Riverbed groundwater interaction – comparison of several methods of groundwater recharge assessment

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Zusammenwirkung von Flussbett und Grundwasser – Vergleich verschiedener Verfahren zur Erfassung der Grundwasserneubildung

Zusammenfassung

Das Zusammenwirken von Oberflächen- und Grundwasser kann als dynamischer Prozess mit ausgeprägter raumzeitlicher Variabilität angesehen werden. Im Rahmen einer Fallstudie am Fluss Leitha in Niederösterreich wurden lokale Infiltrationsverluste entlang eines Flussabschnittes gemessen. Von den angewandten direkten und indirekten Verfahren werden folgende im Beitrag näher erläutert: (1) Kontinuierliche Messung von Abflussdifferenzen entlang definierter Fließabschnitte, (2) lokale Infiltrationsmessung mit Hilfe eines Flussbettlysimeters, (3) inverse Grundwassermodellierung, bei der die Randbedingung der Flussbettinfiltration als unbekannte Variable angesetzt wurde. Der Vergleich der Ergebnisse ermöglichte die Quantifizierung und Eingrenzung der Grundwasserneubildung und bildete die Basis für die Erstellung eines Entscheidungswerkzeuges zur Optimierung der Wasserressourcen im Gebiet.

Schlagwörter: Flussbettinfiltration, Abflussdifferenzmessungen. Flussbettlysimeter, inverse Grundwassermodellierung.

Summary

Surface and groundwater interaction can be considered as a pronounced temporal and spatial dynamic process. A case study at the Leitha river in Lower Austria aimed the assessment of the infiltration losses along the river reach. Among the different direct and indirect techniques that have been applied, the following will be discussed in more detail in the paper: (1) Continuous measurement of differential discharge along the course of interest, (2) local infiltration measurements by means of a riverbed lysimeter and (3) inverse groundwater modelling, where the infiltration boundary condition is regarded as the unknown variable. The comparisons of the particular results have been used to validate the magnitude of groundwater recharge and formed the base for a decision support tool to optimize the multi objective water release strategies.

Key words: Riverbed infiltration, differential discharge measurements, riverbed lysimeter, inverse groundwater modelling.

1 Introduction and objectives

Surface and groundwater interactions are important processes to describe and quantify groundwater recharge. The connectivity is driven by the state of the groundwater level, the temporal evolution of discharge and the related sedimentation and clogging processes along the riverbed. Riverbed infiltration can be considered as a pronounced temporal and spatial dynamic process with strong sensitivities to human interventions like water release, river training activities and sediment mining. The groundwater reservoir of the Southern Viennese Basin is strongly formed by the infiltration of surface water originated by seepage through the highly permeable sediments of the river Schwarza and upper Leitha. This territory is exposed to multiple utilization demands with respect to sectoral activities and ecosystem services like (1) hydro-electric production by small hydropower plants along artificially formed diversions and outlet channels from the main river, (2) potential groundwater resource with qualitative problems due to illegal dumps, (3) ecologically valuable sections for fish and benthic biota and (4) ecological limitations due to local ephemeral runoff conditions. The sectoral requirements exhibit partly contradictory aims and consequences. For instance a higher water release from the river would improve the hydro-electric capacity along the outlet channel but deteriorate low flow conditions and the related hydro-ecological behavior along the downstream part of the river. Figure 1 gives an overview of the river network and the corresponding diversion channel nodes, where water from the main river is distributed to the artificial channels to enable hydropower production. The location of hydropower plants is indicated by the signs "HPP no" in figure 1. The different grey shades along the river Leitha indicate particular sections, which were relevant for the groundwater infiltration boundaries.

Reasonable water managemental planning considering all prevalent demands requires a deep understanding of the spatio-temporal behavior of surface-groundwater interactions. A research project funded by public authorities (see acknowledgement) aimed at the comparison of different direct and indirect observation approaches to quantify the riverbed infiltration losses along the Schwarza – Leitha river system (see HOLZMANN & NACHTNEBEL, 2001). Continuous measurements of differential discharge along the river course, local infiltration measurements by means of a riverbed lysimeter and inverse groundwater modelling have been carried out in the project frame. These techniques will be described in more detail in this paper. Besides these measurement activities some further methods like double ring

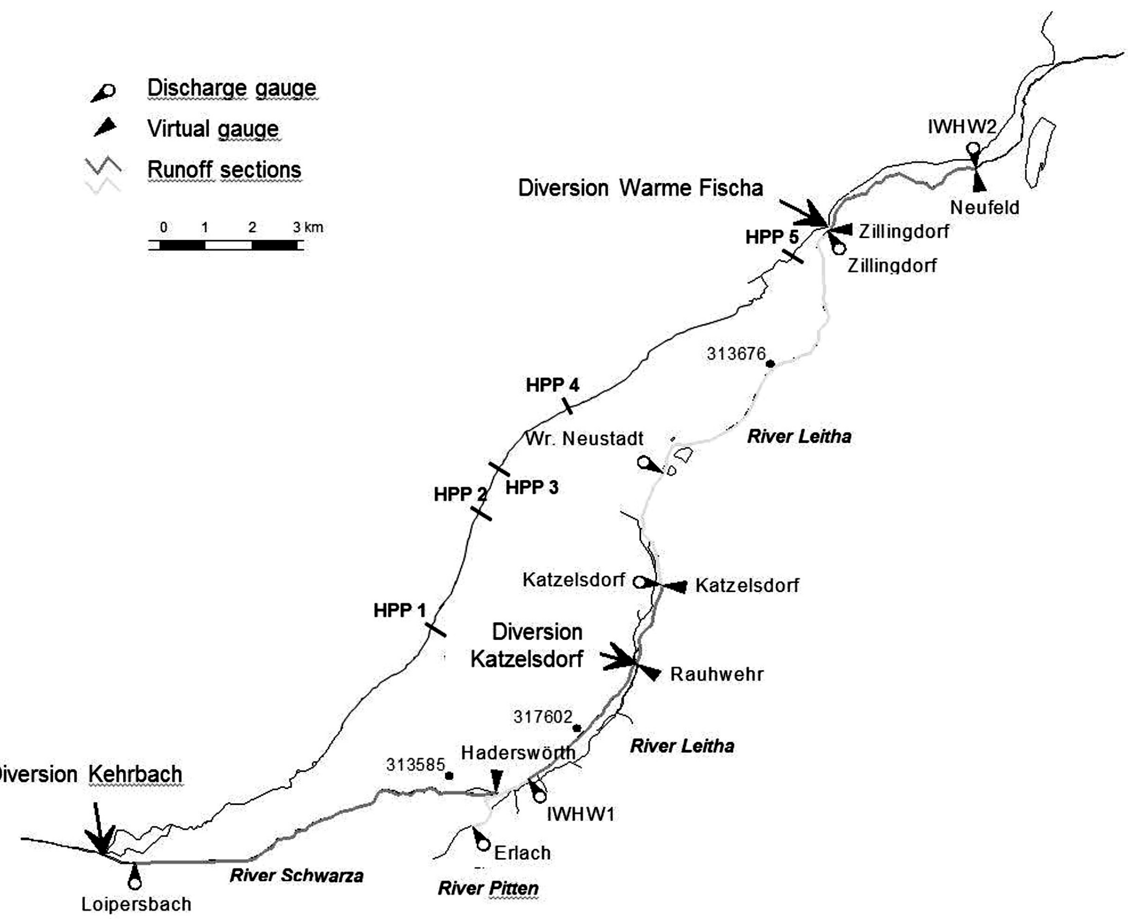

Figure 1: Scheme of the Schwarza/Leitha river sketch
Abbildung 1: Gebietsbeschreibung des Schwarza/Leitha Flussabschnitts

infiltration experiments, soil (sediment) sample analysis and related infiltration formulas and experimental plot in the hydraulic lab were used (see HOLZMANN et al., 2002), but will not be presented here.

2 Methods

Riverbed infiltration along a river branch exhibits high spatio and temporal variabilities. Therefore its quantification for water balance calculations and for related water management measures is not an easy task and can be a source for estimation errors. In the following three different approaches for the assessment of riverbed infiltration are described which supported the identification of the system behavior and to confirm future management strategies. In particular (1) differential discharge measurements (2), riverbed lysimeter observations and (3) results from inverse groundwater modelling are described and compared, which enables to quantify the variety of the process.

2.1 Differential discharge measurements

Along the course of the investigation domain of Schwarza – Leitha river there exist five runoff gauges from the hydrological survey, where mean daily discharge data were available from 1979–1996 (see also figure 1). Two further gauges were installed during the project phase and provided data for the years 1999 and 2000. So called "virtual gauges" along the river sectors were introduced, where calculations of the runoff balance were carried out to document the evolvement of the spatial (longitudinal) riverbed infiltration losses. The runoff differences between upstream and downstream gauges were interpreted as infiltration losses into the aquifer. The scatter plot in figure 2 shows the relation between infiltration along the river reach from Loipersbach to Haderswörth and the upstream discharge in Loipersbach for the period 1999–2000.

The high variance of the infiltration estimates can be caused by variable riverbed conductivities due to dynamic sedimentation and clogging processes, non-stationary runoff conditions or varying connectivity between surface and

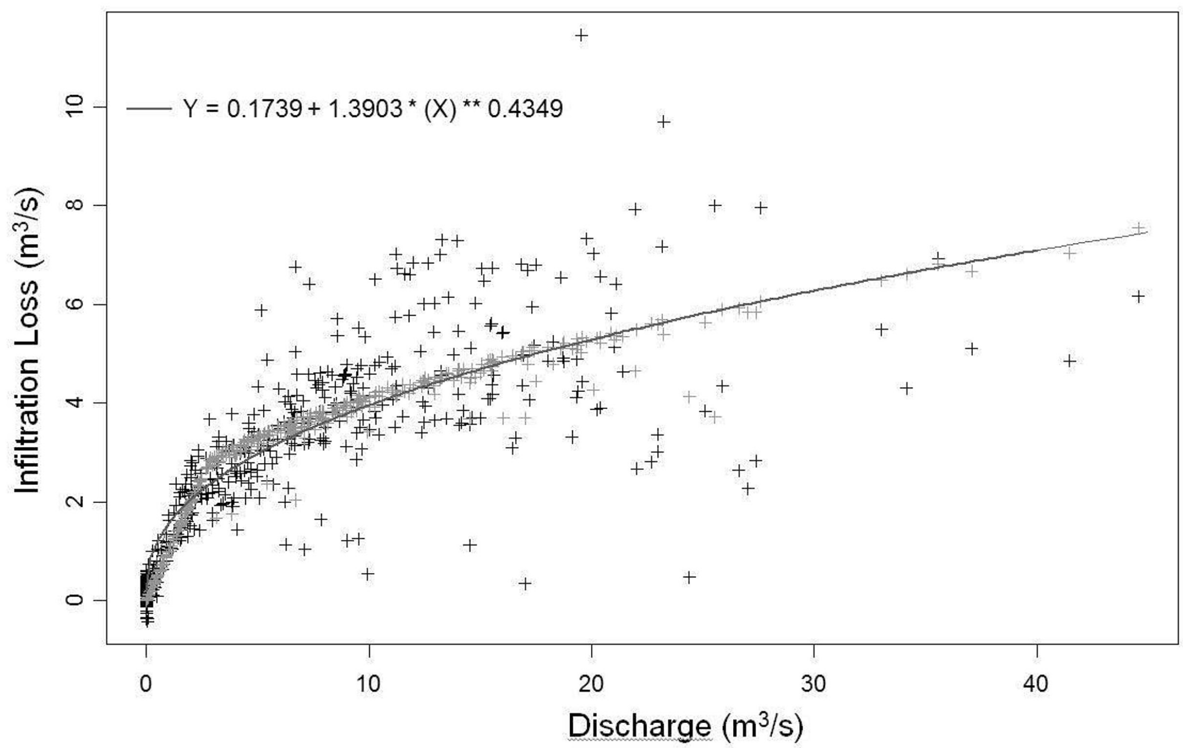

Figure 2: Discharge – infiltration loss relation for the period 1999–2000 (black cross … observed, grey cross … multiple regression, grey line … non-linear regression)

Abbildung 2: Beziehung zwischen Abfluss und Infiltrationsverlust für den Zeitraum 1999 bis 2000 (schwarze Kreuze … Beobachtungswerte, graue Kreuze … Berechnungswerte aus Mehrfachregression, graue Kurve … Berechnungswerte aus nichtlinearer Regression) groundwater. The mathematical formulation of the relation between discharge and infiltration was defined by regression analysis and will be described in more detail in chapter 3.

2.2 Riverbed lysimeter

The temporal dynamics of the riverbed infiltration was studied by means of a riverbed lysimeter. Due to the ephemeral runoff conditions at the Schwarza river, where usually no runoff occurs during the late autumn and winter months, installation work could be easily carried out. The lysimeter itself comprises of a bucket (500 litres), which is partly filled with natural riverbed sediment. A fine meshed grid plate separates the sediment backfill from the drain space (see figure 3). During the periodic pumping experiments the pumping rate is recorded with respect to the actual state conditions (water table in the river). The pumping experiment lasted several hours to provide steady state infiltration. To enable proper interpretation of the infiltration the following prerequisites have to be achieved: (1) Low groundwater table (below the lysimeter) and (2) high sediment conductivities to have downward directed (one-dimensional) seepage flow. Details can be found in HOLZMANN & NACHTNEBEL (2002) and in HEINDL (2001).

The pumping experiments were carried out during the wetting phase (February to May 2000), when the groundwater table was low. Considering different levels of surface water table and sedimentation depth the following equation was applied to estimate the hydraulic conductivity *K*.

$$K = q_{LY} \cdot \frac{L_{LY}}{\Delta H + L_{LY}} \tag{1}$$

where K [m/s] … saturated hydraulic conductivity
q_{LY} [m/s] … drainage rate of lysimeter
L_{LY} [m] … seepage distance
ΔH [m] … water depth
$(\Delta H + L_{LY})$ [m] … hydrostatic pressure

2.3 Inverse groundwater modelling

Groundwater models solve the spatio-temporal evolvement of the water transport in saturated porous media. The transport is driven by the hydrogeological conditions of the aquifer (hydraulic conductivity, depth of layer) and the boundary conditions. The latter is defined by the areal recharge and sink conditions inside the domain and along the outer boundaries. In our case the reach of the Schwarza and Leitha rivers and their drainage capacities form the second type (Neumann type) boundary condition.

Figure 4 shows the computational, triangular mesh of the applied groundwater model FEFLOW (WASY, 1997) based on finite element algorithm. The black dots represent the constant head boundaries gained from spatial interpolation of groundwater wells. The grey shaded lines indicates the rivers reaches of Schwarza and Leitha, which are generating the riverbed infiltration (flux boundaries). Hydrogeological data like aquifer depths and conductivities were available from previous groundwater studies in the area. Inverse

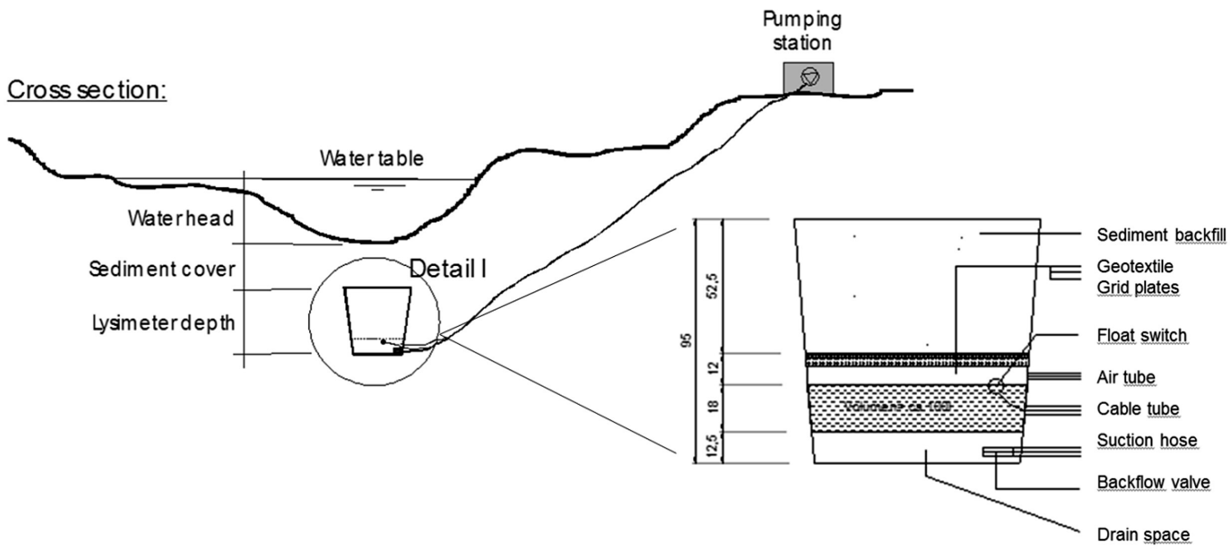

Figure 3: Riverbed lysimeter: Location in the cross section and detailed technical description. The distance units in detail I are centimeters
Abbildung 3: Flussbettlysimeter: Lage im Gerinnequerschnitt und Detail. Distanzmaße im Detailplan I in cm

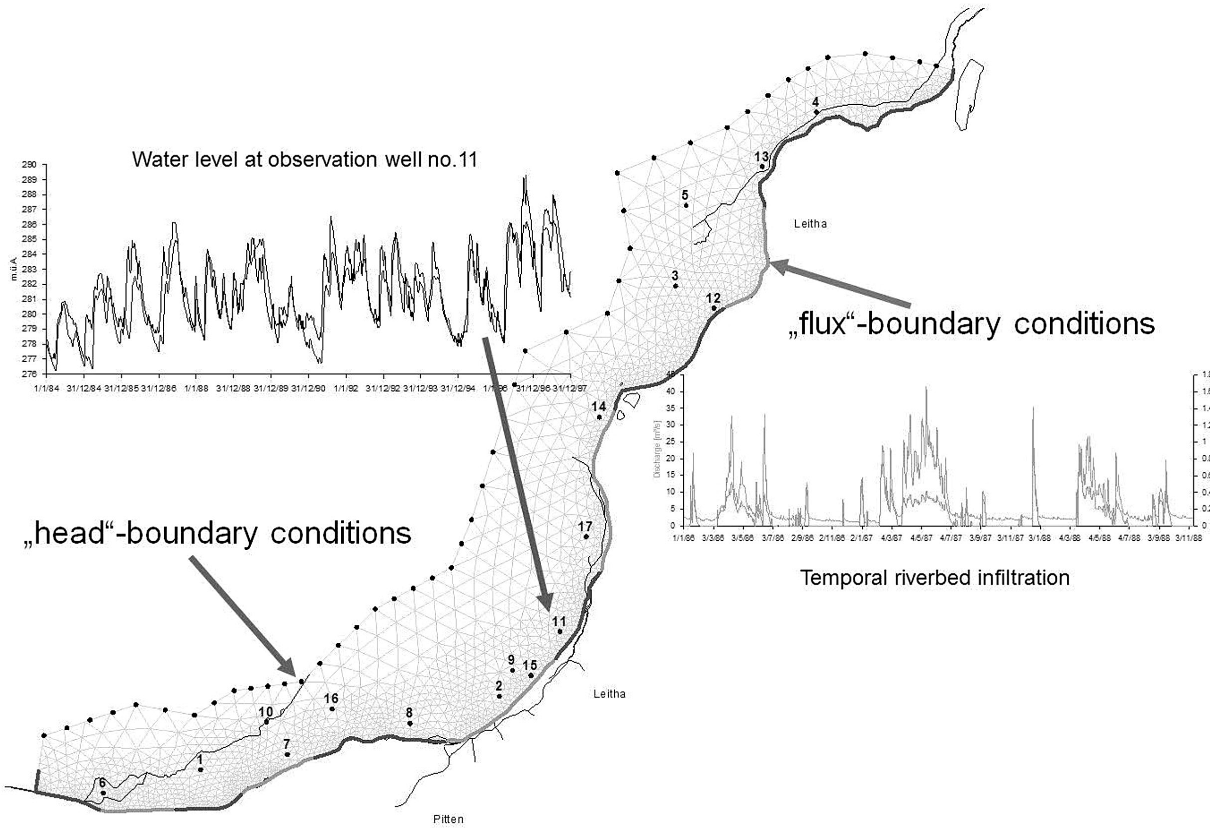

Figure 4: Domain of inverse groundwater modelling. Numbered dots indicate observation wells, where time series of water levels are available. The included graph of (1) flux boundary conditions shows the temporal behavior of infiltration with respect to the upstream discharge (1986–1988), where (2) the second exhibits water level comparison of observed (well no. 11) and computed time series (1984–1997). Different grey shades along the river Leitha indicate different flux boundary conditions

Abbildung 4: Bereich der inversen Grundwassermodellierung. Nummerierte Punkt zeigen Beobachtungsbrunnen mit verfügbaren Wasserstandszeitreihen. Die Grafik der Flux-Randbedingung zeigt den zeitlichen Verlauf der Infiltration als Funktion des Abflusses (1986–1988), die zweite Grafik zeigt den Vergleich von beobachteten und simulierten Grundwasserstände am Brunnen Nr. 11 (1984–1997). Die Graustufen entlang der Leitha zeigen Abschnitte mit unterschiedlichen Flux-Randbedingungen

modelling means in this context the iterative estimation of the dynamic flux boundary conditions (riverbed infiltration rate) to meet good accordance of the estimations with the observed groundwater state conditions (groundwater table at observation wells, see figure 4, numbered dots). As a first guess the sectoral non-linear relations between discharge and infiltration (see equation 2) were applied. Due to the spatial-temporal variation of the flux boundary condition a dynamic pattern of the groundwater table was calculated with good agreement to the observed data (see observation well 11, figure 4).

3 Results and Discussion

The regression analysis between discharge and riverbed infiltration were conducted by means of the following assumptions. Firstly a non-linear regression with discharge Q_L as the predictor variable and infiltration *Inf* as the dependent (see equation 2) and secondly a multiple regression relation (see equation 3), where discharge Q_L, groundwater level *GW* and the first derivative of the groundwater level D*GW* served as predictor variables. The equations with the corresponding coefficients for section 1 from Loipersbach to Hadersswörth are given as follows:

$$Inf = 0.174 + 1.390 \cdot Q_L^{\,0.435} \tag{2}$$

$$\begin{aligned} Inf = {} & \exp(-41.7 + 0.19 \cdot \log(Q_L) + 0.139 \cdot GW \\ & + 0.208 \cdot \Delta GW) - 0.150 + 0.063 \cdot Q_L \end{aligned} \tag{3}$$

Equation 3 considers a higher variability based on varying state conditions (see bright blue scatters in figure 2). The non-linear regression model described in equation 2 can also be used for predictive purposes regarding different release scenarios, where equation 3 can only be used for ex-post analysis, due to lacking groundwater data for the scenario assumptions.

In the presented study several methods for the estimation of riverbed seepage losses have been compared. With the exception of empirical formulas based on soil particle distribution, which tend to overestimate the infiltration capacity, the remaining methods gave comparable results for the potential riverbed infiltration capacity. Differential discharge measurements and inverse groundwater modelling reflect methods, which have been continuously conducted for a longer time period considering also ephemeral (dry) conditions. They gave comparable results but the mean values are smaller than the respective results from the other techniques (see table 1).

Therefore, it can be concluded that the differential discharge methods and the derived non-linear relations (see equation 1) can be used to estimate the spatio-temporal behavior of the riverbed infiltration rates. Based on these findings a decision support tool for the entire river course was developed, which enables the consideration of different scenarios of release water quantities at the upstream weir diversion and their impact on the downstream runoff and infiltration, respectively. Figure 5 shows the scheme of the local infiltration losses for the status quo conditions and for a release scenario, where up to 3 m^3/s are recharged into the original riverbed. This scenario would improve the hydro-ecological conditions due to a reduction of dry phases and would increase the groundwater recharge capacity from 3,5 m^3/s to 5,7 m^3/s. On the other hand the runoff along the diversion channel and the related hydro-electric potential of the power plants would be reduced. More details are described in HOLZMANN & NACHTNEBEL (2001).

Table 1: Comparison of different methods for the estimate of riverbed infiltration
Tabelle 1: Vergleich verschiedener Verfahren zur Abschätzung der Flussbettinfiltration

	estimation of infiltration (in mm/s)		
Method	**Minimum**	**Mean**	**Maximum**
Riverbed lysimeter	1.0×10^{-4}	1.2×10^{-4}	1.5×10^{-4}
Double ring infiltrometer	1.9×10^{-5}	1.7×10^{-4}	3.8×10^{-4}
Sample analysis	4.9×10^{-6}	4.7×10^{-4}	3.9×10^{-4}
Empirical formula	2.0×10^{-4}	7.4×10^{-3}	3.4×10^{-2}
Differential discharge	8.0×10^{-6}	9.0×10^{-5}	2.8×10^{-4}
Inverse GW-modelling		3.0×10^{-5}	

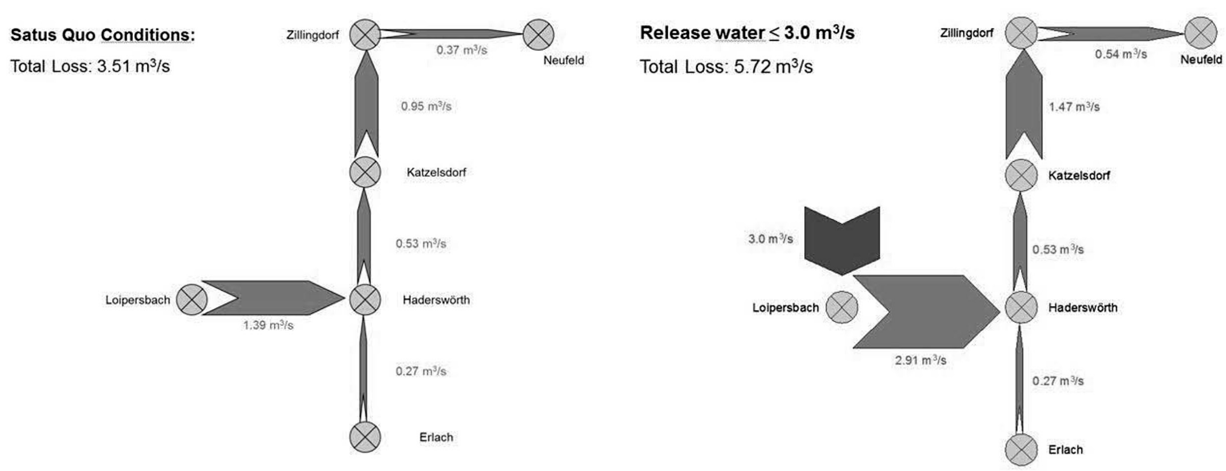

Figure 5: Local riverbed infiltration losses for (a) the status quo and (2) for release water of 3 m^3/s
Abbildung 5: Lokale Infiltrationsverluste für (a) den Ist-Zustand und (2) bei einer Restwasserabgabe von 3 m^3/s

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