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Field evidence of a dynamic leakage coefficient for modelling river–aquifer interactions

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Summary In groundwater flow modelling, the interaction between rivers and aquifers is usually modelled with spatially and temporally constant leakage coefficients. We used conventional model calibration techniques to investigate the time-varying river–aquifer interactions in the sandy gravel aquifer of the upper Limmat valley in Zurich (Switzerland). The aim of the study was to determine whether the leakage coefficients have to be treated as time-dependent in order to adequately model the dynamics of the groundwater flow. A transient horizontal two-dimensional groundwater flow model was established together with a one-dimensional hydraulic model for river flow, as well as a scheme calculating groundwater recharge and lateral inflow from meteorological data and a soil water balance model. The groundwater flow model was calibrated using hydraulic head data from May and June 2004 and July and August 2005. The verification period covered 13 years using hydraulic head data from 90 piezometers. The comparison of the model results with the measurements in the verification period revealed three phenomena concerning river–aquifer interaction which all showed up as systematic deviations between model and observations. (1) The major flood event in May 1999 had a significant and persistent influence on the river–aquifer interaction. In an impounded river section upstream of a weir, the infiltration of river water was enhanced by the flooding probably due to erosion processes. (2) Seasonal river water temperature fluctuations influenced the infiltration rate, due to the temperature dependence of hydraulic conductivity of the river bed. (3) Depending on geometry and hydraulic characteristics of the riverbanks the leakage coefficient can be a function of the river stage. With higher water levels, additional

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areas can contribute to the infiltration of river water. Therefore, in modelling groundwater flow with strong river—aquifer interactions, it can become necessary to consider dynamic leakage coefficients and to recalibrate periodically.

Introduction

The interaction between groundwater and rivers plays a role in almost any groundwater model. Rivers may gain water from aquifers or may lose water to aquifers. The water fluxes between a river and an aquifer may be considerable and therefore have to be taken into account in the water balance of a groundwater system. The exchange fluxes (infiltration and exfiltration rates) depend on the hydraulic head distribution within the aquifer and the river as well as the hydraulic conductivity distribution within the aquifer and the riverbed.

Various concepts exist to model the interaction between river and groundwater. Often a linear relationship is postulated between the exchange rate and the difference between river head and groundwater head (e.g., Rushton and Tomlinson, 1979). In groundwater models (e.g., McDonald and Harbaugh, 1984) the exchange flux per unit area of riverbed is usually modelled with the help of a leakage concept based on Darcy's law:

$$q_{\text{leakage}} = \frac{K_{\text{riverbed}} \cdot (h_{\text{river}} - h)}{d_{\text{riverbed}}} \tag{1}$$

where q_{leakage} [LT^{-1}] is the specific leakage rate or exchange rate per unit horizontal area of riverbed, K_{riverbed} [LT^{-1}] and d_{riverbed} [L] are the hydraulic conductivity and thickness of the riverbed, h_{river} [L] is the hydraulic head of the river (assuming hydrostatic conditions within the river), and h [L] is the hydraulic head of the aquifer below the river. The assumption of the leakage concept is that the hydraulic conductivity of the riverbed is smaller than the hydraulic conductivity of the aquifer because of colmation processes (clogging). The clogging layer therefore controls the exchange rate. In horizontal two-dimensional groundwater flow models the exchange rate either has the quality of a local specific recharge rate (for an aquifer below a river) or of a Cauchy type boundary condition if the river is deeply incised into the aquifer. In the former case the groundwater head h represents the mean head in the aquifer volume below the river. The two quantities K_{riverbed}, d_{riverbed} are often combined to a leakage coefficient l_{leakage} [T^{-1}] as follows: $l_{\text{leakage}} = K_{\text{riverbed}}/d_{\text{riverbed}}$. If unsaturated conditions prevail between river bottom and aquifer the exchange rate is often approximated by: $q_{\text{leakage}} = l_{\text{leakage}}(h_{\text{river}} - z_{\text{riverbottom}})$ where the hydraulic head h below the riverbed is replaced by the level of the river bottom thus assuming zero water pressure below the clogging layer. Furthermore it has to be noted that in some models the leakage rate per unit length along the river is used instead of a rate per unit area of riverbed.

The adoption of Dupuit's assumption for the representation of the flow conditions between river and aquifer in horizontal two-dimensional groundwater models clearly represents a simplification of the true three-dimensional flow situation thus leading to a modelling error by neglecting vertical flow components. According to Bear (1979) essentially horizontal flow conditions occur only at a distance larger than about 1.5 or twice the aquifer thickness from the river. The introduction of a leakage coefficient is recommended (Anderson, 2005) even in the absence of a clogging layer at the riverbed in order to reduce global errors in the hydraulic head. Commonly an additional hydraulic resistance within the riverbed, caused by clogging of the riverbed due to colmation processes, exists. As a matter of fact this resistance is strongly spatially variable within the riverbed. Moreover, it is thought that the resistance could be time-dependent due to transient sedimentation and erosion or biochemical processes. For the formation of a clogging layer it is also relevant whether infiltration or exfiltration conditions prevail. Both conditions may be present at the same time in a given cross section of the river. The effects of sediment transport and the related settling and entrapment of suspended matter leading to river bed clogging (colmation) have been experimentally investigated on various occasions (e.g., Cunningham et al., 1987; Rehg et al., 2005). As expected, infiltration conditions favour the forming of clogging layers. On the contrary, such a layer formation may be inhibited in the case of exfiltration conditions. In the case of impounded rivers, the riverbed clogging is mainly due to sedimentation and deposition of fine material on the riverbed.

A difficulty in groundwater modelling is the estimation of the leakage coefficient. The leakage rate can be locally measured by seepage meters (e.g., Kaleris, 1998). The infiltration rate of extended losing river reaches can be assessed by river discharge measurements along the river. Kaleris (1998) discussed the reliability of these two techniques for estimating the exchange rate between groundwater and small streams. The usual way to determine or estimate the parameters of the exchange rates (e.g., leakage coefficients) is by model calibration using field data (head data, tracer data, etc.). Zechner and Friedlingsdorf (2004) used head and tracer data to calibrate a groundwater system with strong river—aquifer interactions. The use of head data to calibrate leakage coefficients is standard in model calibration, mainly for steady-state conditions. However, how successful are such parameters when modelling uncalibrated periods? Is the relationship between head difference and leakage rate linear or non-linear? What are controlling factors of the leakage coefficients? Are the leakage coefficients constant over time? This latter question was investigated experimentally by Blaschke et al. (2003) at river Danube in Vienna (Austria). They estimated the leakage coefficient with the help of piezometric head data below the riverbed and an analytical model assuming that the groundwater flow direction below the river coincides with the measurement profile of piezometers and assuming constant aquifer thickness and hydraulic conductivity. Their resulting leakage coefficient showed a clearly transient behaviour, which they attributed to flood events and the related sediment transport processes.