A numerical study of surface-subsurface exchange processes at a riffle-pool pair in the Lahn River, Germany

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[1] Hyporheic exchange is an ecologically important process, controlling the nutrient supply in the upper sediments and thus benthic habitat quality. Hydraulic exchange at a riffle-pool sequence in the Lahn River, Germany, was analyzed using HEC-RAS to simulate the surface water flow as a boundary for the subsurface flow and MODFLOW, MODPATH, and MT3DMS to reproduce the transport in the subsurface. Solute transport and residence times of surface water in the subsurface were simulated after calibrating sediment properties to fit simulated hydraulic head to measured subsurface head from the riffle-pool pair. Three surface water flow rates were considered. Results indicated that exchange increases with increasing surface water flow. However, the hydraulic conductivity of the riverbed sediments influences the mass transfer more than the surface water flow. The ratio of the infiltration rate to the surface water flow is of the same order of magnitude for all the considered flow conditions. Residence times of surface water in the subsurface varied inversely with the flow rates in the river.


1. Introduction

[2] The flow of water across a riverbed into and out of the near-stream sediment, also called hyporheic exchange flow, plays an important role in many stream ecosystems as it transports nutrients and dissolved organic carbon into the hyporheic zone, where fauna and microbes transform them [e.g., Triska et al., 1993; Findlay, 1995; Borchart and Fischer, 1999; Hinkle et al., 2001]. However, as Kasahara and Wondzell [2003, paragraph 2] state, “quantifying the relative effect of hyporheic processes on stream ecosystems remains difficult because the measurement of the amount of hyporheic exchange flow and the residence time distribution of water in the hyporheic zone is not easy”.

[3] In general, the surface-subsurface head gradients drive the surface water into the subsurface under the riverbed and through shallow streamside aquifers. Small-scale morphologic elements, e.g., cobbles and small riffles, are very important in controlling the amount of vertically exchanged water at the Lahn River, Germany [Lenk, 2000; Saenger, 2000]. Studies of the habitat function of the hyporheic zone [Altmoos et al., 2005] show that the distribution of the fauna in the riverbed agrees with hydraulic experiments [Saenger and Zanke, 2005]: They both support the existence of an active exchange zone within the upper 20 cm of the sediment. The exchange decreases with depth; further down groundwater flow dominates. Hutchinson and Webster [1998] and Vollmer et al. [2005] report on the flow around an individual sphere that is half buried in a homogeneous riverbed in laboratory experiments and small-scale mathematical models. This sphere-induced flow in the subsurface is shallow.

[4] Furthermore, the field experiments at the Lahn River indicate that the present flow and the flow history in combination with clogging and declogging processes (due to the ingress of fines into the interstices and the growth of biomass on the sediment) control the hydraulic head and the flow rate in the sediments of the upper 10–20 cm of the riverbed [Saenger, 2002]. Flume experiments by Packman and MacKay [2003] show that fines, transported by the surface water, infiltrate into a riffle mainly at the upstream side of the riffle. Similar patterns are found in field investigations [Seydell and Saenger, 2002]. The infiltration of fines increases head losses in the upper sediment layers and reduces the infiltration of surface water into deeper layers. The surface-subsurface head gradients in the upper few decimeters of the riverbed sediment indicate that these upper sediment layers control the vertical exchange.

[5] Laboratory experiments and mathematical models were used to investigate the exchange at a sand bed with dunes [Elliott and Brooks, 1997a, 1997b] and to analyze the parameters that control colloid transport between a stream and a sand streambed with bed forms [Packman et al., 2000]. In a recent study, Salehin et al. [2004] investigated the effect of riverbed heterogeneity on the hyporheic exchange with flume experiments and a numerical groundwater flow model; they use a random field generator to construct correlated random hydraulic conductivity fields.

[6] Only a few numerical studies consider the influence of natural channel morphology and surface water elevations on the hyporheic flow. Kasahara and Wondzell [2003]...
analyze the extent of natural hyporheic zones, residence times, and gaining and losing stream reaches at the scale of a couple of hundred to fifteen hundred meters. They focus on the relative influence of channel and valley floor morphologic features on hyporheic zones in mountain streams of different sizes, considering lateral and vertical exchange. Wroblicky et al. [1998] investigate the magnitude, direction, and spatial distribution of lateral (horizontal) stream-groundwater exchange. Harvey and Bencala [1993] analyze the influence of the morphological structure of a meander on the lateral surface-subsurface exchange and the impact that groundwater has on the hyporheic flow. Storey et al. [2003] investigate the exchange at a riffle with a three-dimensional groundwater flow model and consider vertical and lateral exchange at a homogeneous, anisotropic riverbed. They show for their study site that the exchange flow is most sensitive to changes in head differences between the upstream and downstream end of the riffle, slightly less sensitive to changes in hydraulic conductivity, and least sensitive to changes in groundwater discharge. So far, no parametric study has analyzed numerically the effect of various flow and sediment properties on vertical exchange into and out of a natural hyporheic zone with heterogeneous sediments.

Our aim is to gain insight into the influence of surface water flow rates and sediment properties on transport processes in the hyporheic zone of a riffle-pool pair. We are interested in the vertical transport due to surface water head on the riverbed. Therefore we limit our attention to vertical and longitudinal transport processes, taking a one-dimensional (surface water) and two-dimensional (groundwater) approach. We use numerical surface water and groundwater models and focus on a field study conducted at a pool-riffle sequence in the Lahn River, Germany, from 1997 to 2000 [Lenk, 2000; Saenger and Lenk, 1999; Saenger, 2000]. For a longitudinal profile of the riverbed with a length of 90 m and a depth of 2 m we utilize parameters that are consistent with measured data. The steady state surface water flow is analyzed with HEC-RAS [U.S. Army Corps of Engineers, 1995]. The surface water elevations are then imported into the groundwater flow model as head boundary conditions along the riverbed. MODFLOW [McDonald and Harbaugh, 1996], MODPATH [Pollock, 1994], and MT3DMS [Zheng and Wang, 1999] are used to analyze the influence of sediment properties on the hyporheic flow, as well as the residence time distribution in the hyporheic zone for different flow situations.

In this study we define the hyporheic exchange flow to be the flow across the riverbed per unit area $[L^3/(T \cdot L^2)] = L/T$, with $L =$ length and $T =$ time with infiltration of surface water into the subsurface taken as positive and exfiltration out of the riverbed into the surface water taken as negative values. The hyporheic exchange fraction [%] is the percentage of surface water flow that infiltrates into the riverbed. The residence time $[T]$ is the time a particle that is injected in the upper boundary of the riverbed resides in the subsurface before it enters the surface water again.

2. Study Site

The study site is located at the Lahn River in the center of Germany and is a right bank tributary of the middle part of the River Rhine. The Lahn has a total length of 245 km. The research reach is situated near Marburg, about 53 km from the Lahn source, with a drainage area of 453 km²; here, the Lahn River is a fifth-order stream. The hydrological yearbook appoints the mean flow to be 7.3 m³/s; the base flow is 0.567 m³/s [Landesumweltamt Nordrhein-Westfalen, 1993]. The Upper Lahn has a mean slope gradient of 0.00236. The study site is about 450 m long and includes two pool-riffle pairs with an inlet from a sewage treatment plant between the two pairs. At the study site, the Lahn has a natural gravel bed with an armoring layer consisting of ellipsoidal pebbles and cobbles. Here, we focus on the upstream riffle, a 90 m long reach.

3. Methods

3.1. Field Measurements

Multilevel samplers were deployed in the riverbed to measure hydraulic head in the subsurface [Boulton, 1993] and to extract pore water [Lenk et al., 1999]. Fluorescein was injected at a constant rate over several hours into the river water about 1100 m upstream from the study site. Tracer-laced samples were taken in the surface water and also in the subsurface water at certain depths via the multilevel samplers. Overall 50 samplers were installed in seven cross sections. Short samplers had extraction levels at depths of 5, 15, 25 and 45 cm, longer samplers extracted at 55, 65, 75 and 95 cm below the river bottom. Methods and field measurements can be found in detail elsewhere [see, e.g., Lenk et al., 1999; Saenger and Lenk, 1999; Saenger and Zanke, 2005]. Here, we describe only the essentials required for the understanding of the present numerical study of the flow through the riffle and pool. We consider data from the three cross sections at the upstream riffle (transects I, II, and III), where short and long samplers were installed in the middle of the riverbed, one meter apart from each other, and a short sampler was deployed at each side of the riverbed (see Figure 1). Hydraulic heads were measured at the samplers in the middle of the stream (samplers I2, II3, and III2). For calibration purposes of the surface water model we also integrate a further downstream measuring point at the end of the 210 m reach. In this study we consider measurements for three different flows, $Q = 470 L/s$, $Q = 2820 L/s$, and $Q = 5460 L/s$, which we characterize as low flow after a long period of low flow in August 1997 ($Q = 470 L/s$), medium flow after floods in May 1998 ($Q = 2820 L/s$), and high flow in September 1998 ($Q = 5460 L/s$) (see Table 1).

Tracer experiments were carried out only at low and medium flow; at high flow the installation of the tracer extraction and head measurement equipment was not possible. Tracer was injected for three hours into the river water. Samples were taken in the surface water above the samplers and in the subsurface via the samplers. We sampled all ports in the three cross sections (samplers I1, I2, I3, II2, II3, III1, III2, and III3; see Figure 1) every 30 minutes for the first 5 h of the experiments and then at longer intervals. The riverbed topography was surveyed in cross profiles about every 4 m in the summer of 1997, and its contour map is shown in Figure 1. Frozen cores [Bretschko and Klemens, 1986] with a length of 1 m were withdrawn after the winter floods 1998 to gain an insight.
into the riverbed sediments. Surface water gauges and groundwater pressure gauges were also deployed. As the numerical simulations focus on the vertical section of the riverbed along the longitudinal axis that runs through the center of the river, we utilize in the numerical models information about: the hydraulic heads in the surface and subsurface water; the tracer concentrations in the surface and subsurface water; the riverbed topography; and the frozen cores.

### 3.2. Model Simulations

To simulate surface water profiles, HEC-RAS [U.S. Army Corps of Engineers, 1995], a one-dimensional model for computing surface water profiles for steady state, spatially gradually varied flow, is applied for a 210 m long riffle reach that incorporates the 90 m long reach analyzed with the groundwater flow model. The program requires topography, flow, and roughness data. We added computational nodes between the measured cross sections, such that the nodes have a spacing of 0.1 m in the flow direction. Then we imported the longitudinal profile of the topography in the middle of the stream as the upper boundary (riverbed) into MODFLOW, interpolating between measured cross sections as necessary to provide values at all nodes. The three flow conditions shown in Table 1 are analyzed here. HEC-RAS requires values for Manning’s roughness coefficient, $n$, of the riverbed. The roughness coefficient is calibrated so that the surface water elevations measured above the multilevel samplers match the simulated surface water elevations (see Figure 2).

The Root mean square error (RMSE) is used to compare the calculated to the measured heads in the surface water and in the subsurface. The RMSE is defined as

$$RMSE = \sqrt{\frac{1}{m} \sum (y_i - \hat{y}_i)^2}$$

with $m$ = number of observations, $y_i$ = simulated values, and $\hat{y}_i$ = observed values. The closer RMSE is to zero, the better the model reproduces the observed data.

The groundwater flow model MODFLOW [McDonald and Harbough, 1996], using the interface Groundwater Vistas by Environmental Simulations, Inc. [2003], is utilized to calculate the two dimensional flow in the porous medium, the riverbed, as influenced by topography, surface water flow and sediment properties. The groundwater model domain represents a vertical cross section along the longitudinal axis of the river with a length of 90 m and a height of 2 m. Given that our aim is to analyze the exchange of surface water with the subsurface within the first few decimeters of the riverbed, we construct a multilayer block center finite difference grid with a cell length of 0.1 m and a height of 0.02 m to achieve resolution at the scale of the samplers. With this scale we do not capture small-scale dynamic effects, e.g., temporal and spatial pressure variations associated with turbulence in the wake of cobbles protruding into the surface water. To include such small-scale effects is beyond the scope of this work and would require simulations of both the surface and subsurface flows at much finer scales than the one resolved in this study. At the upper boundary (river bottom), the imposed conditions are the head values imported from the surface water model. Head values equal to the corresponding surface water elevations are used at the upstream and downstream boundaries (see Figure 3). At a sediment depth of 2 m we assume a no-flow boundary. Given that this is a fully saturated, steady flow of incompressible fluid, the net flow through the boundaries is zero.

We specify sediment properties consistent with field measurements. Sieve analysis of each of the three frozen cores taken in the three cross sections gave mean hydraulic conductivities of about $3 \times 10^{-2}$ m/s [Saenger, 2000].

![Figure 1. Contour map of the River Lahn riffle upstream of the sewage treatment plant. I, II, and III, multilevel samplers; SW, surface water gauge; GW, groundwater gauge.](image-url)

### Table 1. Characteristics of Study Site

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Stream flow, L/s</td>
<td>470</td>
<td>2820</td>
</tr>
<tr>
<td>Reach length, m</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Channel gradient, m/m</td>
<td>0.0041</td>
<td>0.0041</td>
</tr>
<tr>
<td>Surface water gradient, m/m</td>
<td>0.0046</td>
<td>0.0039</td>
</tr>
<tr>
<td>Mean cross-sectional area A, m²</td>
<td>3.17</td>
<td>6.90</td>
</tr>
<tr>
<td>Wetted top width, m</td>
<td>16.01</td>
<td>18.44</td>
</tr>
<tr>
<td>Mean velocity, m/s</td>
<td>0.23</td>
<td>0.51</td>
</tr>
<tr>
<td>Mean surface water elevation, m</td>
<td>0.09</td>
<td>0.25</td>
</tr>
</tbody>
</table>
used this data in three ways. First, for illustration of basic properties, we consider homogeneous, isotropic and also anisotropic sediment with a hydraulic conductivity of $3 \times 10^{-3}$ m/s and an effective porosity of 0.2. Then, we calibrated two models to reproduce the measured heads in the subsurface. In the first calibrated model, we divided the model domain into seven zones with different sediment properties. Although the hydraulic heads were reproduced well, the exchange pattern appeared unrealistic with abrupt variations where sediment properties changed. Therefore the division into multiple zones was deemed unsuccessful and not considered further. The second calibration applies a certain conductivity to each cell of the upper 0.16 m of the riverbed in order to represent the change of sediment properties over the riffle, for example due to the infiltration of fines. With this approach we achieve a smooth change in conductivity in the sediment properties of the riffle. Figure 4 (top) displays the calibrated values of the different flows; sediment deeper than 0.16 m has a hydraulic conductivity of $3 \times 10^{-3}$ m/s. Porosity varies with surface water flow conditions for reasons discussed in section 4.2.2 but is kept constant over the domain of the groundwater flow model.

4. Results

4.1. Surface Water Elevations

[16] The surface water profile fluctuates when we use the measured topographical data in HEC-RAS as the slope changes at the measured cross sections. We used the running mean of five measured cross sections (this means a window size of 20 m), gained a smoother transition of riverbed slopes, and consequently a smoother surface water profile. Manning’s roughness coefficient, $n$, is calibrated in such a manner that the calculated surface water elevations agree with the measured surface water elevations at the three samplers I2, II3 and III3. Manning’s $n$ varies between 0.02 and 0.05 in the longitudinal and lateral directions on the riverbed; the roughness of the riverbed in the area of the pool downstream of transect II at the left shore of the river is defined by the higher values depending on flow conditions. As Figure 2 shows, the measured and the calculated surface water elevation for all considered flows agree at the first and third cross profiles. A maximum deviation of 0.05 m had to be accepted at the second transect for the medium-flow condition. The Root Mean square Error for the simulated surface water elevations at transect I, II and III compared to the measured elevations at the transects is low, with 0.013 m for August 1997, 0.027 m for May 1998, and 0.01 m for September 1998.

4.2. Subsurface Flow

4.2.1. Basic Conditions

[17] Groundwater Vistas enables stepwise and, when the change of the topography is small enough, terrain-following grids [Environmental Simulations, Inc., 2003]. Grid building and topography impact the infiltration and exfiltration into and out of the porous medium, the sediment layer underneath the riverbed. We analyzed the effect for a model domain with homogeneous, isotropic sediment. The stair step grid of our riffle shows more exchange flow over the model domain than the terrain-following grid. The exchange patterns for the stair step grid reflect the stairs rather than the topography. In contrast, the infiltration and exfiltration on the terrain-following grid depend on the topography and do not leave the domain as they do on the stair step grid. Therefore we prefer the terrain-following grid.

Figure 2. Calibrated and observed surface water elevations for different flow conditions.

Figure 3. Schematic of domain and boundary conditions.
For two different model domains each with a terrain-following grid, we analyze the impact that the topography has on the exchange at a homogeneous, isotropic riverbed. For one domain the upper boundary follows the measured topography. For the other domain the topography was smoothed by taking the running means of five values of the measured topography (the same approach we chose to calculate the surface water profiles) and used at the upper boundary, the riverbed. Infiltration and exfiltration at the riverbed are always higher for the smooth longitudinal profile than for the measured longitudinal profile; however, the difference is small, being between 0.8 and 1.9% for the different surface water flows and the whole riffle. The breakthrough patterns adjust to the different topographies but do not really change in character. We adopted the measured profile for the groundwater flow simulations.

We also investigated the influence of the bottom boundary on the exchange at the riverbed. One model had an even bottom elevation at 189.5 m (the riverbed elevation varies between 191 and 191.5 m), the other model’s bottom boundary follows the same slope as the topography of the riverbed. In this latter case, the subsurface model domain is a constant 2 m deep. For low-flow conditions, the bottom boundary has little influence on the exchange (10% more infiltration with the constant 2 m deep model domain). However for medium and high flow, there is respectively 28% and 60% more infiltration with the constant 2 m deep model domain than with the model with the flat bottom boundary. Less exfiltration occurs at low flow (34% less) with the 2 m thick domain than with the domain with the flat bottom boundary; with medium and high flow more exfiltration (respectively 10% and 34%) occurs. We adopted the bottom boundary that follows the slope of the riverbed.

4.2.2. Sensitivity Analysis and Calibration of Sediment Properties

Natural riverbed sediments exhibit spatial and temporal variability. To include this variability in the numerical models, we vary hydraulic conductivity, porosity and anisotropy when simulating the measured hydraulic heads and tracer breakthrough curves in the hyporheic zone for different surface water flows. As stated by Freeze and Cherry [1979] and Huggenberger et al. [1998], the anisotropy ratio of horizontal to vertical conductivity in fluvial sediments may be on the order of \(10^3\) and \(10^4\). We did not measure anisotropy ratios in our field studies. The calibration of the sediment properties according to measured head values and breakthrough curves in the subsurface indicates that a value of ten may be appropriate for our study site. Solute transport in the subsurface is dominated by advection, and thus dispersion and diffusion are not considered here.

We interpolated the hydraulic conductivities for each cell using the error function, such that the transition occurs smoothly over a distance of about 10 m. The conductivities for each cell in the upper eight layers of the sediment are shown in Figure 4 (top). The conductivity of the sediments deeper than 0.16 m is set to \(3 \times 10^{-3}\) m/s. Figure 4 (top) also shows that conductivities are lower at low surface water flow than at higher flows. As the measurement at low flow in August 1997 is conducted after a long period of low flow it is reasonable to assume that during the long low-flow period fines intruded into the subsurface (abiotic clogging). Furthermore algal and microbial growth may also have had an influence on the permeability of the riverbed within the upper sediment layers (biotic clogging). The measurement at medium flow in May 1998 is conducted after floods; a plausible explanation of the higher
conductivities is that fines which previously had clogged the interstices resuspended from the sediment matrix with higher surface water flows. The highest conductivities are determined for high flow. Figure 4 (bottom) shows that overall, the observed hydraulic heads are reproduced by the calculated heads. For the measurement at low flow in August 1997, the mean RMSE for transects I, II, and III are 0.015, 0.023, and 0.015 m, respectively, for the experiment at medium flow in May 1998 they are 0.022, 0.061, and 0.032 m, and for high flow in September 1998 the RMSE are 0.015, 0.027, and 0.033 m. Two discrepancies occur at medium flow and lead to the higher RMSE at transects II and III: (1) At transect II, the simulated values in the subsurface are offset from the measured values, because the calibrated surface water elevation is higher than the measured elevation. The result is a RMSE = 0.061 m at this sampler. (2) The value for the hydraulic head at transect III at 0.45 m depth differs from the values at 0.25 m and 0.55 m depths (RMSE = 0.032 m). As other field experiments give no evidence for a sediment layer with different permeabilities, we conclude that this measurement is wrong.

We simulate the tracer experiments conducted at low (Q = 470 L/s) and medium flow (Q = 2820 L/s) with the package MT3DMS [Zheng and Wang, 1999]. The measured concentrations in the stream are imported as a conservative tracer to the upper boundary of the model which represents the stream. The three measured breakthrough curves in the surface water are similar, so that we used the average of the three surface water curves as the boundary condition to each cell. Parameters that were varied to reach good agreement between the simulated and the measured concentrations in the subsurface are effective porosity and anisotropy; the hydraulic conductivity was calibrated by fitting the simulated to the measured hydraulic head, as previously described. Adjusting the anisotropy had only a small effect on the distribution of the simulated hydraulic head in the subsurface. The degree of anisotropy is considered uniform over the model domain. As noted above, our calibrations suggest an anisotropy ratio of ten for all flow conditions. For low flow the effective porosity was calibrated as 0.04 in the upper 16 cm of the riverbed sediment and 0.1 in the deeper sediments and for medium flow, an effective porosity of 0.1 reproduced the breakthrough curves. As the calibrated conductivities are also higher at higher flow we set the effective porosity for higher flow to be 0.1 as well. Having a low porosity at high flows is also suggested by field experiments conducted after floods at the same study site [Seydell et al., 2005]; Seydell et al. estimate effective porosities from frozen cores with computer tomography to range from 0.1 to 0.16. Figures 5 and 6 show a comparison of the measured and the calculated concentration, normalized by the maximum concentration measured in each experiment. Figures 5 and 6 show the measured concentrations for the three samplers in the transects in comparison to the simulated concentration in the middle of the river. At low flow the concentrations measured at the 5 cm depth are simulated very well. The curves at transect I and II at 25 and 45 cm depth show long tailing, with considerable tracer concentrations at...
late time. At medium flow the measurements in transect I are reproduced well. The RMSE are displayed for each sampler in Figures 5 and 6; mean values for the transects are 0.14 (transect I), 0.15 (transect II), and 0.14 (transect III) for low flow in August 1997, and for medium flow in May 1998 the RMSE are 0.09 (transect I), 0.14 (transect II), and 0.07 (transect III). Some of the measured breakthrough curves show high concentrations, where a low concentration is simulated with the numerical model (see medium flow, transect III); reasons for this may be that we did not capture the three dimensionality of the flow processes in this study, and also that the model simplifies the complex heterogeneity of the riverbed sediments.

[23] Given the calibrated sediment parameters for low and medium flow, the hyporheic exchange flow is distributed along the riffle as shown in Figure 7. The results show that the exchange pattern moves upstream with increasing flow and that one distinct infiltration and one distinct exfiltration zone occur. As displayed in Table 2, the (bold) value for infiltration at the riverbed at low flow is about twice the value for exfiltration. With increasing flow, this pattern changes to more flow in through the upstream model boundary, less infiltration at the riverbed, and more exfiltration at the riverbed than flow out of the downstream model boundary.

[24] We calculate the amount of infiltrating surface water into the subsurface. As our groundwater model domain represents only the 1 m wide middle part of the riverbed, the surface water flow over the model domain is calculated with the continuity equation as the product of the mean velocity, the mean water depth, and the width (1 m). The infiltration rate is the ratio of the infiltrating surface water at

Figure 6. Calculated concentration used in simulation (lines), observed mean through flow curves in the surface water (diamonds), and observed (sampler at left shore (pluses), sampler in middle of riverbed (stars), and sampler at right shore (crosses)) through flow curves at medium flow with calibrated sediment. RMSE is calculated for the mean observed concentration and the calculated concentration. See Figure 1 for location of transects and samplers.

Figure 7. Hyporheic exchange along the river reach. Positive values indicate infiltration into the riverbed, and negative values indicate exfiltration of subsurface water in the surface water.
the upper 90 m long boundary (riverbed) and the surface water flow over the 1 m wide model domain. The infiltration rates are 0.14% (for low flow), 0.08% (for medium flow) and 0.14% (for high flow), as displayed in Table 2. The infiltration rates are all of the same order of magnitude. However, the infiltration rates at low and high surface water flow are almost twice the infiltration rate at medium flow. Taking these rates for calculating the infiltration for a 100 m long river reach with flows of 470, 2820, and 5460 L/s respectively, we estimate that about 65 L/s of the surface water would flow through the hyporheic zone at low flow; for the medium surface water flow about 220 L/s of the surface water would infiltrate. At the high flow, about 750 L/s of the surface water flow infiltrates over a 100 m long river reach.

Table 2. Sensitivity Analysis for Low, Medium, and High Flow Over the Different Sediments*

<table>
<thead>
<tr>
<th>Surface Water Flow</th>
<th>Infiltration at Upper Boundary, L/s</th>
<th>Exfiltration at Upper Boundary, L/s</th>
<th>Ratio of Infiltration to Streamflow Over the Upper Boundary, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 1997</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>0.0256</td>
<td>−0.0125</td>
<td>0.1424</td>
</tr>
<tr>
<td>Medium</td>
<td>0.0008</td>
<td>−0.0496</td>
<td>0.0006</td>
</tr>
<tr>
<td>High</td>
<td>0.0005</td>
<td>−0.0463</td>
<td>0.0002</td>
</tr>
<tr>
<td>May 1998</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>0.4127</td>
<td>−0.4932</td>
<td>2.2927</td>
</tr>
<tr>
<td>Medium</td>
<td>0.0948</td>
<td>−0.3656</td>
<td>0.0790</td>
</tr>
<tr>
<td>High</td>
<td>0.0613</td>
<td>−0.3266</td>
<td>0.0267</td>
</tr>
<tr>
<td>September 1998</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>0.6308</td>
<td>−0.6112</td>
<td>3.5044</td>
</tr>
<tr>
<td>Medium</td>
<td>0.4148</td>
<td>−0.5617</td>
<td>0.3456</td>
</tr>
<tr>
<td>High</td>
<td>0.3179</td>
<td>−0.4940</td>
<td>0.1382</td>
</tr>
</tbody>
</table>

*The bold values in each case correspond to the actual field conditions at the given time; other values indicate what would happen if different flows occurred for that sediment condition.

Figure 8. Normalized flux-weighted residence time for low, medium, and high flow.

In order to analyze the influence of the surface water flow and the sediment properties on the surface-subsurface exchange processes, we analyzed all available combinations of flow and sediment properties. Only the calibrated simulations (that means for example, low flow and sediment properties for low flow) reflect the measured hydraulic heads in the subsurface; these are indicated by the bold values in Table 2. The calibrated cases show that the exchange increases with increasing flow. Utilizing the sediment properties for low-flow conditions and together with medium and high surface water flows results in less exchange than for the calibrated case (see Table 2). In comparison to the calibrated cases, the combination of sediment properties for medium flow conditions with low and high surface water flow show more exchange with low flow and less exchange with high surface water flow. Sediment properties calibrated for high-flow conditions combined with low surface water flow results in much more infiltration than the calibrated case. The calculation of medium surface water flow over sediment calibrated for high flow indicates also more infiltration than the calibrated flow. Thus the available combinations of flow and sediment properties show that exchange decreases with increasing flow for surface water flow over sediment properties not related to a specific surface water flow. The calibrated cases however indicate that the exchange increases with increasing flow. This shows that at our study site the sediment properties are more important for controlling the exchange flow than the surface water flow.

Also we examined the influence that the location of the samplers have on the breakthrough curves in the subsurface. For that purpose we simulated the tracer breakthrough at virtual samplers within one meter upstream and downstream of the field samplers. The simulated breakthrough curves show up to 25% less tracer at locations 0.5 and 1.0 m upstream of sampler II for low flow; for medium flow, simulations show about 10% more tracer in the upper sediments. With these concentration variations of about ±20% in mind, the simulated curves resemble the measured curves at the samplers well.

Residence time of surface water in the hyporheic zone is estimated with MODPATH [Pollock, 1994]. One particle is injected into each cell in the upper layer of the model domain. Figure 8 shows the flux-weighted residence time (i.e., the infiltrated surface water per cell times the residence time in the subsurface of the particle injected into the same cell divided by the overall sum of the flux times the residence times) as a function of residence time for low, medium, and high surface water flows. Figure 8 shows that although long residence times of surface water occur in the subsurface, the most surface water is transported in the subsurface with short residence times, e.g., for low surface water flow, 40% of the infiltrated surface water stays about
3 h, 80% is transported less than 11 h in the subsurface. Only a small quantity of surface water shows long residence times in the subsurface. This reflects that most of the exchange occurs where the sediment shows higher hydraulic conductivities, at the peak of the riffle (see Figures 4 and 7).

5. Discussion

[28] Only a few numerical studies have dealt with the estimation of hyporheic exchange processes at natural riverbeds with numerical groundwater models [Harvey and Bencala, 1993; Wondzell and Swanson, 1996; Wroblicky et al., 1998; Kasahara and Wondzell, 2003; Storey et al., 2003]. Wroblicky et al. [1998] focused on the horizontal, lateral exchange with a one-layer model with cell dimensions of 0.5 m. Kasahara and Wondzell [2003] chose a grid with dimensions of 0.3 or 0.5 m and five layers to investigate lateral and vertical exchange flow. In a three-dimensional groundwater flow model, Storey et al. [2003] utilized a 1.0 m x 1.0 m grid to study the flow through a riffle. In our study we focus on the vertical exchange with grid dimensions of length 0.1 m and height 0.02 m. The comparably small height was needed to reflect the measuring depths of the piezometers used in the field studies.

[29] The advantages and disadvantages of applying a groundwater model to estimate hyporheic exchange flow have been discussed by Kasahara and Wondzell [2003]. We emphasize here only some characteristics that we encountered during our study. We use field data from three cross sections in the riverbed of the Lahn River, Germany (with a distance between them of about 25 m), each equipped with several samplers; data were measured in the surface water and at different depths of the subsurface for three flow rates. This resolution is better than at most field studies, but numerical groundwater models require boundary conditions and sediment parameters with a much higher resolution. So, interpolation is needed to distribute the parameters in between the measurement points, and there may exist more than one distribution that is consistent with the measured heads and tracer curves. That is, the estimates are likely not unique. Furthermore, we reduced the dimensions of the transport processes. Over the course of a riffle, our focus was on the vertical exchange processes between surface and subsurface water that are mainly driven by the surface water flow. So, we assumed that it was appropriate to simplify the processes and run a one-dimensional model to define the surface water elevations as input values for the two-dimensional groundwater flow model of the vertical cross section along the longitudinal axis of the riverbed.

[30] In this study, steady state flow conditions have been simulated for a case study of the reach of the Lahn River. However, our methodology is general and can be applied to different sites. Also, since changes in surface water flow impact the exchange flow, unsteady flow conditions could be investigated, as hydrologic streamflow and groundwater models can capture unsteady flow.

[31] The hydraulic head at the river bottom forms one of the most important boundary conditions for the subsurface flow. For the low and the high flow, our one-dimensional approach to calculate the surface water elevations reproduces the measured values very well. For medium flow a deviation of 5 cm (i.e., an increase in water depth from 14 cm (measured) to 19 cm (calculated)) had to be accepted at the riffle peak. Considering that (1) the measurements were taken in a natural river with a gravel bed, (2) each measurement is a one time, one point measurement (see discussion above), (3) the surface water elevation was calculated only one-dimensionally with HEC-RAS, and (4) the variation of the estimated overall roughness of the riverbed is incorporated in the calculation of the surface water elevations, the agreement is satisfactory. Using a surface water flow model, we calculate the hydraulic head for each cell of the upper layer of the groundwater flow model. The hydraulic head is then imported into the groundwater flow model as the fixed-head boundary at the riverbed. As HEC-RAS uses impermeable riverbeds to calculate surface water flow, flux into and out of the riverbed sediments are not accounted for in the water column. However, our simulations show that the percentages of surface water that infiltrate into the subsurface are very low and therefore we believe that the effect may be neglected. In comparison to previous approaches, our approach provides a physically based and more detailed distribution of the hydraulic heads at the riverbed. However, individual cobbles protruding into the surface water and/or turbulence are not included in the surface water flow simulation as these processes occur on a finer spatial and temporal scale than the ones considered in this study. Also, the surface water model does not capture flux into and out of the riverbed due to the acceleration of streamflow over bed forms and separation of the flow at the crest, known as "pumping" [Elliott and Brooks, 1997a, 1997b]. The groundwater flow model reflects the variation in riverbed topography and roughness only through the imported hydraulic head, which results from the HEC-RAS simulation which implicitly incorporates measures of roughness and turbulence via the calibration of Manning’s n used to match the measured heads.

[32] Our simulations of the hyporheic exchange at the Lahn River show different distributions at different flows: For low flow the infiltration focuses around the crest and at the downstream side of the riffle; the infiltration moves to the upstream part of the riffle with increased flow. For medium and high flow more exfiltration of subsurface water into the stream occurs than infiltration of surface water into the streambed, i.e., there is a net flow from the subsurface into the river. For low flow we see about twice the amount of infiltrating surface water as exfiltrating subsurface water and the values are much smaller than for higher flows. However, our models represent only a midstream longitudinal cross section of one riffle-pool pair and we also consider only a small river reach. Models considering the lateral exchange between rivers and the groundwater aquifer, e.g., the one developed by Wroblicky et al. [1998], show an exchange pattern with exfiltration of subsurface water into surface water at low flow and infiltration of surface water into the riverbed at higher surface water flow.

[33] For the three flow rates the calibrated models show a smooth transition from small to higher conductivity values (see Figure 4, top) over the course of the riffle and with this realistic exchange rates. The smooth transition of hydraulic conductivities leads to one distinct infiltration and one distinct exfiltration zone over the course of the riffle for the three flows (Figure 7).
[34] We believe that the higher permeability of the calibrated sediment at medium and high flow is a consequence of the release of fines out of the sediment matrix; fines get deposited in the subsurface by infiltrating flow during low flow periods. With the higher permeability of the upper sediment layers, more surface water infiltrates into the subsurface. Conductivity changes at different locations for the three flows. For low flow the change is situated near the riffle crest, but for high flow it is upstream of the riffle crest. The locations where conductivity changes correspond to the locations where significant infiltration starts. Therefore we conclude that the point where the transport changes from infiltration to exfiltration depends more on the surface water flow and the riverbed topography than on the sediment properties.

[35] In flume experiments, Packman and MacKay [2003] show that clay plugs the streambed starting at the stream-subsurface interface and, in particular, that this phenomenon happens at regions of high infiltration. At riffles, infiltration occurs mostly upstream of riffle peaks. Our calibrated models show infiltration of surface water into the subsurface and smaller conductivities at the upstream part of the riffle than at the downstream part of the riffle, where exfiltration of pore water into the surface water occurs. These calibrated smaller conductivities upstream of the riffle peak may reflect the clogging process at the stream-subsurface interface [Packman and MacKay, 2003].

[36] For heterogeneous sediment that reproduces the hydraulic heads in the subsurface, the exchange increases from isotropic to anisotropic sediment. For low flow the exchange almost doubles with anisotropic sediment (the ratio of mass transfer with isotropic sediment to mass transfer with anisotropic sediment is about 1.9), for medium flow the mass transfer ratio is about 1.7, and at high flow, anisotropy decreases exchange (the mass transfer ratio is 0.83). According to this, the influence of anisotropy on the exchange depends on the distribution of hydraulic conductivities. Interestingly, the anisotropy of the calibrated sediment puts the exchange fraction (this is the percentage of surface water flow that infiltrates into the riverbed) on par for medium and high flow. Although the exchange fraction is higher at low surface water flows (see Table 2), the ratios are of the same order of magnitude for all flows. Again, we see the changing pattern when anisotropy is involved; more exfiltration out of the riverbed occurs than infiltration into the riverbed due to an enhanced inflow at the upstream model boundary. The infiltration percentages from the Lahn River can be compared to the findings of Kasahara and Wondzell [2003] for their study of a reach of Middle Lookout Creek, which is also a fifth-order stream, with a surface water flow of 720 L/s. However, the percentages of infiltrating surface water into the subsurface are about one order of magnitude smaller at our study site. The differences appear to occur due to more densely packed sediment at our study site than at the sites Kasahara and Wondzell [2003] analyzed. In addition, in our 90 m long reach the riverbed had a smaller slope gradient (0.004 m/m) than at the step-pool sequences under investigation by Kasahara and Wondzell [2003] with channel gradients of 0.01–0.13 m/m.

[37] Figure 8 shows that most exchange occurs at shorter residence times. Short residence times with significant mass transfer appear especially at low and medium flow. This phenomenon is consistent with an upper sediment layer that is biogeochemically highly active; these transformations need a supply of fresh surface water. Flume experiments show that the influence of small-scale features, such as cobbles, may be larger than expected [Vollmer et al., 2005]. At higher flow these obstacles may be less significant in determining mass exchange than at low flow, as residence times are longer.

[38] At our study site, the head difference is almost the same between medium and high flow (see Table 1), low surface water flow results in a larger head difference. According to Storey et al. [2003], who conducted an intense parameter study, the most sensitive factor for the exchange flux is the change in head difference from the upstream to the downstream end of the riffle. This supports our results. However, it does not explain the difference in exchange flow with medium and high surface water flow. Our sensitivity analysis shows that the surface-subsurface exchange is sensitive to changes in the sediment properties. Therefore we assume that for our study site, the hydraulic conductivity is the controlling factor of the exchange flow.

[39] Finally, we consider the ecological relevance of these findings. Findlay [1995] indicates the significance of the hyporheic zone for the ecosystem’s budget by correlating the biogeochemical processes with the proportion of the surface water flow that infiltrates into the hyporheic zone. The higher the surface water infiltration rate, the greater the potential for the hyporheic zone to influence stream biogeochemical budgets. Laboratory experiments by Ingendahl et al. [2002] indicate that respiration increases up to 30% and nitrogen production increases up to 60% when the flow in the sediment core taken from the same study site at the Lahn triples. Our parameter study shows that the exchange fraction is higher for anisotropic than for isotropic heterogeneous sediment. Comparing the infiltration fraction for calibrated sediment for the three flows, their values are about the same. Ibisch et al. [2005] demonstrates in field investigations at the same riffle-pool sequence at the Lahn River that the growth of periphyton (which is a complex matrix of algae and heterotrophic microbes attached to submerged substrata in almost all aquatic ecosystems) is correlated with the decrease of infiltration velocities. In the context of our numerical study, this indicates that the low conductivities we calibrated for low flow may be not only dependent on the infiltration of fines due to a long low-flow period, but also on biological processes, here the growth of periphyton.

6. Conclusions

[40] Hyporheic exchange processes at the investigated riffle-pool pair at the Lahn, Germany, are controlled by surface water flow and even more by sediment properties of the riverbed. Numerical models are capable of simulating the hyporheic exchange processes and the controlling parameters and processes can be analyzed. Numerical models are constructed to represent realistic conditions measured at the Lahn River. The sediment parameters are calibrated to fit measured hydraulic heads and tracer breakthrough curves. To reproduce spatial and temporal changes in fluvial sediment properties we determine sediment parameters for three different surface water flow rates and
distribute them smoothly over the longitudinal profile of the river reach. The results show that although the surface water flow plays an important role for the hyporheic exchange at the study site, the influence of the sediment properties on the hydraulic exchange is larger. The percentage of surface water that enters the hyporheic zone for the calibrated sediment is lower for medium surface water flow and has about the same value for low and high flows. Densely packed sediment reduces the absolute exchange. Anisotropy increases the hyporheic exchange for low and medium surface water flow and has the opposite effect for high flow. Small-scale exchange has an impact on the exchange for low flow, but the influence decreases with increasing surface water flow. Although our approach analyzes hyporheic exchange with a higher vertical resolution than previous studies, it was beyond our scope to include small-scale exchange due to cobbles protruding into the surface water. However our study indicates that these cobbles may have an impact on the hyporheic exchange especially at low surface water flow.

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