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Assessing the effect of different river water level interpolation schemes on modeled groundwater residence times

Samuel Diem [a,b,*], Philippe Renard [b], Mario Schirmer [a,b]

[a] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Water Resources & Drinking Water, Überlandstrasse 133, 8600 Dübendorf, Switzerland
[b] University of Neuchâtel, Centre for Hydrogeology and Geothermics, Rue Emile-Argand 11, 2000 Neuchâtel, Switzerland

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SUMMARY

Obtaining a quantitative understanding of river–groundwater interactions is of high practical relevance, for instance within the context of riverbank filtration and river restoration. Modeling interactions between river and groundwater requires knowledge of the river's spatiotemporal water level distribution. The dynamic nature of riverbed morphology in restored river reaches might result in complex river water level distributions, including disconnected river branches, nonlinear longitudinal water level profiles and morphologically induced lateral water level gradients. Recently, two new methods were proposed to accurately and efficiently capture 2D water level distributions of dynamic rivers. In this study, we assessed the predictive capability of these methods with respect to simulated groundwater residence times. Both methods were used to generate surface water level distributions of a 1.2 km long partly restored river reach of the Thur River in northeastern Switzerland. We then assigned these water level distributions as boundary conditions to a 3D steady-state groundwater flow and transport model. When applying either of the new methods, the calibration-constrained groundwater flow field accurately predicted the spatial distribution of groundwater residence times; deviations were within a range of 30% when compared to residence times obtained using a reference method. We further tested the sensitivity of the simulated groundwater residence times to a simplified river water level distribution. The negligence of lateral river water level gradients of 20–30 cm on a length of 200 m caused errors of 40–80% in the calibration-constrained groundwater residence time distribution compared to results that included lateral water level gradients. The additional assumption of a linear water level distribution in longitudinal river direction led to deviations from the complete river water level distribution of up to 50 cm, which caused wide-spread errors in simulated groundwater residence times of 200–500%. For an accurate simulation of groundwater residence times, it is therefore imperative that the longitudinal water level distribution is correctly captured and described. Based on the confirmed predictive capability of the new methods to estimate 2D river water level distributions, we can recommend their application to future studies that model dynamic river–groundwater systems.

1. Introduction

Groundwater flow and transport modeling is a valuable and frequently applied tool to gain a process understanding of surface water–groundwater systems, providing quantitative information on flow paths, mixing ratios and residence times (Wondzell et al., 2009). It is well known from synthetic modeling studies that riverbed morphology affects the river water level distribution, which in turn drives the exchange with groundwater (Cardenas, 2009; Cardenas et al., 2004; Woessner, 2000). Therefore, an important prerequisite for the set up of a groundwater flow and transport model of a real surface water–groundwater system is an accurate description of the water level distribution at the surface water boundary conditions.

A quantitative assessment of groundwater flow paths and residence times is of particular interest for riverbank filtration systems (Tufenkji et al., 2002). Groundwater residence time is an important parameter in determining the effectiveness of the natural attenuation processes that occur during riverbank filtration (Eckert and Irmscher, 2006). River restoration measures, such as riverbed enlargements, potentially lead to reduced groundwater residence times. This, in turn, bears the risk of drinking water contamination (Hoehn and Scholtis, 2011) that contradicts the original purpose of river restoration (Brunke and Gonser, 1997; Woolsey et al., 2007). Groundwater flow and transport modeling could help to mitigate this conflict of interest, by providing a quantitative assessment of

* Corresponding author. Address: Überlandstrasse 133, P.O. Box 611, 8600 Dübendorf, Switzerland. Tel.: +41 58 765 5519; fax: +41 58 765 5028.

E-mail addresses: samuel.diem@eawag.ch (S. Diem), philippe.renard@unine.ch (P. Renard), mario.schirmer@eawag.ch (M. Schirmer).

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the groundwater flow paths and residence times (Hoehn and Meylan, 2009).

Restored river systems may have complex water level distributions characterized by nonlinear longitudinal water level distributions, morphologically induced lateral water level gradients, disconnected river branches and hydraulic jumps. Such water level distributions need to be characterized by their full spatial (i.e. two horizontal dimensions) and temporal variability and ideally are extracted from hydraulic models (Derx et al., 2010; Doppler et al., 2007; Engeler et al., 2011). However, the setup of a hydraulic model is time consuming and requires a considerable amount of data input. Diem et al. (2013) proposed two new alternative interpolation methods to estimate time-varying one- and two-dimensional (1D, 2D) surface water level distributions of dynamic rivers based directly on measured water level data.

In this study, we assess the predictive capability of the new alternative methods proposed by Diem et al. (2013) with respect to simulated groundwater residence times and the effect of reducing the considered level of detail in the surface water level distribution. Thereto, steady-state surface water level distributions at a partly restored riverbank filtration system are generated with both alternative methods and a reference method, as well as with two simplified methods. The resulting water level distributions are then assigned to a 3D groundwater flow and transport model. After calibration against groundwater heads for each model scenario, the spatial groundwater residence time distribution is predicted within the modeling domain.

2. Interpolation methods

The interpolation methods used in this study are based on those established by Diem et al. (2013). A brief description of the methods is provided in this section, but for a more detailed description the reader is referred to Diem et al. (2013). The new alternative methods and the reference method are referred to as "complete interpolation methods", as they cover the full level of detail including lateral water level gradients and nonlinear longitudinal water level distributions.

2.1. Complete interpolation methods

Both new alternative interpolation methods proposed by Diem et al. (2013) are based on the concept of combining continuous water level records (h^G) from water level gauges (G) with periodic water level measurements (h^F) at fixpoints (F) between water level gauges. By combining this data, the water level distribution between the water level gauges is obtained at a higher resolution. Fixpoints are defined as reference points in the river whose absolute altitude is known. The first alternative "RM method" (Regression of measured data) applies a polynomial regression technique to predict water levels at fixpoints from any water level at a specific water level gauge, while the second alternative "IM method" (Interpolation of measured data) uses a nonlinear interpolation approach between two water level gauges.

Depending on the lateral extent, the river might be considered as a 1D or a 2D domain. In the latter case, the river is discretized by multiple lines parallel to the main flow direction of the river and several sections of support points (S) perpendicular to the flow direction (Fig. 1). Sections of support points are defined at locations where a water level gauge or a fixpoint exists. One fixpoint per section is sufficient to capture the water level distribution across the river unless lateral water level gradients are observed, in which case a fixpoint should be defined on both shorelines.

The water levels at the support points (h^S) are estimated from the water levels at the fixpoint in the simplest possible manner.

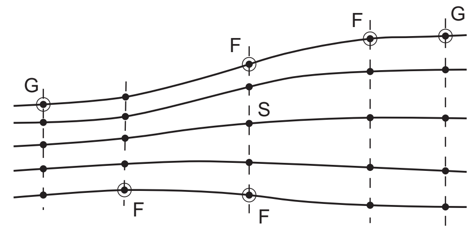

Fig. 1. Schematic illustration of a river system with multiple lines and sections of support points (S, filled black circles). The open black circles indicate the water level gauges (G) and fixpoints (F). Adapted from Diem et al. (2013).

If no lateral water level gradient exists, the water level of the fixpoint is assigned to all support points on the same section. If a second fixpoint was defined to capture lateral gradients, assigning water levels to the support points should be based on field observations. The final interpolation of water levels from the support points to the river boundary nodes of the numerical model is identical for all the interpolation methods and is performed by a linear interpolation along the set of lines.

The third "RH method" (Regression of hydraulic model data) applies a polynomial regression technique, similar to the RM method, but is based on water levels extracted from a hydraulic model at each support point directly. The RH method is therefore considered as reference method among the complete interpolation methods.

2.2. Simplified interpolation methods

In addition to the predictive comparison of the complete interpolation methods described above, we assessed the difference in residence time prediction that evolves when the water level distribution of the river is simplified. Thereto, we applied two progressively simplified methods, both based on the complete IM method. The first simplified method ignores lateral water level gradients and is denoted as "Interpolation of measured data without lateral gradients" (IM_wo_lat). The second simplification additionally assumes a linear interpolation between the river water level gauges and is called "Interpolation of measured data assuming a linear interpolation" (IM_lin).

3. Application to the Niederneunforn field site

This section provides a description of the Niederneunforn field site (Section 3.1) and a review of the implementation of the interpolation methods by Diem et al. (2013) at this field site (Section 3.2). Section 3.3 presents the generated surface water level distributions, which we assigned to the groundwater flow and transport model to simulate the spatial groundwater residence time distribution (see Section 4).

3.1. Field site

The Niederneunforn field site (Fig. 2) is located at the Thur River in NE-Switzerland, approximately 12 km upstream of the confluence with the Rhine River. The Thur River is a peri-alpine river draining a catchment area of 1730 km^2. It is the longest river in Switzerland without a retention basin and therefore has a very dynamic discharge regime. Discharges range from 3 to 1100 m^3/s, with an average discharge of 47 m^3/s.

The field site was instrumented with more than 80 piezometers (2″) during the interdisciplinary RECORD project (Restored corridor dynamics, <http://www.cces.ethz.ch/projects/nature/Record>; Schirmer (2013), Schneider et al. (2011)) in the context of