WATER QUALITY HAZARDS AND DISPERSION OF POLLUTANTS

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Chapter 10

INFLUENCE OF HYPORHEIC EXCHANGE ON SOLUTE TRANSPORT IN A HIGHLY HYDROPOWER REGULATED RIVER

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1. INTRODUCTION

Hydropower regulation of rivers introduces changes in the natural transport of solute elements as well as in the decomposition of biological and geological material in contact with the river. The regulation has been found to lower the in-river transport of solutes due to the lower water velocities and the smoothing out of seasonal variations in the discharge. The change in transport characteristics alters the residence times available for reactions in the river and, hence, the impact on aquatic ecosystems in the river as well as in recipient waters.

One of the prime factors influencing the solute residence time in rivers is the exchange of water between the flowing river water and the hyporheic zone (Hinkle et al., 2001; White, 1993). Especially for reactive solutes the hyporheic exchange causes a retention that has been found to have great impact on solute stream transport (Jonsson et al., 2003 a). Studies have shown that nitrate reduction in the hyporheic zone can significantly affect the nitrate concentration in the river (Grimaldi and Chaplot, 2000; Hill et al., 2000; Martin et al., 1999; Hinkle et al., 2001). Rutherford et al. (1995) studied the controlling hydromechanics for the oxygen exchange between the river and the hyporheic zone and its effect on Fe transport. Such an exchange influences the redox potential in the hyporheic zone and determines whether the hyporheic zone acts as a source or a sink for phosphorus (Mulholland, 1992). The importance of the hyporheic zone has

been particularly stressed in studies of the impact of hydropower regulation on hydrogeochemistry (Ingri et al., 1997; Mörtz et al., 1999).

Several studies have clarified that the hyporheic exchange is driven by the pressure variability on the bed surface for both inert (Thibodeaux and Boyle, 1987; Bencala and Walters, 1983) and reactive substances (Runkel et al., 1996 a and b; Jonsson et al., 2003 b). Wroblicky (1995) and Wroblicky et al. (1998) studied the exchange between the river water and the connecting groundwater aquifer due to the curvature/meandering of the stream. Floods have also been identified as an important exchange mechanism for solute elements in rivers (Macklin and Klimek, 1992; Maas and Macklin, 2002).

This study aims to clarify the role of hyporheic exchange in inert solute transport in the hydropower-regulated Lule älv (Lule River) in northern Sweden. Since the river is not meandering and, because of the regulation, floods are generally prohibited, we believe that the hyporheic exchange due to the pressure variability on the river-bed is one of the main factors that retard inert elements in the river system. One objective is to quantify the effect of the hyporheic exchange on the transport of an inert substance both before and after regulation. A one-dimensional model approach is taken in this first qualitative study, but this simplification is believed to be of minor importance for the study of retention of solutes in rivers originating from diffuse sources.

It is difficult to measure the direct effect of the hyporheic exchange in a large river. Natural variations of solute transport are often superimposed due to a marked scatter of the sources of substances in the catchment, and tracer experiments may require huge amounts of tracer substances to be detectable over large distances. Numerical simulations, however, enable one to estimate the effect of the hyporheic exchange. Hence, the proposed methodology is based on numerical models of the water flow and the solute transport, which are consistent with the data of the river geometry, hydrology and regulation strategy.

During the last decades there has been a rapid development of models of solute transport in streams with regard to dead zones (Hays et al., 1966; Schmid, 1995; Czernuszenko and Rowinski, 1997; Lees et al., 2000). Similar or identical models have been developed also for solute transport with account to solute exchange with the hyporheic zone (Bencala and Walters, 1983; Runkel et al., 1996 a and b; Wörman, 2000; Jonsson and Wörman, 2001). Main issues have been to clarify the appropriate mathematical representation and the magnitude of hyporheic exchange. A related issue is to provide a physical framework from which it is possible to generalize experimental results to other conditions than those under which the data were obtained. This is particularly important for prediction of conditions,

like, for instance, those prevailing before the regulation of the Lule River during a period of time for which relevant data hardly exist at all.

As a basis of the generalization we used conventional theory for open channel flow (Chow, 1959) and recent theory for the hydrodynamics of the hyporheic exchange (Elliott, 1990; Elliott and Brooks, 1997 a and b; Eylers, 1995; Wörman et al., 2002). Wörman et al. (2003) demonstrated a similar scaling procedure for the P-retention in a stream network on a catchment scale. The basic idea in this study is to use the results gained from a tracer experiment in a smaller stream system (the Säva Stream, Uppland County, Sweden) and generalize them to a larger river (the Lule River, northern Sweden) to investigate the effect of the hyporheic exchange of inert solutes in this larger, regulated river.

By means of the model framework it is possible to estimate the hydrodynamic effect of the river regulation on both the in-stream solute transport as well as the exchange with the hyporheic zone. This approach facilitates in particular a quantification of the hyporheic exchange and testing of the hypothesis that hyporheic exchange can have a substantial impact on the solute transport in rivers and that river regulation significantly alters the hyporheic zone interaction. Such an alteration may have direct effects on benthic biota as well as the overall riverine ecosystem.

2. MODEL APPROACH

As mentioned, models can be used to predict the effect of hyporheic exchange in rivers that are too large for conducting tracer experiments. A model can also be used to compare the effect in the present river system with that in the former unregulated system, from which relevant observations are seldom available.

In this section, we present the modelling approach used to evaluate the influence of hyporheic exchange on solute transport in the Lule River before and after regulation. The aim is to investigate how the hyporheic exchange will influence solute transport in the river, by studying the retention and distortion of a solute pulse travelling through the river system. A belief is that the hyporheic zone alters the flow patterns of solutes in a river, which can be important for, among other things, the nutrient status of the sea. A specific aim of the model is to investigate whether the effect of the hyporheic exchange differs before and after the regulation of the river.

The modelling of the transport of solutes has been divided by means of the uncoupling of the hydraulic model from the solute transport model. First, the hydraulic modelling is performed to determine the properties of the water

flow such as the water depth, water flow velocities and cross-sectional areas of the flow. This information is used in the solute transport model.

Both models are one-dimensional and this limitation can be essential for certain conditions where there is a non-uniform concentration distribution across the river. Well-mixed conditions have been found to require very long mixing distances (Fischer et al., 1979). However, for a diffuse source distribution, as for natural elements coming from several tributary streams and groundwater, the dispersion due to lateral mixing has a smaller effect and is neglected in this study for simplicity. Furthermore, the dispersion does not significantly affect the retention of solute elements, which is the main target variable in this study.

2.1 Hydraulic model

The water dynamics of the river can be formulated in one dimension according to Saint Venant's equations (Chow, 1959). A basic simplification accepted here, however, is that the time derivatives of the formulation can be neglected, i.e. quasi-steady flow is assumed. This is acceptable if temporal variations in the discharge are much shorter than the residence time in the river. Hence, those short-term variations are not important for the long-term transport of solute elements, which is more affected by the seasonal variation in discharge. The simplification of quasi-steady flow should apply to solute transport calculations before the regulation, because the discharge varies much more over the seasons (see section 3.2) than its short-term variations. Thus, the short-term variations in discharge are relatively unimportant. Further, the residence time of the river is relatively short (see section 4.2) and this motivates the assumption of quasi-steady flow.

In the regulated river, the head loss due to friction on the stream reaches generally is small compared to the head loss at the hydropower stations. Practically speaking, the water of the regulated Lule River forms a staircase with stepwise changes in energy potential at the hydropower stations. In dam brake scenarios, however, it would appear that inertia effects are essential to consider.

The friction head loss on the reaches between the hydropower stations is based on the Manning friction loss formula, geometrical properties of the river channel (hypsographs) and friction coefficients. The Manning equation is written as:

$$Q = UA = \frac{R_h^{\frac{2}{3}} S_b^{\frac{1}{2}}}{n} A \quad (10-1)$$

where Q is the water discharge (m^3/s), R_h the hydraulic radius (m), S_b the slope of the channel, A the cross-sectional area of the flow (m^2) and n is the Manning roughness coefficient for the channel surface. The Manning equation is based on the assumption that the flow is quasi-stationary, i.e. the conditions are assumed to be stationary and inertia effects are not taken into account. Further, the energy grade line is equal to the water surface slope, which is an assumption that is justified when the velocity head is small.

At sub-reaches between the hydropower stations, where the Froude number, $Fr < 1$, normal depth is assumed to prevail, while for reaches with $Fr > 1$ the water depth is determined with an iterative step method (finite difference method) performed up-streams. The Froude number is determined as

$$Fr = Q / (A \sqrt{gA/b})$$

where b is the width of the free water surface (m) and g is the acceleration due to gravity (m/s^2). The iteration starts with the water depth at the dam or with the critical depth determined iteratively by means of the relationship

$$Q_k = \sqrt{gA_k^3/b_k}$$

where Q_k is the critical discharge (m^3/s), A_k the cross-sectional area of the flow under critical conditions (m^2) and b_k the width of the free water surface under critical conditions (m).

In our calculations of the water velocities and cross-sectional areas of the flow, we use time series of the water discharge and the dammed water conditions for the regulated river, i.e. the water depth at the dam furthest downstream. The water discharge varies with time, but is assumed to be constant in space along the sub-reaches between the dams, with the discharge increasing step-wise at each dam.

2.2 Solute transport model

A general model framework describing solute transport in the river has been developed with an optional number of phases of the studied substance both in the river water and in the hyporheic zone. The mass transfer rates between the different phases are described as first-order equations (Fig. 10-1). All solute phases in the river water are advected with a certain velocity that can be explicitly prescribed, based on the independently performed hydraulic analyses. There is no advection for the phases in the hyporheic zone.

Figure 10-1. Example of model structure with different phases of the solute at a fixed position along the river. Phase 1 is assumed here to be in the river water, while phases 2 and 3 are in the hyporheic zone. Boxes represent mass conservation relationships and arrows mass transfer relationships (c_i is the concentration of the different phases and λ_{ij} is the rate coefficient regulating the transfers between the different phases).

A mass conservation relationship of the solute mass can be expressed in a matrix form as:

$$\frac{\partial \mathbf{c}}{\partial t} + \frac{\mathbf{c}}{\mathbf{A}} \frac{\partial \mathbf{A}}{\partial t} + \mathbf{S}\mathbf{c} + \frac{1}{\mathbf{A}} \frac{\partial (\mathbf{U}\mathbf{A}\mathbf{c})}{\partial x} - \mathbf{E} \frac{\partial^2 \mathbf{c}}{\partial x^2} = \mathbf{S}_q \quad (10-2)$$

where $\mathbf{c}$ is a vector describing the concentrations for the different phases (arbitrary number) (kg/m^3), $\mathbf{S}$ a matrix with rate coefficients between the different phases (λ -values in Fig. 1) (s^{-1}), $\mathbf{U}$ a vector with velocities for the different phases (m/s), $\mathbf{A}$ a vector with areas for the different phases (i.e. cross-sectional area of the water flow or the area of the hyporheic zone) (m^2), $\mathbf{S}_q$ a vector with sources/sinks of the solute ($\text{kg}/(\text{m}^3\text{s})$), x the coordinate along the river, $\mathbf{E}$ a vector with longitudinal dispersion coefficients ($E=0$ for phases with zero advection) (m^2/s) and t is the time (s). The system of equations is numerically solved using finite differences. Appendix A contains the discretization of the model equations.

The present study focus on the exchange of inert substances between the hyporheic zone and the stream water, and therefore a model with only phases 1 and 2 in Fig. 10-1 will be used for the effect studies.

The hyporheic exchange due to pressure variations on the sediment surface has previously been found to retard solute transport in streams, and the solute residence time in the hyporheic zone has been evaluated (e.g. Wörman et al., 2002; Jonsson et al., 2003 a and b). Previously gained

knowledge of physical processes in a stream or river system is utilised in a “box model” representation.

Wörman et al. (2002) proposed a model for solute transport, where the longitudinal transport in the stream is coupled with a flow-induced (advective) uptake in the hyporheic zone. According to their theories, it is possible to relate the expected residence time in the hyporheic zone to measurable stream properties. This allows for generalizations of experimental results either to other flow conditions or to another stream. In this study, we use these theories to generalize the exchange intensities found in the Säva Stream by Wörman et al. (2002) to determine the exchange rates with the hyporheic zone. Fig. 10-1 shows the exchange rates and coefficients λ_{12} , λ_{21} , etc.

The expression in which the residence time in the hyporheic zone due to a pumping exchange is related to stream properties is written as (Wörman et al., 2002):

$$\frac{\langle T \rangle K}{h} = C \frac{gh}{U^2} \quad (10-3)$$

where T is the residence time in the hyporheic zone (s), K the hydraulic conductivity (m/s), h the hydraulic radius (m), C a constant that includes the effects of several geometric parameters related to hyporheic exchange, g acceleration due to gravity (m/s^2) and U is the flow velocity in the main stream channel (m/s). Wörman et al. (2002) evaluated the proportionality coefficient in this relationship by means of the observations made during a tracer experiment in the Säva Stream and evaluated one value of the coefficient for the upper reach of the stream that flows through coniferous forest ($C=0.14$ [-]) and another value for the lower reach in agricultural land ($C=0.013$ [-]). This result was recently confirmed by another study in the same stream (Salehin et al., 2003). These proportional coefficients are used in the present study together with an assumed hydraulic conductivity of 10^{-3} m/s (hydraulic conductivity for gravel/sand (Freeze and Cherry, 1979)). In this manner we could estimate the residence time in the hyporheic zone in the larger Lule River and use this to investigate how the hyporheic exchange will influence the solute transport. Further, we assumed the quotient between the areas of the hyporheic zone and the river water to be constant, equal to unity, regardless of discharge and water depth. This is in fair agreement with the findings of Wörman et al. (2002) and Salehin et al. (2003). Hence, the inverse of the residence time, i.e. $1/\langle T \rangle$, will correspond to the rate coefficient between the river water and the hyporheic zone, λ (s^{-1}). The rate coefficients λ_{12} and λ_{21} in Fig. 1 are expressed as:

$$\lambda_{12} = \lambda_{21} = \alpha \frac{U^2}{h^2 g} \quad (10-4)$$

where $\alpha = K/C$ ($\alpha = 0.0071$ m/s and $\alpha = 0.0769$ m/s, respectively) and where the velocity, U , and the hydraulic radius, h , are determined with the hydraulic model. The investigated magnitude of the exchange intensity should only be treated as a rough approximation.

To get some idea about the possible variation of the effect of the uptake, we also performed a sensitivity analysis, by utilizing previously determined estimations of the residence time in the hyporheic zone. A compilation of reported residence times by Wörman et al. (2002), later extended by Jonsson et al. (2003 b), yields a rather extensive variation in possible residence times, in the order of 5-600,000 s. A sensitivity analysis of the corresponding range of the rate coefficients will be performed.

Field equations for boundary value problems are often solved for a Dirac pulse in time due to the possibility to use convolution to account for a time-varying boundary condition. In the present study we therefore assume a boundary concentration as a short pulse during 20 h for our effect studies. In comparison with the total residence time in the river, the duration of this pulse is comparatively small and can be regarded as an infinitesimal unit pulse. The comparison is based on introducing the same amount of solute mass in the regulated and unregulated cases, which is consistent with setting the upper boundary concentration to 100,000 [kg/m³] in the regulated case, while the concentration is 41,138 [kg/m³] in the unregulated case. A condition with an equal amount of mass introduced would be justified from a physical point of view where, for instance, the run-off from the landscape or an accidental release will provide the same amount of mass into the system, irrespective of whether the river is regulated or unregulated.

In the simulations, the Manning roughness coefficient, n , and the dispersion coefficient, E , were assumed to be constant. The Manning roughness coefficient was assumed to be equal to 0.04, which corresponds to canals and rivers with many stones and weeds (Fox and McDonald, 1994). The dispersion coefficient was assumed to equal 10 m²/s, where the assumption on the magnitude was based on literature information on evaluated dispersion coefficients in other streams (Fischer et al., 1979).

3. CASE STUDY: THE LULE RIVER IN NORTHERN SWEDEN

The Lule River is located in the boreal region in northern Sweden with a drainage area of 25,200 km² and a length of 450 km (Forsgren, 1990)

(Fig. 10-2). The river is strongly regulated with 15 hydropower stations, which generate about one-eighth of the total electricity production in Sweden. Large reservoirs are located in the upper part of the river, where storage of water is possible, whereas the damming at the downstream reach is restricted to enlargement of the river to provide smaller reservoirs. The river has two branches, Lilla Lule älv (Little Lule River) and Stora Lule älv (Big Lule River). The Little Lule River joins the Big Lule River approximately at the midpoint of the river (at Porsï). In the present study, we focus mainly on the transport in the Big Lule River.

3.1 Geometrical data

The geometrical information needed to perform hydraulic calculations is defined in terms of hypsographs of the cross-sections along the river. The hypsographs used in this study either originated from actual measurements or were calculated by a calibration procedure of the reservoir areas using aerial photos (data from Vattenfall AB, the company operating the hydropower stations along the Lule River).

The sections with specified geometry are located with varying distances along the river with a more detailed geometrical description in the lower part of the river. For the “unregulated Lule River” we assumed that the geometry is the same, i.e. the regulation does not influence the hypsographs, but only the damming and the flow conditions.

3.2 Hydraulic data

The hydraulic data needed to determine the water velocity and cross-sectional areas of the flow are the regulated water discharge, the water depth at each dam during regulated conditions and the estimated run-off for each sub-reach. The data used in this effect study were taken from daily observations of the respective parameters during the year 2000-2001 i.e. water flows during regulated and (assumed) unregulated conditions were estimated based on the same hydrological period.

Figure 10-2. Map showing the Lule River with the hydropower stations marked.

To estimate the unregulated discharge, we summed the run-off for the sub-reaches estimated from a water mass balance that takes into account changes in reservoir volumes and regulated discharges. Fig. 10-3 visualizes the regulated and estimated unregulated discharge at Vietas, the first hydropower station on the Lule River, for the period June 2000 - May 2001. It is obvious that the regulation of the river has led to changed flow patterns during the year, where the large seasonal flow variations have been smoothed out in the regulated system. During the period under consideration, the largest difference in the flow is during June and July, when the spring flow in the regulated river is stored in the upstream reservoir. During the winter, when the demand for electricity is high, the regulated flow is on the contrary higher than the natural flow in the river.

Figure 10-3. Example of the changed flow pattern after regulation of the Lule River. Observed regulated and estimated unregulated discharge at Vietas. The period plotted is from June 20, 2000 to May 31, 2001.

4. RESULTS

To study the effect of hyporheic exchange along the Lule River, we evaluated the distortion of the unit solute pulse, introduced at Vietas which travels along the river. As the propagation of the pulse might differ due to different times for the release of the pulse, we also investigated such an effect. As measures of the pulse translation and distortion we used the times corresponding to the passage of 25, 50 and 75% of the total mass at Boden ($t_{25\%}$, $t_{50\%}$, $t_{75\%}$) (determined by integrating the mass of the BTC simulated at Boden). These measures under the influence of hyporheic exchange were compared with the corresponding measures when no hyporheic exchange was assumed to be present, both for the regulated and the unregulated case.

To quantify the relative spread of the breakthrough curves, we use the quotient $(t_{75\%,\alpha} - t_{25\%,\alpha})/t_{50\%,\alpha}$, referred to as $RS(t)$. A distortion of a pulse due to hyporheic exchange indicates that the hyporheic zone can be important for smoothing out temporal variations of solute concentrations in the river, which can be important for the water quality in the recipient water. The retention of a substance in the system due to hyporheic exchange also lead to changed reaction times in the river that might be important for several biological and chemical processes.

4.1 Effect of hyporheic exchange in the regulated river

Fig. 10-4 shows the solute breakthrough curves in the river water at Boden, when a short unit pulse of an inert solute (concentration: 100,000 kg/m³ for 20 h) is assumed at Vietas and the river is regulated for hydropower production, i.e. the water is dammed up and the natural flow variations are smoothed out over the year (exemplified in Fig. 10-3). No sources or sinks of solutes were considered along the river, since they are assumed not to affect the fate of the short pulse. Simulations were performed for the case where it was assumed that there was not any hyporheic exchange and for the two hyporheic exchange intensities found in the Sáva Stream rescaled with geometrical dimensions and water flow velocities (see section 2.2), i.e. $\alpha=0.0071$ and $\alpha=0.0769$, respectively. The value 0.0071 was found to apply for flows through an area of coniferous forest, where the river bottom consists of boulders and stones, whereas the value 0.0769 applies for the flatter reach that flows through arable land, where the sediment is finer and more clayey (Wörman et al., 2002; Salehin et al., 2003).

Figure 10-4. Simulated solute breakthrough curve in river water at Boden in the regulated Lule River when a short pulse is released at Vietas on day 0. Breakthrough curves are presented for the case with no hyporheic exchange (solid line), with hyporheic exchange where $a_{12} = a_{21} = 0.0071$ (dashed line) and with hyporheic exchange where $a_{12} = a_{21} = 0.0769$ (dotted line).

The two values of the exchange coefficient are assumed to delimit a range of possibilities for the Lule River and can be regarded as a part of a sensitivity analysis. Which exchange intensity that best represents the actual conditions of the Lule River is subject of a few speculations. In the regulated river, the lower flow velocities will allow for increased sedimentation and an accumulation of fine sediment on the surface of the bed compared to the unregulated case. As the intensity $\alpha=0.0769$ originated from the reach of the Säva Stream where the sediment consisted of more fine-particulate material, this intensity might be more likely in the regulated Lule River.

From the water breakthrough curves at Boden it is possible to observe a substantial increase in variance and skewness compared to the introduced unit pulse in the upper part of the Lule River, at Vietas (Fig. 10-4). The total residence time of the solute from Vietas to Boden is in the order of a few thousand hours. The length of the residence time is mainly an effect of the regulation strategy with dammed water conditions and storage of water in the reservoirs.

The information on the times taken for the different percentages of the mass in the river water to pass Boden and the relative spread can be found in Table 10-1. The quotient $t_{50\%,\alpha}/t_{50\%,\alpha=0}$ indicates how much the expected value of the breakthrough curve with hyporheic exchange differs from the one without hyporheic exchange. For both exchange intensities we can find a significant increase of the arrival time compared to the case without hyporheic exchange. However, the retardation for the lower exchange intensity is limited to 9%. A larger effect of the hyporheic exchange is found when the

Table 10-1. The times taken for different mass fractions in the river water to pass Boden and the relative spread of the breakthrough curves when the river is regulated and a short unit pulse is released at Vietas on day 0.

α	$t_{25\%}$ (h)	$t_{50\%}$ (h)	$t_{75\%}$ (h)	$\frac{t_{50\%,\alpha}}{t_{50\%,\alpha=0}}$	$RS(t) = \frac{t_{75\%,\alpha} - t_{25\%,\alpha}}{t_{50\%,\alpha}}$
0	1661	1801	1905		0.14
0.0071	1796	1970	2299	1.09	0.26
0.0769	1980	2179	3528	1.21	0.71

relative spread of the curves is considered, which suggests that the hyporheic exchange has a significant potential for regulating temporal variations in solute transport. The quotient $(t_{75\%,\alpha} - t_{25\%,\alpha})/t_{50\%,\alpha}$ will be 1.9 and 5.2 times larger in the case where α equals 0.0071 and 0.0769, respectively, than when no hyporheic exchange is assumed to be present. The reason for the greater impact of hyporheic exchange on this measure is that the effect of $1/\alpha$

increases with the order of the central temporal moments (Wörman et al., 2002). Consequently, the hyporheic exchange can regulate the solute transport with temporal variations of between a week and several months. Such variations could be of both anthropogenic origin, related to the hydropower regulation, and natural origin, related to seasonal variations. The smoothing out of seasonal variations in particular may have ecological implications.

Figure 10-5. Water residence time in the regulated Lule River for a period of 200 days. The residence time differs depending on the time of the year when the particle is released. The main part of the total residence time is due to the slow transport in Stora Lulevattnet (Big Lule Reservoir) located in the upper part of the Lule River between Vietas and Porjus.

The mean transport time (and higher-order moments) for the pulse in the above example depends on the water regulation strategy and therefore on the time of the year when the solute pulse is released. By means of particle tracking we determined the residence time for a single water particle versus the day of release. In a first step, we performed these analyses by disregarding dispersion and other mixing processes. As can be concluded from Fig. 10-5, the residence time for a single particle during a period of 200 days will vary over an interval of approximately ~50-80 days. The above results are derived when the pulse is released on day 0 (corresponding to June 20, 2000). We can also see that the total residence time for the Lule

River (from Vietas to Boden) consists mainly of the residence time in Stora Lulevattnet (Big Lule Reservoir), located between Vietas and Porjus. Although this reach is only about one third of the total river length, this part of the river has the longest residence time.

Figure 10-6. (a) Retardation and (b) change in relative spread of a solute pulse at Boden, due to hyporheic exchange, for different times of release of the pulse at Vietas into the regulated Lule River.

Fig. 10-6a exemplifies the way in which the variation in the retardation of a solute pulse due to hyporheic exchange depends on the day of release for the period when the regulated and unregulated discharges differ the most. The retardation of the unit pulse varies slightly with time, but the effect of the retardation is for all investigated cases greater for the higher exchange

intensity, $\alpha=0.0769$. The relative spread, $RS(t)$, of the curve seems, however, to vary more between the different days of release (Fig. 10-6b). For both exchange intensities it is also noticeable that the effect of hyporheic exchange on the quotient of $RS(t)$ is larger than the effect on the quotient of the expected values. The reason for this is that the quotient of $RS(t)$ is more affected by the tails of the breakthrough curves, which become more pronounced with increasing hyporheic uptake.

If the exchange is considered to be sufficiently rapid, a change in α will not significantly affect $RS(t)$. Such a situation occurs after about 40 and 100 days (Fig. 10-6b). Fig. 10-7 shows results of a sensitivity analysis of the retardation coefficient for different exchange intensities, λ . From this figure we can conclude that a low hyporheic exchange intensity, in the order of 10^{-8} s^{-1} , will not significantly retard the transport, and the hyporheic exchange can thereby be disregarded. The retardation will then increase with increasing exchange intensity, while for sufficiently high values, a further increase in the exchange coefficient will not provide any further retardation. This means that for exchange intensities in the order of $\sim 10^{-7}$ - 10^{-5} s^{-1} , the exchange with the hyporheic zone has to be described as kinetic, while for exchange intensities higher than $\sim 10^{-5} \text{ s}^{-1}$, the retardation can be regarded as instantaneous.

If we recalculate the α -values used in the above simulations to λ -values according to Eq. (10-4) by taking an average of the geometrical dimensions over time and space, the λ -values corresponding to $\alpha=0.0071$ and $\alpha=0.0769$ become 1.26×10^{-6} and $1.36 \times 10^{-5} \text{ s}^{-1}$, respectively. From these estimates we can conclude that a kinetic description might be important for the exchange corresponding to the lower exchange intensity ($\alpha=0.0071$), while for the higher exchange intensity ($\alpha=0.0769$) we could substitute an instantaneous description for the kinetic description.

Fig. 10-8 shows the result of corresponding sensitivity analysis of $RS(t)$. For a sufficiently low exchange intensity, the effect of hyporheic exchange on the relative spread can be disregarded. The effect will then increase with increasing exchange intensity until a maximum is reached. A further increase will then lead to a decreased effect of the hyporheic exchange. For a sufficiently high exchange intensity, corresponding to an instantaneous exchange, the relative spread will be the same as when there is no hyporheic exchange. However, as the effect of hyporheic exchange on the relative spread is negligible for the case of instantaneous exchange, the effect on the retardation is simultaneously at its maximum.

Figure 10-7. The retardation of a solute pulse at Boden (when a short pulse is released at Vietas on day 0) into the regulated Lule River versus the hyporheic exchange intensity, λ . The effect of hyporheic exchange is negligible for sufficiently small values of λ , while the exchange can be regarded as instantaneous for sufficiently large values. Between these extremes the exchange is rate-limited.

Figure 10-8. The change in relative spread of a solute pulse at Boden (when a short pulse is released at Vietas on day 0) into the regulated Lule River, versus the hyporheic exchange intensity, λ . The effect of the relative spread is negligible for sufficiently small and large values of λ , while the effect is at its maximum for intermediate exchange intensities.

4.2 Effect of hyporheic exchange in the unregulated river

Fig. 10-9 shows the solute breakthrough curve in the river water at Boden when a short unit pulse of an inert solute (concentration: $41,138 \text{ kg/m}^3$ for 20 h) is assumed at Vietas and the river is unregulated, i.e. the flow is assumed to follow the estimated unregulated flow curves, exemplified for Vietas in Fig. 10-3. Simulations have, also here, been performed for the case with the assumption of no hyporheic exchange and for the two exchange intensities i.e. $\alpha = 0.0071$ and $\alpha = 0.0769$, respectively.

Figure 10-9. Simulated solute breakthrough curve in river water at Boden in the unregulated Lule River when a short pulse is released at Vietas on day 0. Breakthrough curves are presented for the case with no hyporheic exchange (solid line), with hyporheic exchange where $a_{12} = a_{21} = 0.0071$ (dashed line) and with hyporheic exchange where $a_{12} = a_{21} = 0.0769$ (dotted line).

The higher water velocities and the lower water depths that prevail in the unregulated river compared to the regulated river prevent an accumulation of fine sediment. In sections with high flow velocities, the northern rivers in Sweden are often armoured with boulders. It is therefore more likely that the sediment in the unregulated river consists more of boulders and stones than the sediment in the regulated river. This suggests that $\alpha = 0.0071$ applies best

as a rough approximation (see also section 4.1). However, these conclusions should be subject of further investigations in the future.

The total residence time of the solute in the unregulated river between Vietas and Boden, when the pulse is released at the above-mentioned time of the year, is in the order of a few hundred hours, i.e. much shorter than for the regulated case (Table 10-2).

Table 10-2. The times taken for different mass fractions in the river water to pass Boden and the relative spread of the breakthrough curve, when the river is unregulated and a short unit pulse is released at Vietas on day 0.

α	$t_{25\%}$ (h)	$t_{50\%}$ (h)	$t_{75\%}$ (h)	$\frac{t_{50\%,\alpha}}{t_{50\%,\alpha=0}}$	$RS(t) = \frac{t_{75\%,\alpha} - t_{25\%,\alpha}}{t_{50\%,\alpha}}$
0	154.0	158.2	162.5		0.05
0.0071	197.7	230.7	304.0	1.46	0.46
0.0769	241.3	263.6	290.5	1.67	0.19

Figure 10-10. Water residence time in the unregulated Lule River between Vietas and Porjus. The residence time differs depending on the time of the year when the particle is released.

Like the case with the regulated river, the hyporheic exchange will retard the solute pulse, and the expected value of the solute residence time distribution increases with increasing exchange intensity, α (Table 10-2).

The retardation is more pronounced in the unregulated case than in the regulated one. The reason for this is that a higher flow velocity and lower water depth promote an effective filtration of the water in the hyporheic zone.

Figure 10-11. (a) Retardation and (b) change in relative spread of a solute pulse at Boden, due to hyporheic exchange, for different times of release of the pulse at Vietas, into the unregulated Lule River.

In the unregulated river, too, the residence time in the river depends on the day of release, as the unregulated water flow varies considerably over the year (Fig. 10-3). During the investigated period, the water residence time for Stora Lulevattnet, i.e. the reach between Vietas and Porjus, varies approximately in the range 4-30 days (Fig. 10-10). Compared to the

regulated river, the water residence time in the unregulated river is shorter for the whole investigated period, but the relative variation in residence time is much higher. The reason for this is that in the unregulated river, there exist large seasonal variations that have been smoothed out by the regulation.

It is possible to see a slight variation with time of the quotient of the expected values of the residence times. Here, too, the effect is most pronounced for the higher exchange intensity (Fig. 10-11a). However, the lower exchange intensity provides a more spread-out curve than the higher exchange intensity (Fig. 10-11b). The reason for this is that both exchange intensities are higher than that corresponding to the maximum spread as discussed in section 4.1. (Fig. 10-13).

The sensitivity analysis of the unregulated case, provides a similar pattern as for the regulated case concerning both the retardation and the relative spread (Figs. 10-12 and 10-13). The corresponding λ -values in the unregulated case calculated with Eq. (10-4) from the α -values 0.0071 and 0.0769, where an average of the geometrical dimensions over time and space is used, are 2.66×10^{-4} and $2.88 \times 10^{-3} \text{ s}^{-1}$, respectively. From Fig. 10-12 we can see that the hyporheic exchange could have been described as an instantaneous exchange to get a correct description of the retardation.

Figure 10-12. The retardation of a solute pulse at Boden (when a short pulse is released at Vietas on day 0) into the unregulated Lule River versus the hyporheic exchange intensity, λ .

Figure 10-13. The change in relative spread of a solute pulse at Boden (when a short pulse is released at Vietas on day 0) into the unregulated Lule River, versus the hyporheic exchange intensity, λ .

5. COMPARISON OF HYPORHEIC EXCHANGE DURING REGULATED AND UNREGULATED CONDITIONS

The solute residence time in the Lule River for the investigated period is approximately more than 10 times as long for regulated than for unregulated conditions (provided the pulse is released at time zero in Fig. 10-3). This delay is due to the storage of water in the reservoirs for hydropower production. This difference in water residence time between the unregulated and regulated system will in turn influence any further effect of hyporheic exchange on the solute transport.

The value of the exchange intensity α is probably not the same for the regulated and unregulated conditions due to differences that probably exist in sedimentation characteristics, as mentioned before. The water velocities in the regulated case are lower, and an accumulation of more fine-graded sediment probably occurs. Comparison with the results obtained in the Säva Stream (Wörman et al., 2002) indicates that the higher exchange intensity, $\alpha=0.0769$, is probably more applicable in the regulated case, while the lower exchange intensity, $\alpha=0.0071$, might be more applicable in the unregulated case. However, the comparison between the regulated and the unregulated case in Fig. 10-14 is based on the same exchange intensity. Both the retardation and the relative spread due to hyporheic exchange are more

pronounced in the unregulated case for the investigated period. The relative spread of the breakthrough curve in particular is markedly affected by the hyporheic exchange. Hyporheic exchange is, thus, important for both the retardation and the spread of a solute pulse travelling in the river system. The hyporheic exchange will contribute to an increase of the residence time in the river system compared to the case where no hyporheic exchange is present. For reactive solutes, although not treated in the present study, the increase in residence time due to hyporheic exchange enhances the possibility for reactions to occur in the river, which is important for many biological and chemical transformation processes.

Figure 10-14. (a) Retardation and (b) change in relative spread of a solute pulse in the regulated and unregulated river for different times of release.

Changes in yearly, seasonal or daily variations of the run-off of solute elements into the river, will be levelled out partly due to the spreading induced by hyporheic exchange. Based on the spread of the solute pulse in the regulated river, defined as $t_{75\%}-t_{25\%}$, without hyporheic exchange (Table 10-1), we can see that variations with a higher frequency of ~ 10 days will be effectively smoothed out due to dispersion effects. When the hyporheic exchange is added, the same measure increases to ~ 21 or ~ 65 days for the intensities $\alpha = 0.0071$ and $\alpha = 0.0769$, respectively.

In the unregulated case, the results of the same measure is that only dispersion effects will smooth out variations with a higher frequency than ~ 9 h (Table 10-2). If we also add the effect of hyporheic exchange, variations with a higher frequency of ~ 4.5 or 2 days for the exchange intensities $\alpha = 0.0071$ and $\alpha = 0.0769$, respectively, will be smoothed out.

6. DISCUSSION AND CONCLUSIONS

This study is a first step in a research effort aiming at understanding the solute transport and retention processes in a larger river system influenced by hydropower regulation. A solute transport model is developed for a larger river and applied during both regulated and unregulated conditions in the Lule River, northern Sweden. The effect of hyporheic exchange on inert solute transport has been theoretically investigated by means of generalizing empirical exchange relationships that were developed for smaller streams and using hydraulic information i.e. observations of discharge, damming and run-off from the Lule River. Unregulated flow conditions were constructed from information on run-off and changes in the reservoir volumes.

Due to the hydropower regulation, the flow pattern in the Lule River has been altered, where the natural discharge variations over the seasons have been smoothed out. This has led to increased water depths and lower velocities, which have resulted in increased water residence times in the regulated river system. Generally speaking, the solute residence time from Vietas to Boden, i.e. the main part of the Big Lule River, has increased from a few hundred to a few thousand hours. This difference in water residence time will be important for the way in which the hyporheic uptake will further influence the solute transport. This is because changed water depths and water velocities alter the exchange rates regulating the hydrodynamic hyporheic uptake. It was also found that a water particle spends 80-90% of the total residence time in Stora Lulevattnet, a wider and deeper reach of the upper part of the Lule River between Vietas and Porjus that constitutes about one third of the total river length.

The hyporheic exchange gives a clear effect on the retardation and relative spread of an inert solute pulse in both the regulated and the unregulated river. During regulated conditions, hyporheic exchange prolonged the expected residence time of an inert solute pulse by ~10% or ~20-35% for the different approximations of the exchange intensity ($\alpha=0.0071$ and $\alpha=0.0769$, respectively). The corresponding values for the unregulated river were found to be ~40-70% or ~70-100%. Expressed in absolute numbers, the hyporheic exchange was found to prolong the expected value by up to as long as almost a month in the regulated case.

Hyporheic exchange also increased the relative spread defined in terms of $RS(t)=(t_{75\%,\alpha}-t_{25\%,\alpha})/t_{50\%,\alpha}$. For the lower exchange intensity ($\alpha=0.0071$) during regulated conditions, hyporheic exchange increased $RS(t)$ by a factor of ~1.5-2.5 compared to the case with no hyporheic exchange. For the higher exchange intensity ($\alpha=0.0769$), the increase in relative spread of the pulse varied over a larger interval depending on the time of release of the pulse. In this case, hyporheic exchange increased $RS(t)$ by a factor of ~1.5-5.5. During unregulated conditions, the relative spread increased by a factor of ~8-11 for the lower exchange intensity and by a factor of ~3-7 for the higher exchange intensity.

The increase in relative spread will result in a lowering of the peak concentration of a solute pulse in the river compared to where no hyporheic exchange is present. This effect was found especially pronounced in the unregulated river. The presence of hyporheic exchange can, thus, be important for lowering of the maximum concentration in the river water from a sudden pollution spill from anthropogenic activities or natural episodic transport events. As the exchange with the hyporheic zone promotes more uniform solute concentrations in the flowing phase, this counteracts acute contamination effects on biota and provides a more uniform distribution of nutrients.

Roughly, the hyporheic exchange in the unregulated river can smooth out temporal variations in the solute transport that last in the order of months. For the regulated river, the corresponding period is only about a week or so.

According to the developed model, the exchange intensity and filtering of the water in the hyporheic zone increases with hydraulic conductivity of the stream-bed (coarseness of bed material), flow velocity and decreasing water depth. The unregulated river has lower water depths and, thus, higher flow velocities than the regulated river. One can also assume that the coarse armour layer in the unregulated river is more permeable than the more fine-grained material that is more likely present in the regulated river. Consequently, all relevant factors for the hyporheic exchange change due to the regulation in a way that acts to decrease exchange with the hyporheic zone (estimated in terms of retardation of an inert solute pulse). Particularly,

the benthic biota can be affected by this and indirectly, the entire river ecosystem.

A sensitivity analysis revealed that the retardation increased with increasing intensity of the hyporheic exchange until a maximum is reached, after which any further increase in the exchange intensity did not result in any significant additional retardation. The relative spread first increased with increasing exchange intensity until a maximum was reached. After this maximum, a further increase in the exchange rate led to a decrease of the relative spread. This means that for a higher exchange intensity (rapid exchange), the effect of the retardation is at its maximum, while the effect of the relative spread is rather small.

To extend and validate the results obtained with the modelling framework developed in this study, future investigations should compare model results with observations from the actual river under consideration. In this way, it should be possible to investigate whether the predicted behaviour of the hyporheic exchange is consistent with observed concentrations in the river water. However, it is difficult to produce data of the proper type and with sufficient quality needed to identify effects resulting exactly from the hyporheic zone interaction. Therefore, we believe that this generic study is an essential first step in analyzing the effect of the hyporheic exchange on water quality issues.

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APPENDIX A: DISCRETIZATION OF SOLUTE MODEL EQUATIONS

c - concentration for m phases

j - node

k - time

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

$$\frac{1}{\left(\frac{A(j, k+1) + A(j, k)}{2} \right)} \left[\frac{\left[\left[AUC \right]_{j+1} - \left[AUC \right]_{j-1} \right]^{k+1} + \left[\left[AUC \right]_{j+1} - \left[AUC \right]_{j-1} \right]^k}{4\Delta x} \right] -$$

$$\frac{E}{2} \left(\frac{\left[c(j+1) - 2c(j) + c(j-1) \right]^{k+1}}{\Delta x^2} + \frac{\left[c(j+1) - 2c(j) + c(j-1) \right]^k}{\Delta x^2} \right) =$$

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

$$AU = D$$

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

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

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

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