Modelling nutrient fluxes from sub-arctic basins: Comparison of pristine vs. dammed rivers

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Abstract

The deterministic Riverstrahler model of river functioning is applied for the first time to sub-arctic catchments. Seasonal nutrient (N, P, Si) deliveries to the coastal zone are simulated, and nutrient annual fluxes are established for the nearly pristine river Kalix (hereafter called Kalixälven) and the heavily dammed river Lule, (hereafter called Luleälven) both located in Northern Sweden and draining into the Bothnian Bay, Baltic Sea.

For Kalixälven simulations are performed with a runoff calculated from precipitation, evapo-transpiration and temperature data for the period 1990–1999, using a hydrological model calibrated on observed monthly discharges at the river outlet. The same hydrological parameters are used to calculate specific runoff for the Luleälven basin in absence of dam regulation. Reservoir filling and emptying are simulated using a simplified representation of their management rules. Diffuse sources of nutrient are evaluated according to land cover of the catchment. The simulated seasonal trends are within the range of the observed data, in particular for discharge, dissolved silica, total phosphorus, inorganic nitrogen and total organic carbon. Specific runoff is 50% higher in the Luleälven than in the Kalixälven watershed due to higher altitudes and precipitations. Average silica, nitrate and phosphorus concentrations are much lower in Luleälven than in Kalixälven. Comparison of model results for the Luleälven with and without dams shows a reduction of respectively 25% and 30% in silica and phosphorus fluxes delivered at the outlet, while nitrogen delivery is increased by 10% in the dammed vs. undammed river system. The model allows assessing the respective role of reservoir trapping of nutrient in the reservoir through algal uptake and sedimentation, and of changes in the vegetation induced by flooding the valley formerly covered by forests and wetlands.

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1. Introduction

Nutrient fluxes from land-based sources to the ocean play an important role in the ecological and biogeochemical functioning of both the open ocean and the near-shore environments. An important scientific
Humborg et al. (2006a) have shown that even moderate
Friedl et al., 2004; Teodoru et al., 2006) though
site of significant silica trapping (Garnier et al., 2002a;
reservoirs with too low residence time would not be the
the residence time of water within the reservoirs, so that
of uptake, sedimentation and burial strongly depend on
the role of reservoirs is complex because these processes
Vörösmarty, 2005; Humborg et al., 2006a). However,
and Billen, 2002; Garnier et al., 2002a; Meybeck and
(Meybeck and Billen, 1997; Turner et al., 1998; Conley,
1993; Turner and Rabalais, 1994; Justic et al., 1995;
Billen and Garnier, 1997; Turner et al., 1998; Conley,
1999; Cugier et al., 2005; Billen and Garnier, 2007).

Several studies have focused on the effect of river
damming on silica retention and delivery. Budget and
modelling studies have shown that reservoirs are often a
favourable site for diatoms to grow, taking up dissolved
silica to incorporate it into their frustules which sediment
within the reservoirs and are thus permanently buried
(Garnier et al., 1999a; Hungspreugs et al., 2002; Garnier
and Billen, 2002; Garnier et al., 2002a; Meybeck and
Vörösmarty, 2005; Humborg et al., 2006a). However,
the role of reservoirs is complex because these processes of
uptake, sedimentation and burial strongly depend on the
residence time of water within the reservoirs, so that
reservoirs with too low residence time would not be the
site of significant silica trapping (Garnier et al., 2002a;
Friedl et al., 2004; Teodoru et al., 2006) though
Humborg et al. (2006a) have shown that even moderate
residence time has a significant effect on the DSi/BSi
dynamics. The mechanisms involved in silica retention
in river systems thus require a close site specific
examination, preferably in conjunction with an analysis of
the processes of N and P transfer and retention. This is
particularly true for (sub-)arctic rivers which represents a
significant part of the global water discharge to the world
ocean, while their biological and geochemical functioning
are not yet fully understood. Beside silica trapping, Humborg et al. (2003, 2004, 2006b) and Brink et al.
(2007) have stressed the possible importance of the
modifications brought by damming on rock–water–
vegetation interactions in cold climatic conditions, that
would lead to a reduction of weathering in certain areas
of the watershed and hence to a decrease in silica supply
and fluvial silica delivery.

In this study we try to quantify the magnitude of these
different effects by the application of the deterministic
Riverstrahler model to two neighbouring sub-arctic river
systems, one representing a nearly pristine river (Kalix-
älven), the other being heavily dammed (Luleälven).
Several studies have already shown a significant
difference in the mean silica concentration in the water
from the two watersheds, which was attributed to the
hampered role of vegetation in silica weathering due to
inundation in the dammed Luleälven (Humborg et al.,
2003, 2006b), although the role of reservoir as a silica trap
cannot be ruled off. We gather the information required to
apply the Riverstrahler modelling approach to these two
systems characterized by a climatic context completely
different from all previous applications (Continental
climate; Garnier et al., 2002b; Trifu, 2002; Temperate
oceanic climate; Garnier et al., 1999b; Billen et al., 2001,
2004, 2005; Sub-tropical climate: Garnier and Billen,
2002; Le Thi Phuong, 2005). Using this modelling
approach allows to quantitatively test the hypothesis
previously invoked to explain the contrasting silica
behaviour of the dammed and pristine river systems. It
also allows to examine silica cycling in conjunction with
carbon, nitrogen and phosphorus dynamics in these Nordic
river systems.

2. Study site

The Kalixälven and Luleälven river basins are located
in northern Sweden, across the Arctic Circle, between
66°30’ and 68°00’ (Fig. 1). The Kalixälven watershed
sensu-stricto covers an area of 17 818 km². However,
about 57% of the adjacent Torne river basin drains into the
Kalixälven river through a bifurcation at Tarendö
(Dahlqvist et al., 2004), so that the ‘total’ Kalixälven
watershed represents an area of 23 600 km² (Kalixälven
will refer to this extended surface area throughout the
text). The Luleälven watershed area is 25 110 km². Fig. 2
compares the morphology of both basins in terms of
altitude distribution and characteristics of their stream
order properties (Strahler, 1957) (drainage density,
steepness): the Luleälven watershed is steeper, with
25% of the basin area higher than 700 m, the average
upper limit of forest (Humborg et al., 2004), while for
Kalixälven only 10% of the watershed lays over such
altitude. However, the main difference between the two
watersheds is that the hydrographic network of the
Kalixälven river is pristine while the Luleälven river is
one of the most heavily regulated rivers in Europe
(Dynesius and Nilsson, 1994), its dams being able to retain
up to 70% of its natural discharge (Humborg et al., 2006a).

Not less than 11 reservoirs are operated for electric
power generation in the Luleälven basin. The largest
reservoir is Akkajaure which receives water from its
own watershed (4 650 km²) and an additional discharge
through a tunnel coming from another reservoir,
Sitasjaure, located upstream. The dam is located at
453 m above sea level, and the maximum oscillation
Fig. 1. Location of the sub-arctic rivers Luleälven (light grey) and Kalixälven (dark grey), Northern Sweden. The part of the Torne river draining partly to Kalixälven is dashed. The bifurcation is shown as a dashed bold line.

Fig. 2. Morphological characteristics of the Kalixälven (black) and Luleälven (grey) drainage networks and basins. Upper panel: number of tributaries, mean length and mean slope as a function of streamorder. Lower panel: Surface watershed distribution by altitude.
allowed for water is of 30 m, even though the reservoir is deeper than 90 m (Sahlberg, 2004). Collectively all reservoirs represent a total maximum storage volume of 11 km³ covering an area of 900 km² and are entirely located along the 4th and 5th order tributaries, the fluvial corridor of which can be considered either completely flooded or deeply perturbed by these hydraulic works.

Although these two rivers are not discharging into the Arctic Sea, but into the Gulf of Bothnia in the northern Baltic Sea, they can be considered as of arctic-type because of their hydroclimatological characteristics (Bowling et al., 2003; Nijssen et al., 2003). The annual average air temperature in the Kalixälven catchment during the considered period (1980–2000) is −0.5 °C with extreme values of −39.4 °C and +22.6 °C. In the Luleälven watershed the average air temperature is −0.1 °C within a range between −34.0 °C and +21.4 °C. Annual average precipitation is about 538 and 618 mm/yr for the Kalixälven and Luleälven catchments respectively. The yearly average discharge equals 320±295 m³/s for Kalixälven, while the snow melt discharge peak occurring in May or June averages 955±199 m³/s. Another discharge peak is often present in autumn, due to rain. Since Luleälven river is regulated no such difference between its average discharge of 538±140 m³/s and its snow melt season discharge (680±157 m³/s) appears. The number of days with snow cover usually ranges from 175 to 225 days (Carlsson, 1999), the two watersheds not being within the permafrost region. Lakes and reservoirs also present an ice cover which lasts for about 6 months (Eklund, 1998).

About 65% of the Kalixälven basin area is covered by forest, mostly coniferous trees, while flooded wetlands represent 20%, herbaceous areas 7.1%, bare rock 3.5%, lakes 2.5% and cultivated areas 1.2%. Only 0.1% of the watershed is urbanized. About 60 000 people live in the Kalixälven catchment, mostly located at the river mouth with the exception of the city of Kiruna (24 000 inhab.), situated in the Torne catchment connected to Kalixälven at approx. 67° 52’ N and 20° 15’ E and the inland city of Gällivare (19 000 inhab.) in the Kalixälven catchment itself, at 67° 10’N and 20° 40’ E. The Luleälven watershed is less inhabited than the Kalixälven, with a total population of 29 000 inhabitants. Forests constitute 48% of the area, flooded wetlands 14.6%, herbaceous areas 14.5%, bare land 13.3% and lakes 7.4%, the rest being either cultivated or urban areas (Humborg et al., 2006b). Bedrock in both basins is constituted mostly of Caledonides and Precambrian granite basement, and dominant soil type is till with podzol profiles (Fromm, 1965), while glacial and post-glacial river sediments occur close to river and small stream stretches (Land et al., 1999).

3. Simulation of hydrology

The Riverstrahler model, in its previous versions developed for temperate or sub-tropical river systems (Billen et al., 1994; Garnier et al., 1999b; Billen et al., 2001), rests on the calculation of the specific runoff as the sum of two components, namely (sub)-surface runoff and base flow, resulting from the dynamics of two hydrological pools in the watershed, respectively soil water, with short residence time, and groundwater, with long residence time. In the case of arctic mountainous river systems like those studied here, snow represents an additional pool, and snow melt is a major process determining the hydrological regime. The calculation of water flow from precipitation and evapo-transpiration data by the Hydrostrahler model has therefore been modified, according to the conceptual scheme represented in Fig. 3.

Precipitation is considered to be deposited as snow when air temperature is below zero. When temperature is above zero, snow is considered to melt at a rate proportional both to temperature and to the stock of accumulated snow. Snow melt and liquid precipitation feed the pool of soil water. When some saturation level (solssat) is reached, all snow melt and liquid precipitation flow as superficial runoff. Sub-surface runoff occurs at a rate proportional to the size of the soil water pool, which also infiltrates to a groundwater pool. The latter generates the base flow. The three pools involved in the hydrological dynamics of the watershed are split into 20 classes of altitude, from 0 to 2000 m, in order to take into account the altitudinal gradients of temperature and precipitation (air temperature lapse rate of 0.98 °C/100 m, Richardson et al., 2004). The five parameters involved (snow melt rate, soil saturation level, sub-surface runoff rate, infiltration rate, base flow rate) are considered the same over the whole watershed area.

These parameters were determined by optimization on the observed values of daily precipitation, potential evapo-transpiration, temperature and monthly runoff of the Kalixälven watershed for the period 1990–1999 (Table 1); the database was provided by the Department of Applied Environmental Science in Stockholm. Fig. 4 shows a comparison of the simulated to observed discharges; the Nash criterium (Nash and Sutcliffe, 1970) for the ten years series is above 0.66, which is an acceptable score.

For the Luleälven river a direct calibration of the hydrological parameters cannot be achieved due to the regulation by dams; we thus used exactly the same values of the parameters as for the neighbouring Kalixälven to calculate the specific runoff components, from the
precipitation, evapo-transpiration, temperature and altitude data of the basin. From this reconstructed hydrology of the unregulated Luleälven basin, the cumulated curve of filling and emptying of the Luleälven reservoirs was calculated, assuming simple rules that simulate its management for electric power generation. This enables us to compare the effect of river regulation on an otherwise “pristine” river. The ‘collective reservoir’ receives the runoff of a total upstream unregulated watershed of 24 000 km². The outflow represents a constant discharge of 485 m³/s, except when the total stored volume reaches twice the minimum level; in that case the output is reduced proportionally to the distance from the minimum level, so that it would be zero when the minimum level is reached. On the other hand, when the total volume reaches the maximum level, the output is increased to 1.5 times the input flow. Fig. 5 represents the calculated inter-annual variations of the Luleälven discharge and of the stored water volume in the reservoirs, as simulated with these simple rules over the period from 1990 to 1999. Although the idealised formulation of the hydraulic management rules of the reservoir does not allow to reproduce all observed small discharge variations, the general trend is correctly simulated, with a rather constant discharge most of the time and some events of abrupt increase in the period of reservoir filling.

4. Quantification of diffuse and point sources

Diffuse sources of nutrients are taken into account by associating to each three components of the total runoff

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Adjusted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil saturation level</td>
<td>mm</td>
<td>200</td>
</tr>
<tr>
<td>Snow melt rate</td>
<td>day⁻¹ °C⁻¹</td>
<td>0.008</td>
</tr>
<tr>
<td>Sub-surface runoff rate</td>
<td>day⁻¹</td>
<td>0.05</td>
</tr>
<tr>
<td>Infiltration rate</td>
<td>day⁻¹</td>
<td>0.03</td>
</tr>
<tr>
<td>Groundwater runoff rate</td>
<td>day⁻¹</td>
<td>0.004</td>
</tr>
</tbody>
</table>
a concentration of nitrogen (nitrate and ammonia), phosphorus (total inorganic P, TIP), silica (dissolved, DSi, and particulate biogenic silica, BSi), suspended matter (SM) and organic carbon (dissolved, DOC, and particulate, POC). The concentrations associated to each runoff component (see Tables 2a and 2b) depend on the land cover of the catchment of each stream order, and are based on concentrations measured in headwater streams within the Kalixälven and Luleälven basins (Humborg et al., 2004; Brink et al., 2007) or on other data reported in literature for similar regions (Ulen and Jakobsson, 2005).

The land-cover distribution by stream order has been established for the Kalixälven and Luleälven basins on the basis of the overall land cover distribution mentioned in Section 2, and the consideration that 1st and 2nd stream orders entirely englobe the area of the basin above the tree line and are too steep to develop wetlands, while all agricultural and urban lands are located within the 5th and 6th stream order basins (Table 2a.). For what concerns dissolved nutrients the concentrations assigned to melt flow are those measured for rain or snow samples collected in this area (Brink et al., 2007), assuming that snow or ice melting generates a rapid surface
Table 2a
Distribution of land cover classes by stream order direct catchments in the Kalixälven and Luleälven basins

<table>
<thead>
<tr>
<th>Land cover type</th>
<th>Watershed average %</th>
<th>Order 1</th>
<th>Order 2</th>
<th>Order 3</th>
<th>Order 4</th>
<th>Order 5</th>
<th>Order 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalixälven</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>65.1</td>
<td>83.8</td>
<td>45.6</td>
<td>50.7</td>
<td>46.9</td>
<td>47.6</td>
<td>40.5</td>
</tr>
<tr>
<td>Herbaceous</td>
<td>7.1</td>
<td>8.1</td>
<td>13.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Wetlands</td>
<td>20.3</td>
<td>0.0</td>
<td>31.8</td>
<td>49.2</td>
<td>46.9</td>
<td>45.5</td>
<td>40.5</td>
</tr>
<tr>
<td>Water/snow/bare</td>
<td>6.2</td>
<td>8.1</td>
<td>9.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Cultivated soil</td>
<td>1.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>6.2</td>
<td>6.3</td>
<td>16.5</td>
</tr>
<tr>
<td>Urban</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.6</td>
<td>2.4</td>
</tr>
<tr>
<td>Luleälven</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>48.0</td>
<td>39.7</td>
<td>58.0</td>
<td>60.0</td>
<td>61.9</td>
<td>45.6</td>
<td>20.0</td>
</tr>
<tr>
<td>Herbaceous</td>
<td>14.5</td>
<td>20.5</td>
<td>18.2</td>
<td>8.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Wetlands</td>
<td>14.6</td>
<td>5.0</td>
<td>9.9</td>
<td>31.3</td>
<td>38.1</td>
<td>54.3</td>
<td>40.0</td>
</tr>
<tr>
<td>Water/snow/bare</td>
<td>12.5</td>
<td>26.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Cultivated soil</td>
<td>0.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>36.0</td>
</tr>
<tr>
<td>Urban</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 2b
Concentrations of nitrogen (nitrate and ammonia) phosphorus (total inorganic P), silica (dissolved and particulate biogenic silica), suspended matter (SM), organic carbon (dissolved and particulate) associated to base flow, surface flow and melt flow according to the land use type

<table>
<thead>
<tr>
<th>Diffuse source concentrations</th>
<th>Forest</th>
<th>Herbaceous</th>
<th>Wetland</th>
<th>Water/snow/bare</th>
<th>Cultivated soil</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen NO₃, µmol/l</td>
<td>melt</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>surf.</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>base</td>
<td>9</td>
<td>9</td>
<td>0</td>
<td>4</td>
<td>700</td>
</tr>
<tr>
<td>NH₄, µmol/l</td>
<td>melt</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>surf.</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>base</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Phosphorus TIP, µmol/l</td>
<td>melt</td>
<td>0.19</td>
<td>0.21</td>
<td>0.13</td>
<td>0.18</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>surf.</td>
<td>0.16</td>
<td>0.17</td>
<td>0.13</td>
<td>0.14</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>base</td>
<td>0.14</td>
<td>0.14</td>
<td>0.13</td>
<td>0.13</td>
<td>0.2</td>
</tr>
<tr>
<td>Silica DSi, µmol/l</td>
<td>melt</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>surf.</td>
<td>35</td>
<td>15</td>
<td>35</td>
<td>1.3</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>base</td>
<td>150</td>
<td>50</td>
<td>150</td>
<td>25</td>
<td>114</td>
</tr>
<tr>
<td>BSi, µmol/l</td>
<td>Melt</td>
<td>18</td>
<td>25</td>
<td>0.9</td>
<td>14</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>surf.</td>
<td>9</td>
<td>12.5</td>
<td>0.9</td>
<td>1.8</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>base</td>
<td>2.5</td>
<td>3.6</td>
<td>0.35</td>
<td>0.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Susp. Matter SM, mg/l</td>
<td>melt</td>
<td>100</td>
<td>140</td>
<td>5</td>
<td>80</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>surf.</td>
<td>50</td>
<td>70</td>
<td>5</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>base</td>
<td>15</td>
<td>20</td>
<td>2</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Carbon DOC, mgC/l</td>
<td>melt</td>
<td>80</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>surf.</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>base</td>
<td>4</td>
<td>1.5</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>POC, mgC/l</td>
<td>melt</td>
<td>0.5</td>
<td>0.7</td>
<td>0.05</td>
<td>0.1</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>surf.</td>
<td>0.5</td>
<td>0.7</td>
<td>0.05</td>
<td>0.1</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>base</td>
<td>0.15</td>
<td>0.2</td>
<td>0.02</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>TOC, mgC/l</td>
<td>melt</td>
<td>8.5</td>
<td>0.7</td>
<td>0.05</td>
<td>0.1</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>surf.</td>
<td>4.5</td>
<td>2.7</td>
<td>6.05</td>
<td>0.1</td>
<td>3.50</td>
</tr>
<tr>
<td></td>
<td>base</td>
<td>4.15</td>
<td>1.7</td>
<td>4.02</td>
<td>0.05</td>
<td>1.13</td>
</tr>
</tbody>
</table>
runoff which does only marginally acquire some nutrient load. The few analyses available show a nitrate content of 3–12 μmol/l, a TOC concentration close to 1 mgC/l and negligible dissolved silica concentration (below 10 μmol/l). On the other hand melt and surface flows, because of their eroding capacity, are rich in suspended matter. The levels of suspended matter assigned to the three flow components for the different land use types are based on values observed in rivers under temperate conditions (Garnier et al., 2005; Billen et al., 2007). Once suspended matter (SM) values are assigned, particulate nutrient concentrations are deduced from them, based on the following general relationships: particulate organic carbon is considered to represent between 0.5 and 1% of suspended matter, while a concentration of 180 μmol BSi/g SM (Sferratore et al., 2006) is assumed for biogenic silica. For total inorganic phosphorus, we assumed the same general Langmuir relationship between dissolved inorganic phosphorus (oPO₄) and mobile adsorbed forms (PIP) as found in the Seine watershed for non agricultural soils (Garnier et al., 2005; Némery et al., 2005; Billen et al., 2007):

\[
\text{PIP}/\text{SM} = \frac{\text{Pac} \cdot [\text{oPO}_4/(\text{oPO}_4 + \text{KP})]}{1 + [\text{oPO}_4/(\text{KP})]}.
\]

where Pac is the maximum P adsorption capacity of suspended matter (SM) and KP a half saturation parameter (Pac=100 μmolP/gSM and KP=22 μmol/l).

As ortho-phosphate concentrations measured in small headwater streams in the Kalixälven, Luleälven and Torneälven basins are reported around 0.1±3 μmol/l (Humborg et al., 2004), we considered this value representing the equilibrium dissolved phosphate concentration, which implies a mean exchangeable P content of suspended matter issued from soil erosion equal to 0.45±0.15 μmol P/g SM, about ten times lower than in uncultivated soils in temperate basins (Martin and Meybeck, 1979; Billen et al., 2007). Dissolved silica concentration (DSi, μmol/l) in surface and base flow of headwater streams has been shown to be closely related to total organic carbon (TOC, mgC/l) (Humborg et al., 2006b; Brink et al., 2007), indicating the prominent role of biota on the process of rock weathering. Analysing data from a number of Nordic small rivers (basin area from 30 to 4000 km²) published by Humborg et al. (2004) and Smedberg et al. (2006), we found a very significant relationship of both DSi and TOC with the percent watershed area covered by forest and wetland (Fig. 6). We used this relationship to assign the DSi and TOC concentration to the sub-surface runoff and base flow component corresponding to water draining forest or wetlands on the one hand, herbaceous and bare rock on the other hand (Table 2b). Nitrate and ammonium concentrations in sub-surface runoff and base flow are assigned to the different land cover classes on the basis of observed values in headwater streams as well as on small agricultural rivers in Sweden (Ulen and Jakobsson 2005).

The Riverstrahler model assumes that a part of nitrate originating from soil leaching of the watershed might be denitrified in riparian wetlands before it reaches surface water (Billen and Garnier, 1999; Sebilo et al., 2003). In the present application, we considered a riparian retention proportional to the part of wetlands in the direct catchment of each stream order, according to the following empirical relationship, adjusted on the observed nitrate concentration data for Kalixälven: riparian nitrate retention factor=2%watershed occupied by wetlands.

Point sources of organic carbon, nitrogen, phosphorus and silica are calculated from the population

![Fig. 6. Observed relationship between DSi and TOC in small Nordic headwater streams and the fraction of their watershed occupied by forest and wetlands. (Data from Humborg et al., 2004; Smedberg et al., 2006).](image)
data, assuming that wastewater is treated with a classical activated sludge process, and using corresponding per capita loadings cited by Billen et al. (1999), Servais et al. (1999), Garnier et al. (2006) and Sferratore et al. (2006).

5. Model simulation of the river ecological functioning

For the Kalixälven river system, the Riverstrahler model has been run for the hydrological conditions

Fig. 7. Results of measurements and simulations of discharge, chlorophyll a, dissolved silica, total inorganic phosphorus, nitrate and total organic carbon at the outlet of Kalixälven (left column) and Luleälven (without dams, middle column; with dams, right column). Solid black lines indicate results corresponding to average hydrology simulations, dotted lines indicate the range for minimal and maximal hydrology. Dots and error bars indicate observations and their respective standard deviation.
calculated for each year from 1990 to 1999 (Fig. 4), as well as using average, minimal and maximal runoff. The average (or minimum or maximum) hydrological scenarios correspond to the mean (or min or max) values for each ten days period of the whole 10 year series. The same was done for the Luleälven river, ignoring the presence of reservoirs, thus simulating a pre-dam situation. For the dammed situation, the filling/emptying curve of the ‘collective’ reservoir corresponding to the years 1994, 1995 and 1998 were associated respectively to these average, minimum and maximum scenarios, because these years represent indeed the average and extreme amplitude of filling and emptying of the reservoirs, according to our simulations (Fig. 5).

Beside the morphology and hydrology of the two rivers described in Sections 2 and 3, and diffuse and point nutrient sources from the watershed discussed in Section 4, the forcing functions to the model include the seasonal variations of light intensity, photoperiod and water temperature, which were represented by simple trigonometric functions:

\[
\text{Photoperiod (days)} = 12\left[1 - 0.95 \cos\left(2\pi t/365\right)\right]
\]

\[
\text{Mean light intensity over the photoperiod (\(\mu\text{E}/\text{m}^2/\text{s}\)) = 400\left[1 - 0.9 \cos\left(2\pi t/365\right)\right]}
\]

\[
\text{Water temperature (\(^{\circ}\text{C}\)) = 4 - 4\cos(2\pi(t - 30)/365)}
\]

where \(t\) is the time in julian days (the time delay of 30 days in the water temperature function resulting from the fact that the minimum temperature statistically occurs at the end of January).

The kinetic parameters used for the simulation were taken identical to those used in previous applications of the Riverstrahler model to temperate rivers (see e.g. Garnier et al., 1999b, 2002a, 2005), except that the parameters of the relation of biological activities to temperature were adjusted in order to take into account arctic microbial populations. This relationship is classically expressed by a sigmoid function:

\[
\text{Activity (T)} = \text{Activity (Topt)} \exp \left( - \frac{(T - \text{Topt})^2}{(T - \sigma t)\text{to}^2} \right)
\]

with an optimum temperature (Topt) of 8 \(^{\circ}\text{C}\) and \(\sigma t\) set to 8 \(^{\circ}\text{C}\), close to the parameters found for other polar systems (Billem and Becquevort, 1991).

The results of model runs with average, minimal and maximal discharge are presented in Fig. 7 and compared with the observations available for the period 1990–1999. In addition, results of the model for each year in particular allowed to calculate average nutrient fluxes for the decade that can be compared to the observed fluxes at the river outlet (Table 3).

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Kalixälven without dams</th>
<th>Luleälven without dams</th>
<th>Luleälven with dams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge (l/km²/s)</td>
<td>observed 11.5±5 21.4±10 22.5±2</td>
<td>observed 13.7±2 n. d. 22.0±2</td>
<td>observed n. d. n. d. n. d.</td>
</tr>
<tr>
<td>Tot-inorg N (kg/km²/y)</td>
<td>observed 49.0±15 69±20 79±7</td>
<td>observed 36.0±5 n. d. 29.3±4</td>
<td>observed n. d. n. d. n. d.</td>
</tr>
<tr>
<td>Tot-P (kg/km²/y)</td>
<td>observed 8.4±0.9 12.4±2.0 10.7±1.7</td>
<td>observed 8.9±2.6 n. d. 6.6±1.0</td>
<td>observed n. d. n. d. n. d.</td>
</tr>
<tr>
<td>DSi (kg/km²/y)</td>
<td>simulated 740±230 1014±280 824±60</td>
<td>simulated 740±230 1014±280 824±60</td>
<td>observed n. d. n. d. n. d.</td>
</tr>
<tr>
<td>BSi (kg/km²/y)</td>
<td>simulated 75±25 114±15 38±8</td>
<td>simulated 75±25 114±15 38±8</td>
<td>simulated 75±25 114±15 38±8</td>
</tr>
<tr>
<td>Total Si (kg/km²/y)</td>
<td>simulated 815±255 1128±295 862±68</td>
<td>simulated 815±255 1128±295 862±68</td>
<td>simulated 815±255 1128±295 862±68</td>
</tr>
</tbody>
</table>

For both Kalixälven and Luleälven without reservoirs a peak of discharge appears in late spring, related to the snow melt. The increased melt and surface flow components of the average runoff is poor in dissolved silica and nitrate (see Tables 2a and 2b) and the effect of this dilution can be seen in the decrease of their concentration in the period of maximal average discharge. For nitrate, an additional effect of riparian retention at higher temperature plays a role in the observed concentration decrease. The high discharge during melt flow also corresponds to an increase in the concentration of particulate material, and to the dilution of a limited planktonic algal bloom occurring just at the end of the winter, particularly by dry hydrological conditions (Fig. 7). In general, the average, minimal and maximal simulated values for the Kalixälven river are within the envelope of observed data for discharge, dissolved silica, total inorganic phosphorus and total organic carbon. This agreement is also true for the simulations at 4th stream order, which fit to the available observations in headwater streams of the Kalixälven watershed (Fig. 8), confirming that the diffuse sources of nutrients are correctly taken into account in the model. The Luleälven simulated discharge, silica and TOC fluxes are also in agreement with observed data; a much lower silica and nitrate average concentrations appears in Luleälven river, both with respect to Kalixälven, and to the Luleälven in the ‘no dams’ scenario (Fig. 7).

The specific annual discharges calculated for Kalixälven and Luleälven (Table 3) also show a good agreement with observed data, confirming the correctness of the hydrological model. Total inorganic nitrogen export flux is slightly overestimated by the simulations, as well as total phosphorus for the Luleälven river, while
the calculated silica export is within the range of the observations. Luleälven river exports slightly more silica despite its low dissolved silica concentration (Fig. 7) because of its higher discharge. A decrease of about 20% in dissolved silica export, as well as in total phosphorus export, appears when comparing the Luleälven with and without dams. By contrast, the export of nitrogen is 10% higher with than without dams.

6. Discussion

The profound differences between the pristine Kalixälven and the dammed Luleälven river nutrient (N, P, Si) concentrations were already discussed in several papers based on observed levels and seasonal trends (Humborg et al., 2003, 2004). The application of the Riverstrahler model to these sub-arctic river systems offered the opportunity to quantitatively test the coherency of the hypothesis previously put forward to explain these differences, namely the role of retention within the reservoir and the role of the changes in rock–water–vegetation interactions induced by damming.

First of all, the introduction of a snow melt flow component to the Hydrostralher module was necessary to correctly simulate the late spring discharge peak and the correspondent nutrient dilution. The model application also forced us to carefully examine the differences in altitude, hydrology, meteorology and land cover between the two neighbouring basins. These factors already determine significant differences in both runoff and nutrient diffuse sources, which are illustrated by comparing the Kalixälven results to the model reconstructed behaviour of Luleälven without dams (Fig. 7, Table 3).

Further, the comparison of the Luleälven results with and without dams allows us to quantify the role of damming. Because of the long water residence time in the reservoirs, the most obvious effect is the smoothing of the seasonal variations in nutrient concentrations at the outlet, but this in itself does not involve any nutrient retention (Fig. 7). Budget calculations with the model results (Table 3) indicate a significant reduction of phosphorus (over 30%) and total silica (close to 25%) fluxes of the dammed compared with the undammed Luleälven. A part of this reduction can be attributed to the change in land cover induced by flooding the fluvial corridor of the 5th order river (and a part of the 4th stream order): the formerly forested valleys have been inundated, becoming bare rock bottoms of huge reservoirs. This land cover change is taken into account in the model by suppressing the nutrient input contribution from about 2000 km² wetlands and forest area, the estimated basin area flooded by the reservoirs. Wetlands and forests have been shown to be among the most active producers of silica, particularly in high latitude watersheds, because of the vegetation control of weathering rates (Gaillardet et al., 1999; Humborg et al., 2003; Humborg et al., 2004; Brink et al., 2007), and this is reflected in the relationship we used to define nutrient diffuse sources (Table 2b). However, the areas destroyed by damming represent hardly one tenth of the total forested area of the basin, thus limiting the effect of its suppression to about 10% of the overall silica delivery. Incidentally, the disappearance of wetlands from the 5th stream order direct watershed, also results in a decrease of riparian retention of nitrates, which, in the model results of the dammed Luleälven scenario, causes a higher nitrogen flux compared to the no dam scenario (Table 3).

Retention in the reservoir on the other hand is quite evident in terms of particulate biogenic silica, since its export flux decreases from about 114 kg Si/km²/yr in the

Fig. 8. Results of measurement and simulation of discharge, dissolved silica, total phosphorus and nitrate at order 4th of Kalixälven river. Dots indicate measured data, while lines represent model results for the average (solid line), minimal and maximal (dotted lines) hydrology.
Luleälven no dam scenario to about 38 kg Si/km²/yr in the dammed case. The retention of dissolved silica is also significant (20%) and is associated to the slight diatom growth simulated in the reservoir during the summer period (and not only in the spring as in the undammed Kalixälven). However, the depth, and, principally, the very low phosphorus loading limit algal development in this reservoir. A few available measurements of total chlorophyll pigments carried out in early June 2000 in four dams of the Luleälven system revealed concentrations between 1 and 2.5 μg Chl-a/L (Rahm, unpublished), in good agreement with the values predicted by the model. The predicted annual primary production in the reservoir is evaluated by the model to 7 g C/m²/yr, close to the value of 6 g C/m²/yr cited for similar lake systems in the regional literature (Karlsson et al., 2001). With a Si:C ratio of 0.92 by weight (Conley et al., 1989), this primary production corresponds to a retention of 5.8 kton Si/yr in the 900 km² reservoir, assuming a total sedimentation of the diatoms, and no re-dissolution. This calculation sets to a maximum of 230 kg Si/km²/yr, i.e. about 20% of the total specific diffuse silica inputs from the basin, the possible silica retention which could result from the diatom growth and sedimentation in the Luleälven reservoir. The same calculation with a C:N weight ratio of 6 and a C:P ratio of 40, allows to set an upper limit of 1 kton N/yr and 0.16 kton P/yr to nitrogen and phosphorus retention associated to algal uptake in the reservoir, representing 42 kgN/km²/yr and 6.3 kgP/km²/yr in terms of specific fluxes, i.e. 60% and 47% of the N and P fluxes at the outlet of the undammed Luleälven. The model results show on the other hand that benthic denitrification is negligible, as well in the reservoir as in the bottom river sediments.

The modelling approach thus entirely confirms, and allows to quantify, the previous hypothesis that both the effect of vegetation modifications (destruction of forests and wetlands) and direct trapping in the reservoirs play a role in the changes of nutrient delivery caused by damming the Luleälven (Table 3). In the case of silica, both effects result in a decrease of silica fluxes at the mouth by about 20%. In the case of phosphorus, trapping in the dam explains a significant reduction by more than 30%. In the case of nitrogen, the situation is more complex as the two above mentioned factors have opposite effects: the suppression of wetlands reduces nitrate riparian retention, while algal growth in the lake can lead to some retention. Our simulations calculate that these antagonistic effects result in an overall increase in nitrogen delivery, because the decreased riparian retention is not compensated by the retention in the reservoirs (Table 3). The calculated nitrogen delivery at the outlet is however much higher than the observed one, thus making the latter conclusion uncertain.

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References


Sebilo, M., Billen, G., Grably, M., Mariotti, A., 2003. Isotopic composition of nitrate-nitrogen as a marker of riparian and benthic denitrification at the scale of the whole Seine River system. Biogeochemistry (Dordrecht) 63, 35–51.


Smedberg, E., Mört, C.M., Swany, D.P., Humborg, C., 2006. Modeling hydrology and silicon-carbon interactions in taiga and tundra biomes from a landscape perspective: Implications for


