in particular [*Admiraal et al.*, 1990; *Humborg et al.*, 1997]. However, the strong linear Ca/DSi relationship (Figure 3c) in the River Kalixälven shows clearly that diatom production is negligible, because significant removal of $CaCO_3$ due to biological processes or elevated pH values can be neglected for these systems. Thus, both Ca and DSi behave conservative. Therefore, it can be assumed that this applies also for the River Luleälven down to the Porjus Power Plant, which is similar oligotrophic. In fact, chlorophyll *a* (Chl *a*) measurements in June (in the lentic systems of headwaters considered) revealed low concentrations (0.8–1.2 mg Chl $a\ m^{-3}$), supporting the view of an oligotrophic character in both river systems. Moreover, all Swedish rivers referred in Figure 1 are much oligotrophic, with DIP and total phosphorus concentrations less than 0.1 μM and 0.3 μM, respectively. Assuming that phosphorus is the limiting nutrient of the net primary production in these systems, and applying the elemental ratio of C/Si/N/P in diatoms [*Redfield et al.*, 1963; *Brzezinski*, 1985], several micromoles DIP would be required to reduce the DSi concentrations by roughly 50 μM (Figure 1a) through diatom blooms. Hence, a significant influence from uptake by diatoms in these river systems can most likely be ruled out.

5. Outlook

[34] We have demonstrated that the mountainous headwater area of river systems can be of paramount importance for the ionic composition of river water, and consequently for the fluxes of major elements from land to the Ocean. Waters draining from the mountainous provenance are low in ionic strength and become enriched during passage through vegetated areas downstream. High-capacity reservoirs are often built in these mountainous upper reaches of rivers. A loss of upper soils and vegetation through inundation, loss of soil through littoral erosion, underground channeling through tunnels, as well as reduction of water level fluctuations in reaches between the dams, prevents the

contact of surface waters with vegetated soil, and consequently reduces weathering fluxes. The possible ecological effect of decreased DSi inputs to the sea might be of great significance in East Asia [*Ittekkot et al.*, 2000a], where major rivers are being dammed at accelerating rates [*Milliman*, 1997]. The Three Gorges damming of the Yangtze River is an evident example, where significant reductions in nutrient loads to the sea have been recently reported [*Zhang et al.*, 1999]. East Asia is by far the most crucial region for the land-ocean fluxes of dissolved and particulate matter [*Milliman and Maede*, 1983], and thus dam effects could be of global consequences. However, determinations of the global effect on downstream areas of DSi retention will require expanded measurements [*Rosenberg et al.*, 2000].

[35] The perturbed Si cycle places weathering research in a new perspective, differing from that of long-term (multi-million-year timescale) carbon cycling [*Berner*, 1992; *Ludwig et al.*, 1999] or modern acidification [*Strandh et al.*, 1997]. In global Si budgets and models [*Treguer et al.*, 1995; *Treguer and Pondaven*, 2000], river inputs to the ocean are still considered as having been constant during the late Quaternary. Increased aeolian silicate inputs to the ocean are believed to have been responsible for export production in glacial times, resulting in a CO_2 decrease in the atmosphere via the biological pump in the upper layer of the ocean [*Treguer and Pondaven*, 2000]. However, the increase in vegetation coverage on land during deglaciation periods should have increased DSi fluxes to the Ocean dramatically. Hence, we need a much better understanding of changes in the global silica cycle, caused by anthropogenic perturbations or by natural variations through geological timescales, which have the potential to unsettle a host of regulatory functions of the world's water bodies.

[36] **Acknowledgments.** We are grateful to Vattenfall AB (especially Hans Lindmark and Björn Svensson) for generous field support. The staff of the Tarfala Research Station, and Henrik, Nils, and Olof Sarri at Nikkaluokta, kindly assisted us in the field work. Water samples were skillfully analyzed by Anders Sjösten, Heléne Gustafsson, Svante Nyberg, and Inger Hafdell at the Chemistry Laboratory, Department of Systems Ecology, Stockholm University. Also, we thank Ragnar Elmgren, Candida Savage and Lars-Arne Rahm for linguistic improvements of the manuscript, and Fredrik Wulff for support. The Swedish Natural Science Research Council (NFR) was the principal financier of the project (grants to CH and SB). This is a contribution of the Scientific Committee on problems of the Environment (SCOPE) project on "Land-Ocean Nutrient Fluxes: the Silica Cycle."

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