# Effect of hydropower regulation on the transport of metals and nutrients in Lule River

By
Lisbeth Drugge, Karin Jonsson, Anders Wörman and Björn Öhlander

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# Content

# 1. Introduction

## 1.1 Background

In adapting the energy production in Sweden after the liquidation of the nuclear power the economical benefit of other energy alternatives has to be motivated with respect to their environmental impact and sustainability. In order to be able to effectively quantify and formally optimise the use of hydropower it will thus be well justified to use mathematical models that describe the complex interactions of the number of hydraulic and biogeochemical processes that govern the environmental impact.

The use of North Swedish rivers for hydropower production has changed the flow pattern, and the large seasonal flow variations have been smoothed out. As a consequence, nutrients and other elements reach the Gulf of Bothnia in changed amounts during different seasons than what would have been the case for unregulated rivers (Brydten et al., 1990). In addition, construction of reservoirs, artificial lakes, changes the water residence time and may result in increased sedimentation. Earlier studies, based on the relatively sparse data of the national river monitoring program, have suggested that the transport of Si, P, N, K, Fe, Mn and other elements in regulated North Swedish rivers has decreased due to deposition of particulate matter in the reservoirs and due to decreased erosion of the river channels (Brydsten et al., 1990). The effects of river regulation for changed element transport and balance have been studied in several international studies (Kelly et al., 1994; Straskraba, 1995), but the effects in a northerly climat is not well known. Regarding water quality, the effects of river regulation depend on climate, bedrock and soil types, pollution degree, amount of agricultural areas, forests, mires and depth/volume relation in reservoirs (Baxter and Glaude, 1980; Cline and Waed, 1984; Hocking and Straskraba, 1994; Talling, 1987; Jansen, 1994). Humborg et al. (2000) showed that considerable amounts of Si may be retained in reservoirs due to diatom growth, which results in decreased amounts of Si reaching the sea. As a consequence of the changed Si/N in the sea close to river mouths, diatom growth is decreased and the amount of other algaea increases. This may locally change the whole eco system.

The groundwater level is affected several hundreds of metres away from the river channels in regulated rivers. Changed hydraulic effects is thus not restricted to the regulated river, but disturbances occur also in groundwater and tributaries. For a large river, such as the Lule River studied in this project, several hundreds or thousands of km$^2$ are affetced by the changed water level. This changes interactions between water and soils and sediments, which may result in changed element transport in regulated rivers.

When reservoirs are constructed large land areas are usually flooded. A combination of seasonal water level fluctuations and ice and wave erosion results in a wash out of nutrients and organic matter, causing an initial increased biological production (Ahl and Widerholm, 1977). This initial eutrophication is a well-known phenomenon (Neel, 1968), but after this initial supply of nutrients reservoirs have a lower biological production than natural lakes of similar size. In natural lakes water usually leaves in outlets with surface water. In reservoirs it is common with inlets to power stations relatively deep down. Since nutrients often are concentrated in the bottom waters, this may result in that the water leaving the reservois is richer in nutrients than the average reservoir water.

Transport of nutrients and other elements are thus changed in regulated rivers. Since most of the large rivers in Sweden are regulated, there is a need to quantify these changes, and obtain a better understanding of the processes leading to the changes. Because of this, a main purpose of this project is to provide a decision basis about energy systems in the future, especially quantitative environmental effects. To optimize the use of hydropower, where environmental effects are part of the optimization, adequate simulation models are needed.

The hydropower represents almost 50 % of the production of electricity in Sweden. The Lule River is the largest and most important river for hydropower production, with 15 power stations (Fig. 1). This river was therefore chosen for the studies in this project. The Kalix River (Fig. 1) is one of the last major pristine rivers in Scandinavia, as well as in the whole Europe (Dysenius and Nilsson, 1994). Natural geochemical processes in the Kalix River and its watershed, from weathering in soil, via processes in soil water, groundwater, mires, lakes and tributaries to the element transport in the river itself, have been studied at Luleå University of Technology for about 25 years (see summary in Ingri, 1996). Since Lule and Kalix Rivers have drainage basins of similare size, with similar climate, bedrock and soil types, the Kalix River was chosen as a reference for an undisturbed system for our studies of the regulated Lule River.

## 1.2 Objectives and brief status of deliverables

The overall objective of this project was to develop the quantitative understanding of the effect of hydropower regulation on the transport of metals and nutrients in Lule River, the river in Sweden most exploited with respect to hydropower. The quantitative understanding is integrated in terms of a model that describes the transport of metals and nutrients in Lule River. The outcome of such a model can be related to environmental effects in terms of eutrophic level, emissions of green house gases or toxicity of heavy metals. The project has comprised an extensive measuring programme that covers the transport of a large number of elements in several sections of the Lule River during one year. The monitoring was undertaken both along stream sections in lower and upper reaches of the river and in two major reservoirs. Appendix A contains a list of publications that have emerged from the activities of this project.

A detailed study of the interaction between the flowing water and the hyporheic zone has provided a better understanding of retardation processes in rivers. The combination of this improved quantitative understanding of solute transport in regulated rivers can be used to evaluate the total changes of transport of nutrients and metals to the Gulf of Bothnia. These changes are not only reflecting changes of the total load, but, more importantly, the timing (or distribution over time) when nutrients and metals reach the coastal areas.

Several specific objectives have been formulated that are listed below together with comments on the current status of their completion.

- Two PhD-examinations were envisioned. Karin Jonsson has performed her dissertation at Uppsala university and Magali Colomp has taken a licentiate degree at Luleå technical university. To complete the objective, another two year project time was found necessary.
- The project aimed to construct a data-base that covers the transport of a number of metals and nutient fractions in Lule River under one year. The data-base should

also comprise main tributaries and hydrological data like discharge and hypsographs. This data-base is completed.

- Basic mass-balance analyses have been performed.
- A one-dimensional (computer based) models have been developed for both hydraulics and solute mass transport. The numerical framework is completed and the model is adapted to account for hyporheic zone interaction for inert solutes.

## 1.3 Scientific approach

A common approach to modelling reactive transport in aquatic systems is to uncouple the water flow and transformation of mass phase species. In the approaches described by Dagan (1989), Kadlec and Knight (1996) and Rodriguez-Iturbe, I. and Rinaldo, A. (1997) this uncoupling expresses the multi-dimensional nature of transport problems by convoluting the solute mass transport along a distribution of one-dimensional pathways. Here, such a convolution is not important since the problem is basically one-dimensional (along Lule River) and the solute mass transport involves differential advection of mass phase species e.g. in the flow and in the river-bed. The uncoupling is utilised, however, to firstly account for the regulatory effect of water residence times in the stream-channel and, subsequently, to account for solute mass transport.

Consequently, the scientific issues of this project have also been divided in geochemistry of Lule River, on one hand, and the change in hydraulics caused by hydropower regulation, on the other. Main issues related to the geochemistry is to be able to formulate in a quantitative form the impact of sorption of tracer metals to particles in the flowing water as well as in river-bed sediments and biological interaction of Si and nutrients like phopsphorus and nitrogen.

The regulatory effect of hydropower on the water discharge can be expressed in terms of residence time distribution through Lule River. The residence times expresses how the transport of more or less inert solute elements, like e.g. Na and Cl, are retained in the river and, furthermore, govern the times available for reactions of elements like Si, Cr and different nutrients as well as time phase shifts in reactions over seasons. Hence, an improved understanding of the water residence time distribution is important for many aspects of the solute transport in regulated rivers.

The predominant part of the residence time distribution is represented by water in the main stream-channel, but a certain fraction is also affected by the exchange of water between the flowing water and the substratum, the hyporheic zone. Despite the fact that the exchange with the hyporheic zone is relatively small, many studies show that reactive elements are highly influenced in this zone by both biotic and chemical processes (Thibodeaux, L.J. and Boyle, J.D. 1987; Rutherford, et al., 1995; Johansson et al., 2000). For instance, sorption of heavy metals to bed-sediments may prolong the residence time 4-5 orders of magnitude compared to inert elements, which implies a significant change of the overall residence times for that solute in the river.

The empirical studies have comprised primarily a large-scale field investigation of metals (Fe, Al, Mn, Zn, Cu, Cd, Si, Mg, Na, Ba, Mo, Ni och Sr), other solutes (Ca, S, C, P och N) and several other environmental control factors. From general mass balance analysis and interpretation of selected parts of the data-base using the modelling framework, we aim to derive a significantly improved understanding of Lule River as a geochemical system. Comparison with the transport in the unregulated Kalix River system offer a valuable empirical basis for interpretation of the data from the regulated Lule River. Unfortunately very little data on solute transport exists from the pre-regulation period in Lule River.

The important residence times for water in bottom sediments were determined from theoretical studies and tracer tests in smaller streams. For practical reasons, tracer tests cannot be performed in large rivers with a sufficient degree of accuracy and a relevant coverage of sufficient length and time scales. A detailed study was focused on a smaller study-stream located close to Uppsala and the results have been used to develop a scaling methodology (Wörman et al., 2002; Salehin et al., 2002).

Furthermore, an accidental tracer test occurred during the project in the upstream reach of Kalix River system. The water chemistry was studied during this event with respect to a number of trace elements and used as a basis for calibration of the model developed in this project (Collomp, et al, 2002).

## 2. Sampling and analysis

The sampling strategy applied here was to obtain a detailed whole-year cycle of the elemental transport at Boden close to the river mouth. Hence, the sampling was performed once a week during spring flood and every second week otherwise (Fig. 1) and, furthermore, once a month at a number of sampling stations from the mountains in the west and downstream. Some tributaries were also sampled. At the Boden station all samples were filtered through 0.22 µm filters, and both filtered (”dissolved”) and suspended phases were analysed. The results from the Boden station were compared with a detailed whole year cycle in the Kalix River sampled at Kamlunge (Fig. 1), obtained earlier (Ingri, 1996). This allows a direct comparion betwen the unregulated and the regulated rivers, which will be used for a quantification of the total effect of the regulation.

The Boden station is located close to the river mouth. The water quality at this station represents the sum of all upstream processes. To understand the processes along the river that govern the water quality in the river outlet, sampling was performed at a number of stations. Special attention was focused on the Stora Lulevatten reservoir (inlet Vietas, outlet Porjus, Fig. 1). Vietas is actually also the outflow from the Suorva reservoir. At an early planning stage we decided not to perform much sampling in the largest reservoir, Suorva (Fig. 1). This was partly due to logistical reasons, it is very difficult to reach relevant sampling stations, partly due to that a project driven at Stockholm University (Sven Blomqvist, Christoffer Humborg and Magnus Mörth) focuses on the mass balance in this reservoir. We collaborate with this group and will use our combined data together.

### 2.1. Sampling area

The Lule River rises in the Scandinavian Caledonian mountains in northern Sweden, near the Norwegian border, and runs south-east into the Gulf of Bothnia (Fig. 1). The river runs through several national parks (Sarek, Padjelanta, Stora Sjöfallet, and Muddus). There are two branches, the Little Lule River and the Large Lule River, which merge into a single river at Porsi, approximately at the halfway point of the river.

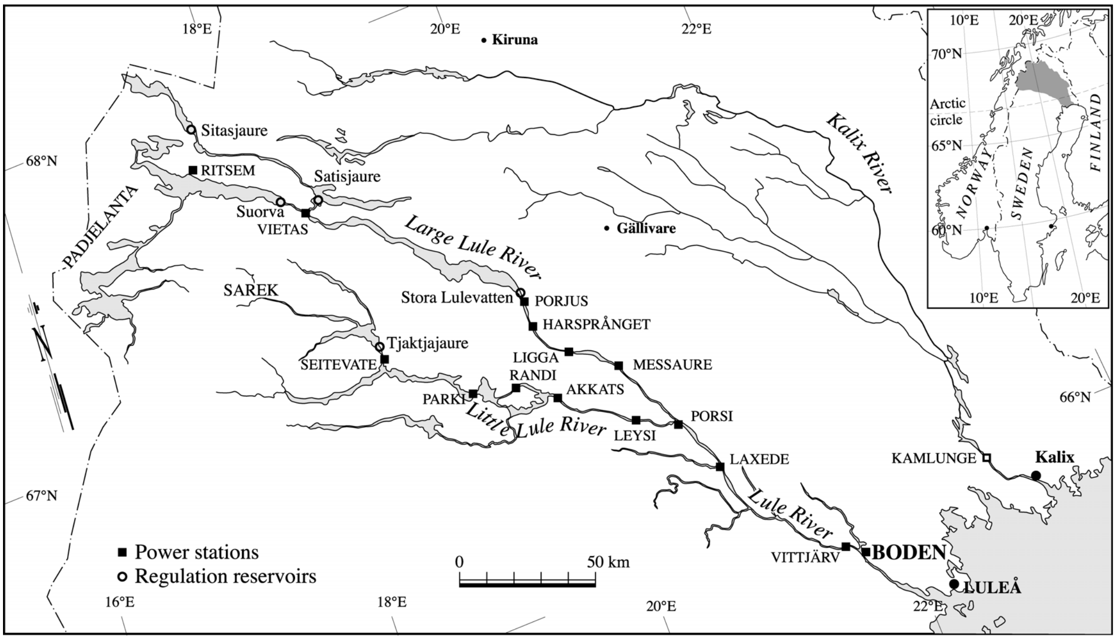


**Figure 1 Lule River and Kalix Rive. The power stations and reservoirs in the Lule River is indicated.**

The drainage area of the Lule River is located in the boreal zone in northern Sweden and covers 24,900 km$^2$ (Table 2). Upstream, in the mountain area, the vegetation is of tundra type, while downstream the landscape is covered by coniferous and birch-trees forests. Lakes and mires are common. The bedrock in the Scandinavian Caledonides, with an age of 0.4 Ga, consists mostly of mica schist, quartzite and amphibolite with some dolomite and limestone from place to place. The Precambrian basement, 1.8-1.9 Ga, consists of acid, intermediate and basic volcanic and plutonic rocks (Gaal and Gorbatschev, 1987). The Quaternary cover is constituted of till with well developed podzol profiles and mixed mires (Fromm, 1965). The climate is sub-arctic, with monthly average temperatures ranging from –15ºC in January to +14ºC in July. The rivers are ice-covered from December to April. There is a rainfall gradient from the mountains, average of 1,000-1,500 mm/year, towards the Gulf of Bothnia, average of 400-700 mm/year, with a low evapotranspiration rate (Raab and Vedin, 1995). About 45% of the precipitation falls as snow, that accumulates during the winter until the snowmelt in May.

The Lule River is strongly regulated with 15 power stations (Fig. 1 and Table 1). Together these hydropower stations can produce nearly 15 TWH/year, representing approximately one-eighth of the total produced electricity and one-fourth of the hydroelectricity in Sweden. The large reservoirs are located upstream in the mountains. Downstream the consequences of damming are restricted to enlargement of the river, forming rather small reservoirs

***Table 1 - The Lule River power stations***

| | **Starting year** | **Yearly prod. (GWh)** | **Power (MW)** | **High of fall (m)** | **Maximal Variations of the water level (m)** | **Volume of the reservoirs ($10^6$ $m^3$)** |
|---|---|---|---|---|---|---|
| **Ritsem** | 1978 | 460 | 315 | 173 | 10 | Sitasjaure - 600 |
| **Vietas** | 1971 | 1130 | 325 | 83 | 19 | Suorva – 5900<br>Satisjaure - 1240 |
| **Porjus** | 1915 (old) – 1980 (new) | 1260 | 480 | 60 | 5.5 | Stora Lule Vatten - 632 |
| **Harsprånget** | 1951 (1980) | 2200 | 940 | 107 | | |
| **Ligga** | 1954 (1982) | 800 | 325 | 40 | 2.8 | |
| **Messaure** | 1963 (1984) | 1930 | 470 | 87 | 2.4 | |
| *Seitivare* | 1967 | 790 | 220 | 180 | 34.5 | Tjaktjajaure - 1650 |
| *Parki* | 1970 | 100 | 20 | 14 | - | |
| *Randi* | 1976 | 230 | 90 | 25 | - | |
| *Akkats* | 1973 | 580 | 145 | 45 | - | |
| *Letsi* | 1967 | 2000 | 450 | 135 | 4.7 | |
| Porsi | 1961 (1987) | 1160 | 265 | 33 | 1.5 | |
| Laxede | 1962 (1986) | 950 | 200 | 25 | 2.5 | |
| Vittjärv | 1974 | 230 | 36 | 6 | 0.5 | |
| Boden | 1972 | 490 | 74 | 13 | 0.3 | |

*(***Large Lule River** –*Little Lule River* – Lule River after the junction*) - Source: Forsgren, 1990*

The Kalix River (Fig. 1) is one of the last major pristine rivers in Scandinavia, as well as in the whole of Europe (Dynesius and Nilsson, 1994). The drainage area of the River (23,600 km$^2$) is mainly covered by coniferous forests and peatlands (Table 2). Four percent of the area is covered by lakes, and less than one percent is used as farmland (Hjort, 1971). Bedrock, soil types, climate, and vegetation of the Kalix River watershed are similar to those of the Lule River, except for the Precambrian basement which differs slightly for the Kalix River as Archean granodiorites occur (Öhlander et al., 1987).

***Table 2- Drainage areas of the Lule River and the Kalix River (data from Skogsvårdstyrelse).***

| | **Lule River** | **Kalix River** |
|---|---|---|
| Drainage area | 24900 km$^2$ | 23600 km$^2$ |
| Forest (% of the drainage area) | 59 % | 58 % |
| Peatlands (% of the drainage area) | 11 % | 23 % |
| Discharge variations for the studied year | 200-1200 m$^3$/s | 80-1300 m$^3$/s |

## 2.2. Methods of sampling and analysis

A detailed study of the seasonal variations of the geochemical parameters in the Lule River were performed at the Boden hydropower station, ca. 30 km from the mouth of the river (Fig. 1). An annual cycle was studied from May 2000 to June 2001. Sampling was performed weekly during the spring flood period (May – June) and bi-weekly the rest of the year.

Temperature, pH, conductivity, redox (ORP) and dissolved oxygen (DO) were measured in-situ with a Hydrolab Surveyor II water quality probe. From April to November, water was collected in-situ, using a tygon tube lowered 50cm below the surface of the river water. During the winter, water was collected inside the Boden power station by connecting tygon tubing to the hydropower tubing before the access to the turbines. The tubing was connected to a portable Masterflex peristaltic pump. The acid-cleaned tubing was rinsed by pumping through 4 to 5 litres of water before sampling. For filtered water samples, filtration was performed in the field, with two filters mounted in parallel (Millipore filters with a diameter of 142 mm and a pore size of 0.22 µm, mounted in Geotech polycarbonate filter-holders). The filtered fraction was defined as the fraction passing through the 0.22 µm filters. Filtered water samples were taken when 1 litre had passed through the filters, collected in acid-leached polyethylene bottles, and conserved with suprapur $HNO_3$. In the laboratory, filters and samples were handled in a clean room. Analyses of Ca, Mg, Na, K and S in the filtered phase were performed using ICP-AES, and all other elements by using high resolution ICP-MS. The anion concentrations (Cl, $NO_3$, $NH_4$ and $PO_4$) were determined by ion chromatography. Water was filtered until the filters were clogged and the filtered water volume measured. For each sampling, two filters with the suspended fraction of the river water (>0.22 µm) were wet-ashed in concentrated suprapur $HNO_3$ in platinum crucibles at 75 °C, and then dry-ashed at 550 °C. The ashed inorganic matter was weighed with a precision of +/- 10 %, and fused with lithium metaborate in graphite crucibles at 1,000°C. The formed beads were dissolved in 10 % suprapur $HNO_3$ (Burman et al., 1978). Main elements were then determined by ICP-AES. Two other filters, also for each sampling, were dissolved with suprapur $HNO_3$ in closed teflon bombs in a microwave oven, and then analysed for trace elements by ICP-AES and ICP-SMS. For each type of sample, the same procedures were also applied to blanks in order to detect any contamination. Unfiltered samples were used to determine alkalinity and TSM (Total Suspended Matter). The water for TSM was filtered separately within two hours from sampling in the laboratory using vacuum filtering equipment and the filters were subsequently weighed. A Falcon plastic tube was filled with 12.5 ml of water and 100 µl of 2 M HCl for TOC (Total Organic Carbon) determination, using a Shimadzu TOC-5000 high temperature combustion instrument. For POC (Particulate Organic Carbon), 25 mm glass microfibre filters (Whatman GF/F, pore size 0.7 µm) mounted in a stainless steel filter holder were used. POC analyses were performed with a Carlo Erba model 1108 high temperature combustion elemental analyser, using standard procedures and a temperature of 1,030ºC. During the sampling period blank values were always less than 5% of the measured concentrations.

The Kalix River data were obtained from a previous study (April 1990 to October 1992; Ingri, 1996). The samples were collected at Kamlunge, approximately 30 km from the mouth of the River (Fig. 1). The same methodology of sampling and analysis as described above was used, except that the filtration was made with 0.45 µm instead of 0.22 µm pore size filters. Another difference was that nitrate and other nutrients were not analysed in the Kalix River. From these data average values for each element in the Kalix River for the one year cycle from May to the following June were calculated and used to compare with the entire year sampled in the Lule River.

In the night of September 8-9 2000, the Aitik copper mine tailings dam, northern Sweden (close to Gällivare in Fig. 1), failed over a length of about 150 m. Nearly 2 millions cubic meters of water and some slurries were discharged first in a downstream clarification pond. The subsequent rise of the water level in the clarification pond led to the release of 1.5 $Mm^3$ mostly clarified water into the environment into the Kalix River system. To study retention processes along the river, sampling was immediately performed with the same methods as at Boden. However, nutrients and C were not analysed. This study has relevance for modeling of element transport in the Lule River.

The seasonal variations of the geochemical parameters along the Lule River were studied at several hydropower stations. The sampling at the power station represents the outflow from the reservoir upstream the power station. At the same time the sample taken at the power station represents the inflow to next reservoir. Water were sampled at Vietas, Porjus, Ligga, Messaure, Letsi, Laxede and Boden (Fig. 1). The sampling at Letsi power station represents the inflow to the Big Lule River from the Little Lule River. Sampling at these points was performed monthly from June 2000 until September 2001. Two important tributaries, Flarkån and Sjaunaätno, were sampled to study the influence from tributaries on the geochemistry of the river. Flarkån is situated between Boden and Laxede and Sjaunaätno is situated between Porjus and Vietas.

Between Porjus and Vietas the reservoir Stora Lulevatten is situated. Three sediment cores were collected from Stora Lulevatten in August 2001. The sampling took place on three different stations in the reservoir by using a modified gravity corer. The cores were sliced into 0.5 cm subsamples the upper 5 cm, then 1 cm subsamples down to 10 cm, and down to the end of the cores at a depth of c. 30 cm, the subsamples were 2 cm thick.The sediment subsamples were dried, weighted and homogenized by grinding. Before grinding subsamples for diatom analyses were taken out. One of the core samples were dated with the $^{210}$Pb method.

In Vietas, water was collected inside the power station from a tap before the water reaches the turbines. The acid cleaned tubing was rinsed by pumping 4 to 5 liters before sampling. The water was collected in acid-leached bottles. At the other power stations, water samples were taken from a bridge with an acid-washed bucket. At the sampling point the water was well mixed and represents well the water column. From the bucket acid leached bottles were immediately filled with the water from the bucket.

Temperature, pH, conductivity, redox (ORP) and dissolved oxygen (DO) were measured every time (except in Vietas Nov-April) with a Hydrolab Surveyor II water quality probe.

For filtered water samples, filtration was performed directly in the field with a syringe, 25 mm filter with a pore size of 0.22 μm. Filtered water samples were taken when 20 ml of water had passed through the filters, collected in acid-leached polyethylene bottles, and conserved with suprapur $HNO_3$. Analyses of Ca, Mg, Na, K and S in the filtered phase were performed using ICP-AES and all others elements by using ICP-SMS. The anion concentrations (Cl, $NO_3$, $NH_4$ and $PO_4$) were determined by ion chromatography. Unfiltered samples were used to determine alkalinity. These samples were analysed the same or the second day. A Falcon plastic tube was filled with 12,5 ml of water and 100 μl of 2 M HCl for TOC (Total Organic Carbon) determination, using a Shimadzu TOC-5000 high temperature combustion instrument. For POC (Particulate Organic Carbon), 25 mm glass microfiber filters (Whatman GF/F, poresize 0,7 μm) mounted in a stainless steel filter holder were used. POC analyses were performed with a Carlo Erba model 1108 high temperature combustion elemental analyser, using standard procedures and a temperature of 1030°C.

The sediment samples were analysed for major and trace elements by ICP-AES and ICP-SMS. C and N were also analysed, by using an elemental analyser.

# 3. Model development

The modeling of the transport of nutrients and metals in the Lule River is divided into two parts by uncouple the hydraulic model from the solute transport model.
Since different substances exist in different phases and are involved in different processes, a general model framework for transformation of solute mass phase species has been built up. In that way it is possible to easily change the model structure when the transport of different substances is simulated. First the hydraulic modeling is performed to determine the properties of the water flow such as water depth and velocity. The information of flow velocities and flow is as are at a later stage used in the solute transport model where the transport of different substances is studied.

## 3.1. Hydraulic model and hydraulic data

The flow in shallow waters can generally be represented by Saint Venant equations (Chow, 1959). However, analyses of the normal flow conditions in Lule River shows that the head loss due to friction on the stream reaches is relatively small compared to the head loss at the hydropower . In table 1, the head-loss is compared with the mean value of the hydraulic radius for each sub-reach. The changes in water depth at the sub-reaches due to friction losses are rather small, in the order of a few percent of the hydraulic radius or less, which justifies a simplified model for the water depth calculations.

***Table 1. Energy losses due to friction at each sub-reach along the Lule River compared to the mean value of the hydraulic radius at that sub-reach. ($h_1$-water depth at the uptream station (m), $h_2$-water dept at the downstream station (m), $R_h$-mean value of hydraulic radius (m) )***

| Sub-reach | $(h_1-h_2)/R_h$ (%) |
|---|---|
| Vietas – Porjus | 0,1 |
| Porjus - Harsprånget | 0,2 |
| Harsprånget - Ligga | 0,8 |
| Ligga - Messaure | 0,2 |
| Messaure - Porsi | 3,2 |
| Porsi - Laxede | 4,7 |
| Laxede - Vittjärv | 15,4 |
| Vittjärv - Boden | 4,7 |

Practically speaking the water of Lule River forms a staircase with stepwise changes in energy potential at the hydropower stations. Furthermore, inertia effects related to spatial and temporal variation in velocity head have an even minor importance in the energy balance during normal flow conditions. Only in dam brake scenarios it would appear that inertia effects is essential to consider. Consequently, a relatively good approximation of both water depth and flow velocity would be to assume horizontal water surfaces in the entire Lule River and use management data of the water levels in reservoirs and discharge.

In this project we have decided to implement the commercially available programme called BOSS DAMBRK as an operational tool for certain potentially important consequence analyses (in the future). DAMBRK reflects the basic formulations of Saint Venants formulation in one dimension. However, normally this programme is not needed in the data treatment and in the envisioned research. As a simpler alternative we have developed a model that calculates the friction head loss on the flow reaches between hydropower stations based on solely Manning friction loss formula, geometric properties of the river channel (hypsographs) and friction coefficients.

The hydraulic model that account only for friction head-loss is implemented in a Matlab environment and used to calculate cross-sectional areas and flow velocities. The calculations are based on the assumption that the friction losses follow Manning equation. The Manning equation is stated as:

$$Q = VA = \frac{R_h^{\frac{2}{3}} S_b^{\frac{1}{2}}}{n} A \tag{1}$$

where Q is the water flow ($m^3/s$), $R_h$ the hydraulic radius (m), $S_b$ the slope of the channel, A the flow area ($m^2$) and n is the Manning roughness coefficient for the channel surface.

Assumptions needed for Manning equation to apply are:

a) The flow is assumed to be stationary and uniform
b) The slope of the energy grade line is equal to the water surface slope (this assumption is justified when the velocity head is small)

To be able to calculate the water depth along the river, geometry data is needed. Cross-section profiles along the whole river and the river surface roughness, expressed by the Manning roughness coefficient, were procured from Vattenfall Utveckling. Also time series for the current period of the water surface elevation and the water flow at each dam is needed for the calculation and was also procured from Vattenfall Utveckling. The distance between the cross-sections with known geometry vary along the river, but generally the cross-sections downstream the river are closer. On average, the cross-sections are placed each 100-400 m at the lower reach of the river. The frequency in the time-series of water elevation and water flow at the power stations is once each day.

Averaging has been applied to the cross-sectional geometry data in the calculations of the water depth. By an iterative calculation procedure, the water depth is determined at the sub-reaches between the hydropower stations (Fig. 2).

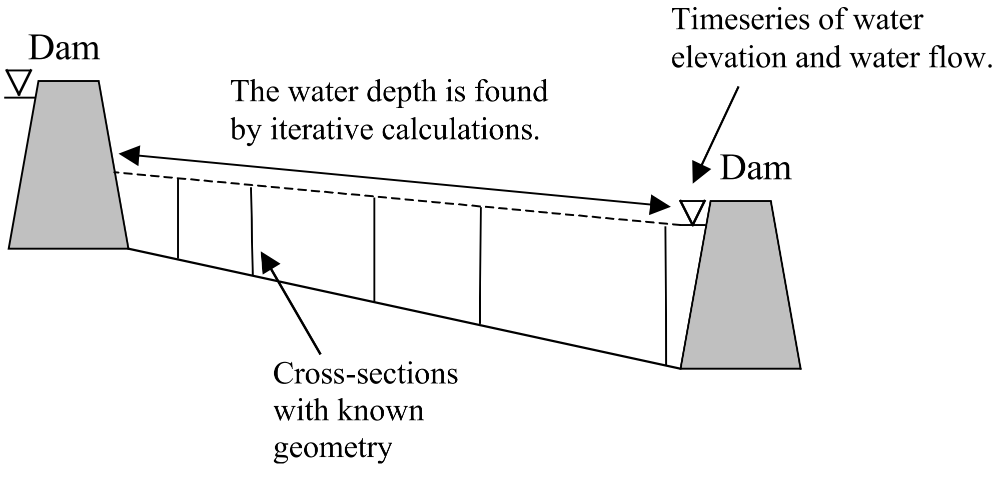


**Figure 2 Simplified representation of the river between the hydropower stations**

### 3.2. Solute transport model

A general model framework describing solute transport in the river is implemented in a Matlab environment. In the model it is possible to choose an optional number of phases of the studied substance as well in the stream water as in the sediment (Fig. 3). The mass transfer rates between the different phases are described as first order equations. All phases are advected with a certain velocity that can be explicitly prescribed based on independently performed hydraulic analyses. As a default option, only the phases in the flowing water are transported due to advection along the river while there is no advection for the phases in the hyporheic zone (in the bed-sediments).

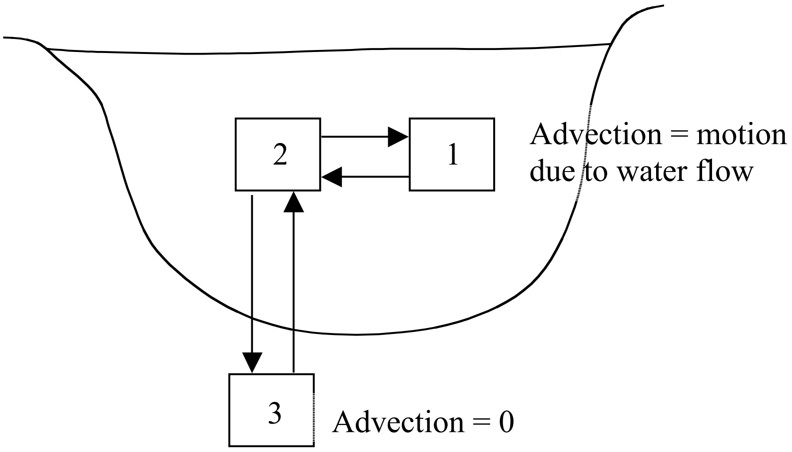


**Figure 3 Example of model structure with different phases of the solute at a fixed position along the river**

As an example for the outlined model structure in Fig. 3, the following formulation can be applied

$$
\begin{cases}
\dfrac{dC_1}{dt} = \dfrac{1}{A_1}\dfrac{\partial(A_1uC_1)}{\partial x} - \lambda_{12}C_1 + \lambda_{21}C_2 \\[2ex]
\dfrac{dC_2}{dt} = \dfrac{1}{A_1}\dfrac{\partial(A_1uC_1)}{\partial x} - \lambda_{21}C_2 + \lambda_{12}C_1 - \lambda_{23}C_2 + \lambda_{32}C_3 \\[2ex]
\dfrac{dC_3}{dt} = \dfrac{A_1}{A_2}(\lambda_{23}C_2 - \lambda_{32}C_3)
\end{cases}
\qquad (2)
$$

where $C_1$, $C_2$, $C_3$ are the solute concentrations in the different phases (kg/m$^3$), A is cross-sectional areas (m$^2$), u is flow velocity in the longitudinal direction (m/s) and $\lambda_{12}, \lambda_{21}, \lambda_{23}, \lambda_{32}$ are first-order rate coefficients (s$^{-1}$). Here it has been assumed that the cross-sectional areas associated with phases 1 and 2 are equal. Generally, the areas can be given explicitly in the user interface. The partial differential equation system is conveniently expressed in a matrix form:

$$\frac{\partial \text{¢}}{\partial t} + \$\text{¢} + \frac{1}{A}\frac{\partial(Q\text{¢})}{\partial x} = Sq \qquad (3)$$

where $\text{¢}$ is a vector describing the concentrations for phase 1-m (arbitrary number), $\$$ a matrix with rate coefficients between the different phases, *Q* the water flow = A u, *Sq* source/sink of the solute, *x* the coordinate along the river and *t* is the time.

The system of equations is solved numerically by using finite differences. In the project we implemented both an explicit and an implicit numerical approximation of system (3) and tested the benefits of the two approaches. The explicit method requires a smaller equation system and smaller time steps than the implicit method. In conclusion, the two methods are nearly equally fast, but the implicit method is "safer". The implicit method is more stable and this provide reliable results even without stability tests. Appendix A contains an implicit discretization of system (3) of the Crank-Nicolsons type.

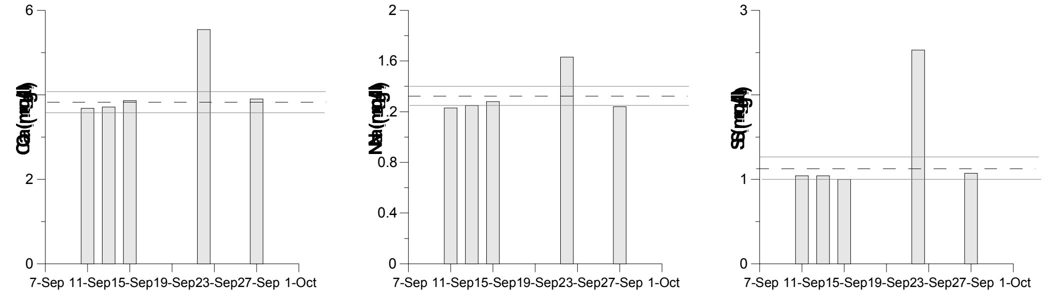
Parameters of the model that is obtained from the hydraulic calculations and hydraulic data are A and u (or A and Q). The mass transfer rates are contained in the $\$$ -matrix, which is obtained either from independent studies or by calibration of the model versus solute phase data from Lule River. The measured concentration curves directly downstream a hydropower station (section 2) is used as boundary condition for the studied sub-reach. A calculated breakthrough curve can then be produced at the down-stream hydropower station. A relevant model structure concerning the number of phases and the governing processes has to be constructed for each studied substance. This should be done by means of literature information and by studying the change in shape of the measured breakthrough curves while the substances are transported along the sub-reaches. Tentative results on this procedure are given in section 5.

## 4. Basic studies on retention processes of water and solute elements in rivers

### 4.1 Solute pulses from Aitik dam failure

In the night of September 8-9 2000, the Aitik copper mine tailings dam, northern Sweden, failed over a length of about 150 m. Nearly 2 millions cubic meters of water and some slurries were discharged first in a downstream clarification pond. The subsequent rise of the water level in the clarification pond led to the release of 1.5 $Mm^3$ mostly clarified water into the environment into the Kalix River system.

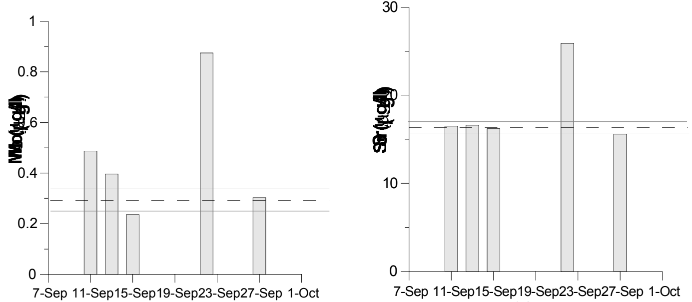
This failure event open for a unique opportunity to follow several solute pulses in an unregulated river system of similar type as Lule River and the project group immediately after the failure set-up a sampling programme. The results showed the geochemical impact of the dam failure on Kalix River system and was used to evaluate the transport time of the released pollutants along the river. A comparison was made between the solute pulses related to the dam failure and natural background values, and an estimation of the relative impact of retention of elements in the hyporheic zone of the river was realised using a mathematical model framework. The pulse of pollution induced by the release of polluted water from the clarification pond was followed along the Kalix River system, and was observed 150 km downstream the dam failure for some element such as Ca, Na, S, Mo and Sr in the filtered phase (Fig. 4). The retention due to hyporheic exchange was found to be of significant



**Distribution of filtered Cu in Kamlunge between the 11th and the 27th of September**

**Distribution of Na in Kamlunge between the 11th and the 27th of September**

**Distribution of S in Kamlunge between the 11th and the 27th of September**



**Distribution of Mo in Kamlunge between the 11th and the 27th of September**

**Distribution of Sr in Kamlunge between the 11th and the 27th of September**

(The dashed line represents the mean value calculated for the months of September 1990, 1991 and 1992, with the 95% confidence interval)

**Figure 4 - Distribution of the values in the filtered phase between the 11th and the 27th of September 2000 at Kamlunge, sampling station K5.**

importance to the element transport in the Kalix River, especially for Mg which is clearly retained along the river-system.

Fig. 5 shows breakthrough curves of Na according to numerical solutions following the model framework described in section 3 (solid and dashed curves) and observations (markers and dotted curves). Practically, Na can be considered to be a non-reactive element and, hence, its transport also reflects that of pure water. The following parameter values were applied in all simulations marked with solid curves: exchange velocity W=1.5e-6 m/s;residence time in hyporheic zone T=26180 s;water depth h=1.1 m; dilution factor b=1; dispersion coefficient E=10 $m^2/s$, dilution factor a=2.1000e-04. The advection velocity were taken as u = 0.4 m/s for the distance x = 20 km and u = 0.24 m/s for the distance 150 km. The dashed curve is obtained by practically eliminating hyporheic flow (W = 1.5e-12 m/s) and in-stream dispersion (E = 1 $m^2/s$). Tentatively, it can be concluded that Na is partly retained in the hyporheic zone.

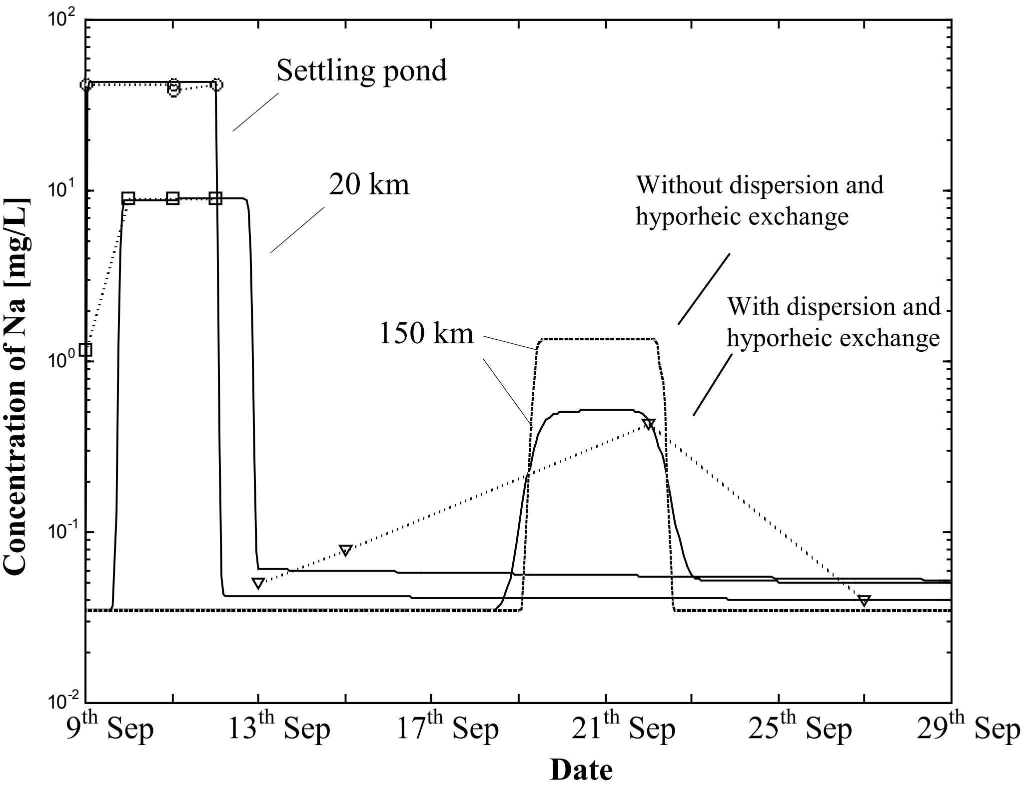


**Figure 5 Breakthrough curves according to numerical solutions (solid and dashed curves) and observations (markers and dotted curves). The dashed curve is obtained by practically eliminating hyporheic flow (W = 1.5e-12 m/s) and in-stream dispersion (E = 1 $m^2$/s).**

## 4.2 Tracer tests of hyporheic zone exchange and scaling methodology

The temporary storage of solutes in rivers is often controlled by flow-induced uptake in hyporheic zones. Pressure variation, induced by stream flow over an irregular permeable bed, leads to a distribution of pore water flow paths in the stream bed and a corresponding distribution of subsurface solute residence times. This uptake in the hyporheic zone retain solute elements and particularly sorbing solutes may experience very long residence times in the hyporheic zone.

To get insight in the hyporheic zone processes in rivers and streams, tracer experiments are valuable tools for the evaluation of proposed mathematical models and have previously been used in many studies (e.g. Bencala and Walters, 1983; Bencala et al., 1990; Harvey et al., 1996, Wörman et al., 1998). Hence, as a support for improved understanding of the solute transport processes in the Lule River (and rivers in general), a tracer experiment with a simultaneous injection of a conservative and a reactive tracer was performed in a 30 km long reach of the smaller Säva Stream (Jonsson et al., 2002). This experiment allowed us to study the properties of transport for both water and sorbing solutes and to evaluate the importance of the hyporheic zone for the solute transport. A reason to perform such a basic experiment in Säva stream is its size, which is considerable smaller than Lule River, and its easy access for the research group. The relatively small size (discharge varied from 0.1 – 0.5 $m^3$/s) implies that reasonable amounts of tracer substances can be used.

The simultaneous injection made it possible to distinguish hydraulic processes from the processes affecting a reactive solute in a way that previously has not been possible. Sampling in both the stream water and the bed sediment also allowed us to compare the parameter values describing specific processes from independent evaluations. In this way it was possible to determine which observations that were needed to quantify certain mechanisms, to get consistence with the observed concentrations in both the stream water and in the sediment.

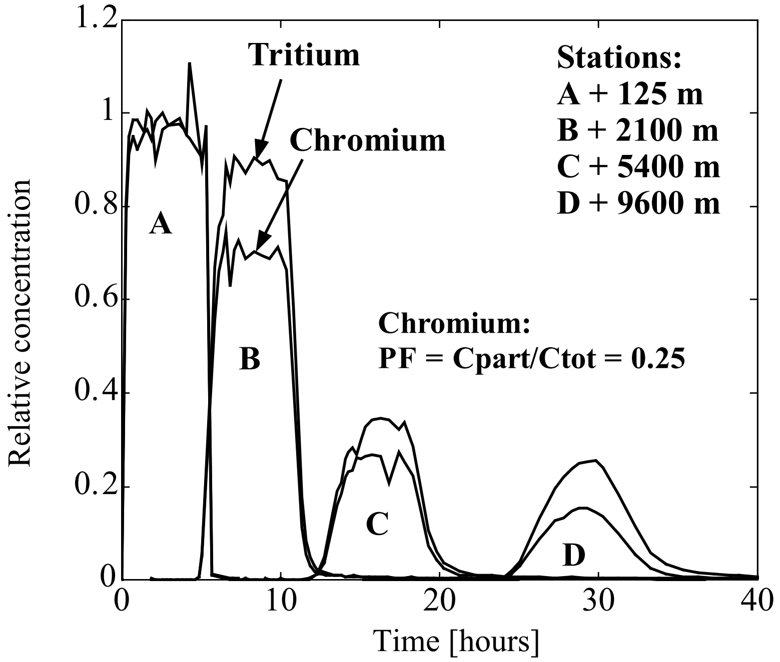


**Fig. 6 Breakthrough curves for chromium and tritiated water in the Säva Brook Experiment 1998 at four of the eight measuring stations.**

A clear difference was found between how the two substances were transported in the stream (Fig 6). The reactive tracer (chromium) was retained in the system mainly due to adsorption in the bed sediment, while the transport of the conservative tracer (tritium) was faster through the system. Only 24% of the injected chromium was found in the stream water directly after the passage of the pulse, 30 km downstream of the injection point. Because the main part of the loss of tracer from the stream water was due to accumulation in the hyporheic zone (i.e. the sediment), this zone was found to be an important part to consider when solutes transport in the system. This knowledge is important to use when the transport in the Lule River is considered. Also here, it is likely that reactive substances are retained in the hyporheic zone. In the Säva Stream, the time to reach a 75% washout of the maximum uptake in the sediment was ~85 times longer for chromium than for tritium.

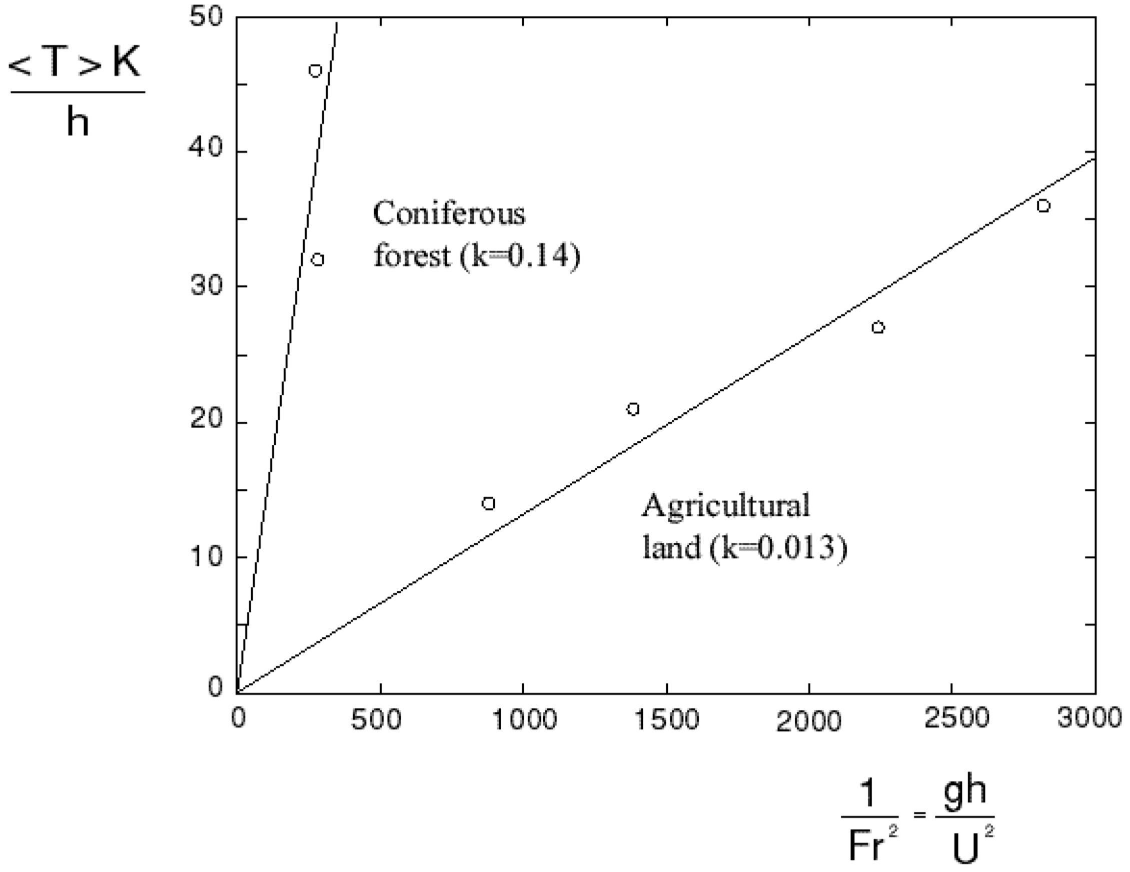
By applying basic hydrodynamic principles we were able to derive the distribution of solute residence times due to pumping. The model provides an accurate representation of the breakthrough curves of the tracer test in Säva Brook along the entire 30 km-reach. Both hydrodynamic theory for pumping exchange and pore water samples obtained from the bed during the tracer experiment suggest that the residence time for solutes in the hyporheic zone is characterised by a log-normal PDF. The new model is advantageous because its fundamentally-derived exchange parameters can be expressed as functions of basic hydrodynamic quantities, which allows the model results to be generalised to conditions beyond those directly observed during tracer experiments.

The hydrodynamic pumping exchange model can be used to generalise the experimental results. Based on the premise that pumping exchange caused by bed roughness dominated the transient storage, approximate constitutive relationships were derived that relate the expected residence time and exchange velocity or exchange rate of the Transient Storage Model with stream properties. Exchange was parameterised to relate the dimensionless hyporheic residence time <T> K / h with the stream Froude number, Fr,

$$\frac{<T>K}{h} = k\frac{1}{Fr^2}$$

where K is the hydraulic conductivity of the substratum, <T> is the mean residence time for water in the hyporheic zone, h is water depth, k is an empirical coefficient and $Fr = u/(g\ h)^{0.5}$ (Wörman, et al., 2002).

This parameterisation allows consideration of hyporheic exchange in different stream reaches independently from variations in stream flow and channel geometry. This approach was successfully used to distinguish hyporheic exchange in sections of Säva Brook with different land use (Fig. 7). An extended study of other land types have also been performed (Salehin, 2002).



$\frac{<T>K}{h}$
50
40
30
20
10
0
Coniferous forest (k=0.14)
Agricultural land (k=0.013)
0
500
1000
1500
2000
2500
3000
$\frac{1}{Fr^2} = \frac{gh}{U^2}$

**Figure 7 Evaluation of the effect of land use or stream morphology on hyporheic exchange, evaluated from the Säva Brook Experiment 1998. The solid lines represent the trends between the dimensionless time and the stream Froude number expected from pumping exchange theory. The theory has been fit to the data by adjusting the proportionality coefficient k, which is the slope of the curves on this dimensionless plot.**

## 5. Discussion of results and tentative conclusions

### 5.1. Flow changes

The weekly average discharge data for the Lule River in Boden (Fig. 8) were provided by Vattenfall, the company operating the dams along the Lule River. The aim of the regulation is to store water during spring and summer to produce electricity in winter. In spite of this, seasonal variations are slightly visible, although the discharge is mainly a function of commercial demand. A spring peak occurs in May (increase from 600 to 1000 $m^3/s$), which reflects snowmelt in the downstream parts of the drainage area. A decrease in discharge takes place in June and July when most of the water is stored in the regulation reservoirs close to the mountains. The increase in the discharge during August and September probably reflects a combination of rains and release of some water when the upstream reservoirs are full. The discharge is lower over the winter but stays above 400 $m^3/s$ due to the demand in hydropower production. For the Lule River, the mean discharge for the studied period was 650 $m^3/s$.

For the unregulated Kalix River two peaks are visible during the period from May to late June. The snowmelt in the woodland results in a strong discharge increase in mid-May, followed by a second peak in June with the snowmelt from the mountains. Some years the two peaks are confounded because of the differences in snowmelting. During the spring discharge in May, only 10 to 15% of the water comes from the mountains, whereas in June and July 30 to 60 % of the water originates from this area (Ingri et al., 1997). Then the discharge remains quite high during the summer with variations due to rains around a mean of 500 $m^3/s$. During autumn, the discharge decreases to reach 200 $m^3/s$ in November. Throughout the ice-covered period during winter, the base flow discharge is almost constant and very low in the unregulated Kalix River with a minimum of 60 $m^3/s$ in March. At this time the discharge difference is most obvious between the two rivers. During the ice-covered period the Kalix River is fed mainly by groundwater (Ingri et al, 1997). For the Lule River, winter is the time when the hydropower stations are running. Water is stored upstream in the mountains during spring and summer and is used to produce electricity all along the river in winter.

Carlsson (1994, 1995) has studied the impact of the regulation on river runoff to the Gulf of Bothnia. The pre-regulation discharge has been estimated from data available in Carlsson (1994, 1995) and shows the same seasonal variations as the Kalix River, i.e. a strong spring peak and very low base flow values during the ice covered winter period (Fig. 8).

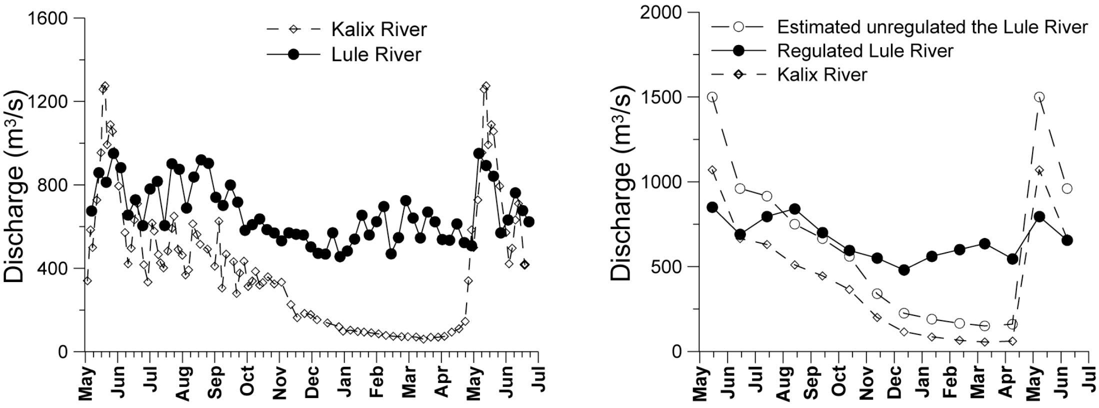


**Fig. 8 Discharge comparison between the Lule River, the Kalix River, and the estimated unregulated discharge in the Lule River.**

## 5.2. Comparison between Lule and Kalix Rivers

The first interpretations of the comparison between the Lule and Kalix rivers were presented by Collomp et al. (2001, manuscript in the licentiate thesis by Collomp, 2001). No data of nutrients were included in this paper due to very late delivery from the laboratory used for these analyses. As an example of the data we have for the Lule River, the $NO_3$ concentration in Boden is shown in Fig. 9. Striking features of this figure is the low concentrations, ranging between 4 and 67 µg/l, and the strong seasonal variations. During the growth season for diatoms and green and bluegreen algae the concentrations are low, and during the winter the concentrations increase, probably due to decay of organic matter (Wetzel, 2001). Unfortunately we have no detailed whole-year cycle for nutrients in the Kalix River, but a comparison between the Lule and Kalix rivers for the years 1997-2000 by data from the national river monitoring program (PMK) is shown in Fig. 10 (upper left figure). Similar seasonal variations as in the Lule River occur also in the Kalix River, but the concentrations are higher. Espcially the winter peaks are much higher, up to 270 µg/l. This can be explained by that melt water from the mountains are stored in the large upstream reservoirs and then used for production of electricity during the winter. This results in an increased flow at Boden of water with lower concentration of $NO_3$. However, also the upstream reservoirs show this seasonal variation, see below.

Also the $PO_4$ concentrations from PMK is shown in Fig. 10 (upper right figure). The concentrations are very low in both rivers, and the data scatter, probably in many cases reflecting values close to the detection limit. It is clear though that the Kalix river has higher concentrations than the Lule River also of $PO_4$.

Since the licentiate thesis by Magali Collomp (2001) is enclosed to this report, we here just give a few glimpses of the results.

Water temperature increases rapidly for both rivers from the spring to reach a maximum above 16ºC between July and August. There is then a decrease during autumn to reach a minimum winter value, which remains rather constant until the ice break up in April. Even if the general pattern is similar in the two rivers, there are two main differences. There is a delay in the temperature decrease in the autumn in the Lule River (the minimal temperature is reached in late October in the Kalix River and in late December in the Lule River). The minimal winter temperature is higher in the Lule River, than in the Kalix River, 1 to 2ºC compared with 0ºC. Other authors, e.g.

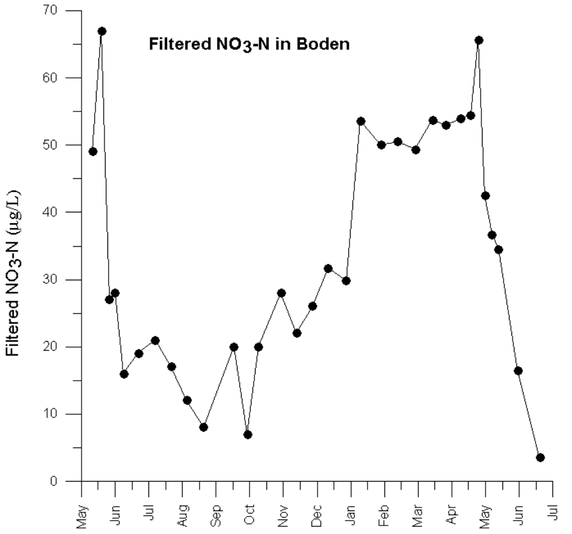


Fig. 9. $NO_3$ concentration in filtered water samples at Boden.

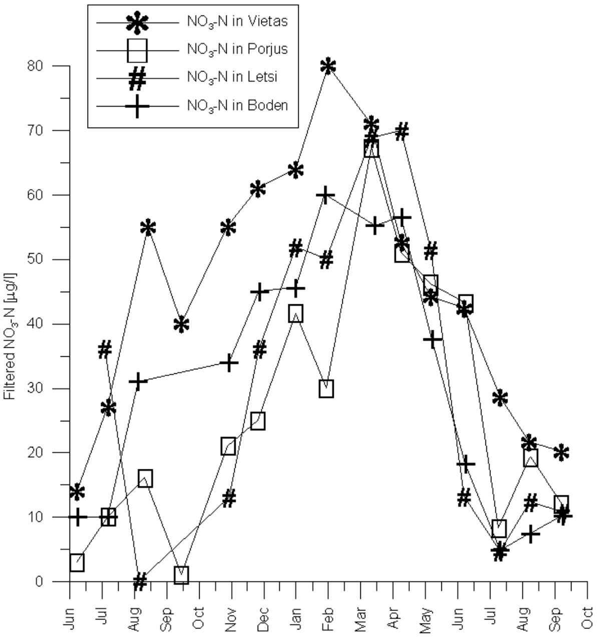


Fig. 10. $NO_3$ (upper left) and $PO_4$ (upper right) concentrations in the Lule and Kalix rivers with data from the national river monitoring program (PMK). $NO_3$ (lower left) and $PO_4$ (lower right) concentrations at some stations along the Lule River (our own data).

Webb (1995) and Webb and Walling (1996) have documented this thermal impact of regulation. From their study of a regulated river system in England, Webb (1995) and Webb and Walling (1996) report a raise in the mean water temperature, changes in the freezing conditions, a depress of summer maximal values and a delay in the annual cycle. The thermal changes were found to not be directly related to water temperature in the reservoirs, but controlled by the mixing of the reservoirs water with water coming downstream from the large dam, i.e. downstream tributaries and groundwater.

During the autumn the release of warmer reservoir-water explains the delay in water temperature decrease in the Lule River. During winter mixed-water conditions still prevail with higher discharge in the regulated Lule River. In the Kalix River, pH values are close to neutral throughout the year except for a drop in the spring and a summer maximum. The drop in pH during the spring is correlated in time with an increase of TOC (see below). Organic acid flushes from mires and the riparian zone can explain the pH spring drop in the Kalix River. The increased pH during the summer is most likely related to an increase in primary production. For the Lule River, no clear trend could be observed, except that winter values are slightly higher with stronger variations.

Dissolved oxygen shows temporal variations. After a decrease of the saturation in early May in both rivers due to an inflow of former anoxic mire water (Ingri et al, 1997), an increase occurs from spring until autumn in the Lule River. Then follows a decrease in October to reach a minimum plateau during winter. During the summer, dissolved oxygen (expressed as % of saturation) is greater than 100% in the regulated river, probably reflecting primary production. This phenomenon is not as obvious in the pristine Kalix River.

One characteristic of the two studied boreal rivers is that total organic carbon (TOC) is the dominant constituent compared to major cations (see the following part), even if the average value is lower than the world average concentration in river of 7 mg/l (Thurman, 1985). TOC is mainly constituted of dissolved organic carbon (DOC), as the particulate organic carbon (POC) represents only 3 to 15 % of the TOC. In the Kalix River there is a seasonal TOC variation with clear spring and autumn peaks (Fig. 11 ). These variations are due to the fact that TOC originates from the riparian zone, which is above the water level during the low winter base flow, and is inundated during high water levels in spring and during autumn rains.

In the Lule River, the TOC does not show any pronounced seasonal variations. This is an important change in the biogeochemistry of the regulated Lule River and shows the importance of the riparian zone for TOC in boreal rivers. As TOC does not clearly show seasonal variations in the Lule River, it seems that the riparian zone processes are modified by the regulation, which maintains a rather high water level. POC and PON (particulate organic nitrogen) follow the same trend, there is a spring peak followed by a slow decrease until the next spring, after a winter minimum plateau (Fig. 11).

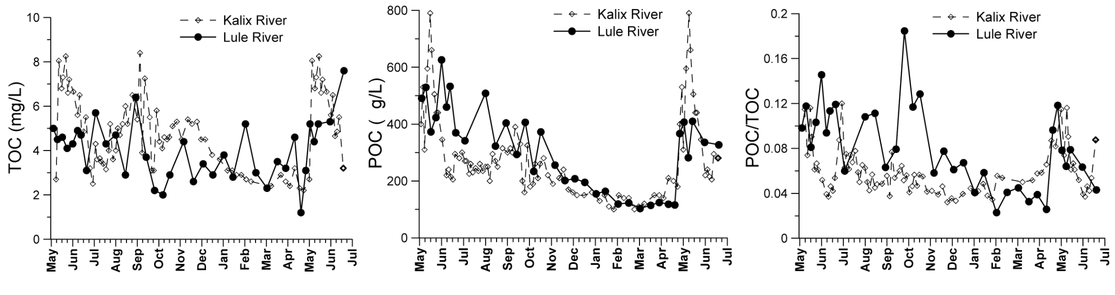


**Fig. 11. Seasonal variations of TOC and POC and the POC/TOC ratio in both rivers.**

In the Kalix River, there is a decrease of the filtered concentration of the major elements Ca, Mg, Na and S during the spring flood in May (exemplified with Ca in Fig. 12). This is due to dilution by melt water discharge from the woodlands in May (Ingri, 1996). The concentrations then increase through June and July and keep the same value until the beginning of the winter when a second increase occurs to reach a maximum value in the end of April just before the spring flood. The high winter concentrations occur during the lowest flow and are caused by that groundwater is an important water source to the river this time of the year (Ingri, 1996). For Si a decrease in concentrations during the summer is probably explained by diatom growth and a larger component of water coming from the mountain area in the river (Ingri, 1996).

In the Lule River, concentrations of the major elements show a totally different pattern than the Kalix River (Fig. 12). For Ca, Na and S, the minimum concentrations are observed in June and July compared to mid-May in the Kalix River. Only a small increase is visible during the winter. For Si, the summer depletion occurs from August to October, which is later than in the Kalix River, and a second decrease is observed from January to late April.

For Fe a spring peak is visible in both rivers (Fig. 12), but is truncated in the regulated Lule River, which shows, like the variations of TOC, a different biogeochemical exchange with the riparian zone.

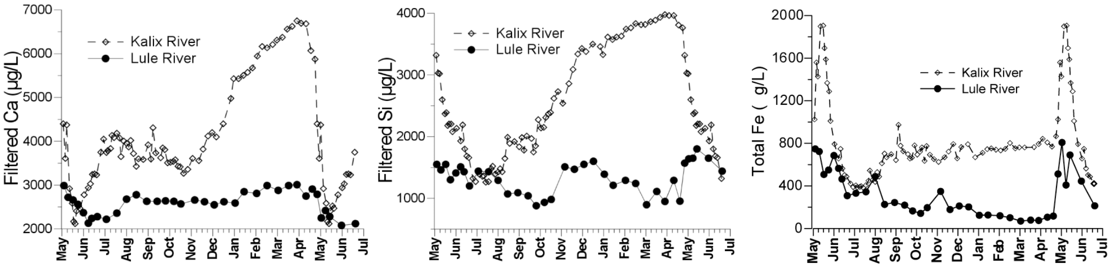


**Fig. 12 Concentrations of Ca, Si and Fe vs. time in filtered water samples in the Lule and Kalix rivers.**

The annual water discharge of the Lule River and the Kalix River into the Gulf of Bothnia is approximately $20\times10^9$ $m^3$/year and $10\times10^9$ $m^3$/year, respectively. As the two rivers have similar watershed characteristics (comparable drainage area size, similar climate, etc), the weathering of the elements per $m^2$ should be comparable in the Kalix River and the Lule River catchments. The reason for the higher discharge in the Lule River is that a larger part of the Lule River basin is located within the mountains where rainfall and snowfall are particularly higher and the evaporation lower.

The annual transport of elements in both rivers has been estimated and is presented in Fig. 13. Higher transport of suspended matter is observed in the Lule River compared to the Kalix River (see more details in Collomp et al., 2001). The increased transport of ashed suspended solid (ASL) is reflected by higher transport of Ca, K, Mg, Na, and especially Al. This higher transport of inorganic suspended matter and POC could be explained by resuspension caused by the release of bottom water from some reservoirs along the river. The higher transport of filtered Ca, Mg and S in the Lule River could be explain by an higher proportion of water coming from the mountains, as the bedrock is slightly different in the mountains with e.g. some lime stone outcrops in the Padjelanta national park. The higher transport of Na and to some extent S in the Lule River could be explain also by the larger influence of the mountain area, as precipitation is enriched in these elements (Ingri, 1996). No clear difference could be observed for filtered Si. On the contrary the transport of Si in the suspended phase is greater in the Lule River than in the Kalix River. Thus the regulation does not change the transport rate of filtered Si, but increased suspended Si could be explained by a greater diatom production, probably induced by the presence of the artificial reservoirs. Iron is the only element presented in Fig. 13 that has a lower transport rate in the Lule River compared to the Kalix River. As P is to a large extent adsorbed on Fe-oxyhydroxides a decreased transport of P is observed in the suspended phase. This decrease is probably due to the modified riparian zone processes and the disappearance of the winter enrichment in Fe from the groundwater observed in the Kalix River.

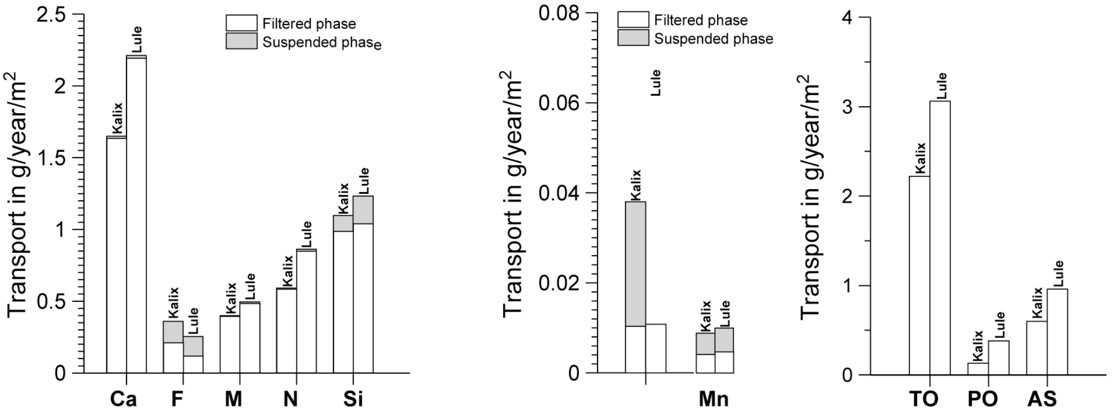


Fig.13. Annual transport in the Lule and the Kalix Rivers (in g/year/m$^2$ of the drainage area)

Some tentative conclusions can be drawn from the comparison between the Lule and Kalix rivers. The stream regulation in the Lule River induces changes in seasonal discharge rates, with high discharge values during the ice-covered winter period and decreased spring peaks. This, in turn, creates always-mixed water conditions of surface water and groundwater, when compared to the natural conditions in the pristine Kalix River, added to a larger influence of water coming from the mountains. In the Kalix River, the spring flood is dominated by woodland water and the summer discharge by mountain water and rainwater. In the Lule River the mountain snowmelt and the summer rainwater are retained in the reservoirs and released during winter for electricity production. Disturbances of parameters such as conductivity, water temperature, pH and dissolved oxygen were thus recorded. Important changes in the biogeochemistry of the Lule River were observed. Seasonal variations of the elements in the filtered and the suspended phase are affected, with recorded delayed summer peak and disappearance of winter concentration increases when compared with the Kalix River. Riparian zone processes appear to be modified by the regulation, which is shown e.g., by the disappearing of TOC seasonal variations and a truncated Fe spring peak compared with the one in the Kalix River. Higher transport of suspended matter was observed in the Lule River compared to the Kalix River, probably caused by resuspension due to release of bottom water from the reservoirs. The transport of Fe was found to be clearly decreased by the regulation.

## 5.3. Upstream processes

Water were sampled at Vietas, Porjus, Ligga, Messaure, Letsi, Laxede and Boden (Fig. 1). At all these station we have complete data sets according to the description of sampling and analysis above. The sampling at Letsi power station represents the inflow to the Big Lule River from the Little Lule River, resulting in an increased water discharge and changed water geochemistry downstream.

To illustrate the type of results we have, som examples are given here. The monthly average discharge data (Fig. 14) were provided by Vattenfall. Comparing Vietas and Porjus there is nearly the same discharge during autumn and winter. The discharge during spring and  summer from Vietas power station is very low compared to Porjus.  During these months water is stored upstreams in the  large Suorva reservoir. The aim with the storing in the reservoir is to use the water during the winter when the inflow of water to the reservoirs is very low. The discharge from the Little Lule River, Letsi, shows higher values during the spring and summer due to the

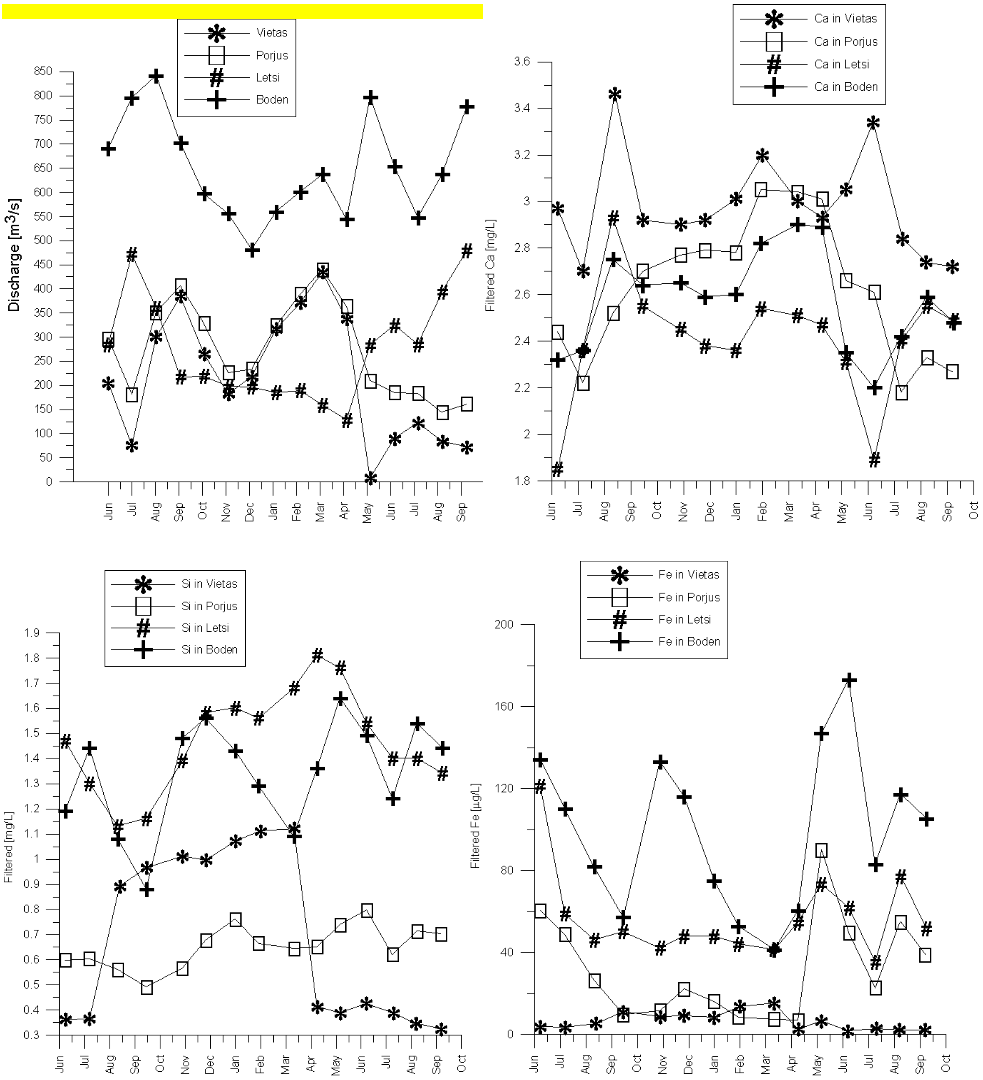


**Fig. 14. Discharge and concentrations  of Ca, Si and Fe at Vietas, Porjus, Letsi and Boden.**

snowmelt and summer rain. Except for the major reservoir Tjaktjaure there are no large reservoirs along the Little Lule River to store the water during the snowmelt. In Boden, the discharge is high during June and July due to the snowmelt from the woodland downstream the reservoirs and the snovmelt discharge from the Little Lule River. During the winter the discharge in Boden shows the same pattern as the reservoirs in the mountains.

Also included in Fig. 14 are the seasonal variations of concentrations of Ca, Si and Fe along the river. Vietas shows the highest concentration of filtered Ca. This is due to the occurrence of some limestones in the drainage area in the western mountains. In Vietas power station, the concentration of filtered Ca is relatively constant over the year, but at Porjus the concentrations of Ca show an increase during winter and diluted concentrations during spring and summer. In Little Lule River (Letsi) the Ca concentrations are lower than in the Big Lule River due to different bedrock composition in the drainage area. The Ca concentrations at Boden are approximately a discharge weighted mixture between the two rivers with some contributions from tributaries. The concentrations of several elements such as Mg, Na, K, $SO_4$ ect at Boden are also a mixture of the contributions from the two river branches.

At Vietas filtered Si shows a totally different pattern than at Porjus. During the winter there is a clear increase of concentration of Si. From April and during the whole summer the filtered concentration decreases strongly. This decrease is probably due to assimilation of silica by diatoms in the Sourva reservoir. In Stora Lulevatten there is no clear variation of the filtered Si concentration, as recorded at the outled Porjus. The data from the tributary between Porjus and Vietas, Sjaunaätno, show that the Lule River gets additional contribution of filtered silica from tributaries. The filtered concentration of Si from Little Lule River (Letsi) shows small temporal variations. A little bit higher concentrations during the winter are followed with low, diluted concentrations during the spring flood. At Boden the results from the two rivers show a mix, when the water retained in the reservoir in the mountain reflects the lower concentration of filtered Si in December, January and March. The decrease in the concentration of filtered Si during spring flood is caused by dilution of melt water from the Little Lule River.

The concentrations of filtered Fe show a different pattern for Vietas in comparison with Porjus. At Vietas the concentration of Fe is very low during the whole year without any temporal variations. The concentrations of Fe at Porjus show temporal variations. During the spring of 2000 and 2001 the concentration is high compared to the rest of the year. This increase is due to the snowmelt from the woodland. The pH in Lule River is close to neutral, so true dissolved concentrations of Fe is very low. The increased concentration during snowmelt could be caused by particles smaller than 0.22 µm. Probably some of these particles consist of iron complex with organic anions and other colloidal iron complex with Fe-oxyhydroxides. From the Little Lule River the temporal variation show the same pattern as at Porjus (but higher concentrations). At Boden there is a mix between the two rivers but there is also an important contribution of filtered Fe from tributaries during the springflood from the downstream woodland.

The $NO_3$ concentrations are higher at Vietas than at Porjus, Letsi and Boden (Fig. 10). There is an obvious seasonal variation with highest concentrations during the winter. During the growth season the $NO_3$ is used and taken up by algaea. The higher summer values at Vietas than at Porjus is caused by algaea growth in Stora

Lulevatten. The $PO_4$ concentrations are low and there are no obvious differences between upstream and downstream stations, and no clear seasonal variations.

The studies of the upstream processes confirm that the major effect of the river regulations is the smoothed discharge without the real strong springflood. The upstream springflood is collected in the large reservoirs, and this has a major impact for the transport of e.g. Fe, K and TOC for which the highest concentrations coinsides with the highest discharge in unregulated rivers. There is a decreased exchange in the shore zone of the river due to the regulation. The difference between the highest and the lowest water level in the Suorva reservoir is 30 m and in Stora Lulevatten 6 m. There is thus a barren shore zone where no elements and organic matter are supplied to the river during (natural) flooding in the spring.

A clear pattern we have observed is that between two power station without a large reservoir inbetween, there are no strong changes of the water geochemistry, except for mixing with tributaries. The concentrations of nutrients such as $NO_3$ and $PO_4$ are not higher close to the coast than in the upstream researvoirs. $NO_3$ is even highest at Vietas.

The results from the sediment sampling in Stora Lulevatten have not yet been thoroughly evaluated, but it can tentatively be concluded that the recent sediment differs from the sediments deposited before the regulation. The $^{210}$Pb dating confirms that these changes occur when the river weas regulated. Fe oxyhydroxides are common in the surface sediments (which they probably were in the surface sediment also before the regulation). There are no obvious signs of changed production of diatoms after the river regulation.

## 5.4 Model behaviour and calibration problems

The hydraulic parameters are determined as previously described by assuming that the flow follows Manning equation. The calculation is made in one step at each sub-reach with average values of the cross-section geometry for that sub-reach. By iteration, the water depth is determined at the different sections. Hence, by knowledge of the cross-section geometry and the water flow, the water flow area and the water velocity are determined. When the hydraulic model is coupled to the solute transport model, the hydraulic parameters are held constant, and the calibration of the model is basically made by determine the values of the rate coefficients ($\lambda$) (cf. system (2)). To be able to determine these rate coefficients an optimisation procedure was written. Here, the coefficients were calibrated by minimizing the sum of distances between the observed and simulated breakthrough curve at the downstream station (the least square estimate). However, this kind of optimisation procedure yields parameter values with a high degree of uncertainty as the model involves too many rate coefficients to obtain a defined optimum. To yield parameter values with higher certainty, it is advisable to first make independent observations or calculations of the rate coefficients that could be independently determined. This can be done partly by making independent observations in the studied system and partly by collection literature information of previous studies relevant for the present study. We have chosen to use this method and therefore the search for relevant literature as well as planning of further possible sampling is proceeding.

## 5.5 Estimate of water residence time in Lule River

Due to varying flow conditions in the Lule River during a year, partly due to the regulation, a distribution of residence times are produced for each sub-reach.
In Fig. 15, a particle tracking analysis is made on the sub-reach Vietas – Porjus to determine the residence time for a single water particle, depending on which day the water particle was released during a period of 270 days. In this example it is possible to see that the residence time for this reach vary considerably, in the range 33-72 days. Such a temporal variation of the water residence times is essential for the understanding of fundamental processes affecting the reactions and biological interactions affecting various solute elements

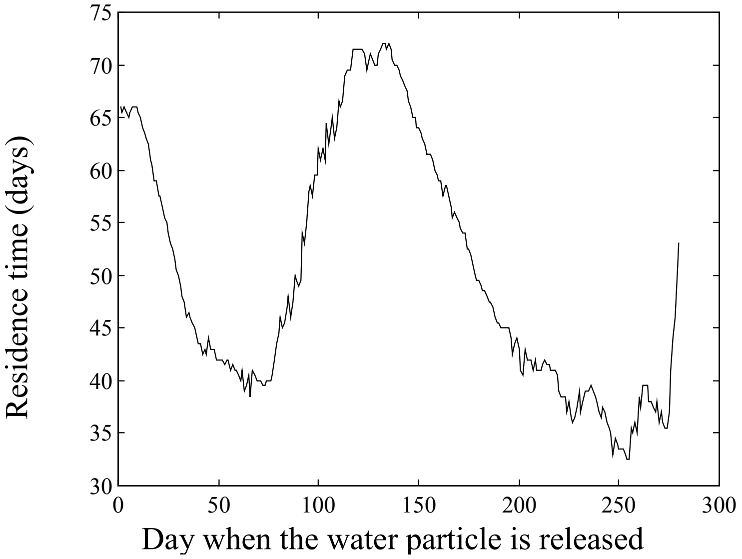


**Figure 15 Residence times for single water particles at the sub-reach Vietas - Porjus. (Day 0 corresponds to the 20th of June 2000).**

In the modelling, it is necessary to calculate a mean value of the residence times, both in time and in space, for use in further analyses. The mean value can be determined in different ways and the different ways and therefore a comparison was made in this project. By first calculating the residence time at each time step by summing the residence times between different cross-sections and then calculating an arithmetic mean value of the different residence times over the studied time-period, the mean residence time in the example (Vietas-Porjus during the study period) is 85 days. In another method, a mean value in space of the velocity for the sub-reach is calculated at each time-step. The residence time is then determined for each time-step and finally a mean value in time of the residence times at each time-step is determined to 42 days. A third method is to calculate a mean value of the velocity both in time and in space before the residence time is calculated. With this method, the mean value of the residence time is 26 days. Obviously, the different methods leads to different results, and it is therefore important to use the method that is most appropriate for the problem formulation. By comparison with Fig 15, we can see that the second method provide the best mean value for the average water parcel that passes through the river.

Consequently, we intend to use either the distribution of residence time according to Fig. 15 or calculate a mean value by first average the velocity in space at each time-step, calculate the residence time is for each time-step and finally equate the a mean value in time.

## 6. Future research needs

A overall evaluation of retention of water and solutes due to regulation in Lule river is an essential objective to complete the first part of this project. The model used to represent the transport of solute elements will be defined for inert solutes of Lule River using the parameter set-up from the independent hydraulic calculations described in section 3.1 and the time scaling methodology for solutes in the hyporheic zone as described in section 4.2. A validation of the model definition will be performed based on data of inert solutes like Na and Cl.

First the modeling is focused on the water balance by using only the hydraulic model. The hypothesis that should be tested is whether the water regulation alone can explain the leveling out of the solute transport during a year, mainly at the outflow at Boden.

The contribution of solutes from the watershed should also be determined. This will be done by first calculating a mean value for the whole area by considering the transport at Boden. A distribution of this mean value along the Lule River is then to be determined by a weighting procedure towards the spatial and temporal variation in the run off. Further, relevant model structures for the different substances should be built-up and the model should be calibrated against the time-series of solute concentrations at the sub-reaches. Also as much independent information as possible should be collected and included in the model, both from literature and from further field measurements.

To be able to describe the conditions in the reservoir in a realistic way, a measuring program of the temperature distribution with depth will be performed in Stora Lulevattnet during the summer 2002. In that way we expect to get information about whether the reservoir is stratified or not which has implications for the turn-over time of the reservoir.

As far as the project budget admits, a measuring program with sampling of bed sediment in the Stora Lulevattnet should also be made. The information of mass of the solutes in the bed should be of great value for the model development as independent observations make it possible to critically test the model.

An experiment at the hydropower station at Vietas is also planned in order to investigate how the solute concentration vary with time if there is a sudden increase in flow from the case with zero flow. Inlet effects at that station can be essential for the measuring results.

The work is planned to be published in international papers as well as in a final report to STEM.

## Appendix A: Publications in this project

"Comparison of the geochemistry of the regulated LuleRiver and the Unregulated kalix River, Northern Sweden.", Licentiate thesis of Mgali Colomp, Luleå University of Technology, 2001:60.

"Effect of Hyporheic Exchange on Conservative and Reactive Solute Transport in Streams: Model Assessments Based on Tracer Tests", PhD-thesis of Karin Jonsson, report Acta Universitatis Upsaliensis, ISSN-1104-232X.

"A geochemical comparison between the regulated Lule River and the unregulated Kalix River, Northern Sweden: effects of the regulation". Collomp, M., Drugge, L., Widerlund, A., Öhlander, B. and Ingri, J., Manucript to be submitted, included in Collomp (2001).

"Effect of Flow-Induced Exchange in Hyporheic Zones on Longitudinal Transport of Solutes in Streams and Rivers" Wörman, A., Packman, A., Jonsson, K., Johansson, H., Water Resources Research, 2002, 38(1), 2:1-15.

"Hyporheic Exchange of Reactive and Conservative Solutes in Streams – Tracer Methodology and Model Interpretation", Karin Jonsson, Håkan Johansson, Anders Wörman. Journal of Hydrology, 278(2003), 153-171.

"Comparison of Hyporheic Exchange in Vegetated and Unvegetated Reaches of a Small Agricultural Stream in Sweden: Seasonal Variation and Anthropogenic Manipulation", Masfiqus Salehin, Aaron Packman and Anders Wörman, Advances in Water Research, 2003, 26(9), 951-964.

"Sorption Behaviour and Long-term Retention of Reactive Solutes in the Hyporheic Zone of Streams", Karin Jonsson, Håkan Johansson and Anders Wörman. **In press:** Journal of Environmental Engineering.

"Tailings dam failure in Aitik, Northern Sweden: A discussion on release, transport and retention in the Kalix River system". Magali Collomp, Anders Wörman, Björn Öhlander, Johan Ingri and Manfred Lindvall, Manuscript.

## Appendix B.

## Discretization of model equations

c – the concentration for m phases
j - node
k - time

$$\frac{c(j,k+1)-c(j,k)}{\Delta t}+\frac{c(j,k+1)+c(j,k)}{2}\cdot\frac{A(j,k+1)-A(j,k)}{\Delta t\left(\frac{A(j,k+1)+A(j,k)}{2}\right)}+$$

$$\frac{S(j,k)c(j,k)+S(j,k+1)c(j,k+1)}{2}+$$

$$+\left[\frac{\frac{\left[(AUC)_j-(AUC)_{j-1}\right]^{k+1}}{A_{medel}}+\frac{\left[(AUC)_j-(AUC)_{j-1}\right]^{k}}{A_{medel}}}{2\Delta x}\right]=$$

$$\frac{Sq(j,k)+Sq(j,k+1)}{2}$$

$$\frac{AU}{A_{medel}}=D$$

$$\frac{c(j,k+1)-c(j,k)}{\Delta t}+\frac{c(j,k+1)+c(j,k)}{2}\cdot\frac{A(j,k+1)-A(j,k)}{\Delta t\left(\frac{A(j,k+1)+A(j,k)}{2}\right)}$$

$$+\frac{S(j,k)c(j,k)+S(j,k+1)c(j,k+1)}{2}$$

$$+\frac{D(j,k+1)c(j,k+1)-D(j-1,k+1)c(j-1,k+1)}{2\Delta x}$$

$$+\frac{D(j,k)c(j,k)-D(j-1,k)c(j-1,k)}{2\Delta x}=\frac{Sq(j,k)+Sq(j,k+1)}{2}$$

$$\left[I+\frac{\Delta t S(j,k+1)}{2}+\frac{\Delta t}{2\Delta x}D(j,k+1)+\frac{A(j,k+1)-A(j,k)}{\left(A(j,k+1)+A(j,k)\right)}\right]c(j,k+1)$$

$$+\left[-\frac{\Delta t}{2\Delta x}D(j-1,k+1)\right]c(j-1,k+1)$$

$$+\left[-I+\frac{\Delta t S(j,k)}{2}+\frac{\Delta t}{2\Delta x}D(j,k)+\frac{A(j,k+1)-A(j,k)}{\left(A(j,k+1)+A(j,k)\right)}\right]c(j,k)+\left[-\frac{\Delta t}{2\Delta x}D(j-1,k)\right]c(j-1,k)=$$

$$=\frac{Sq(j,k)+Sq(j,k+1)}{2}\Delta t$$

$$\left[I+\frac{\Delta t S(j,k+1)}{2}+\frac{\Delta t}{2\Delta x}D(j,k+1)+\frac{A(j,k+1)-A(j,k)}{\left(A(j,k+1)+A(j,k)\right)}\right]c(j,k+1)$$

$$-\frac{\Delta t}{2\Delta x}D(j-1,k+1)c(j-1,k+1)$$

$$=\frac{Sq(j,k)+Sq(j,k+1)}{2}\Delta t-\left[-I+\frac{\Delta t}{2}S(j,k)+\frac{\Delta t D(j,k)}{2\Delta x}+\frac{A(j,k+1)-A(j,k)}{\left(A(j,k+1)+A(j,k)\right)}\right]c(j,k)$$

$$+\frac{\Delta t D(j-1,k)}{2\Delta x}c(j-1,k)$$

The matrix of coefficient is structured according to this equation and the system of equations could be solved.

## Appendix C: References

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