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Research papers

Estimation of stream-aquifer exchanges at regional scale using a distributed model: Sensitivity to in-stream water level fluctuations, riverbed elevation and roughness

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ABSTRACT

Several studies on stream-aquifer interactions focus on the local scale. However, the estimation of stream-aquifer exchanges for a regional river network remains challenging. This study aims at assessing the sensitivity of distributed stream-aquifer exchanges to in-stream water level fluctuations, riverbed elevation and Manning roughness coefficient.

An integrated distributed surface-subsurface model is applied to the Loire river basin (117,480 km^2, France), where in-stream water level fluctuations are taken into account with a simplified Manning-Strickler approach. The stream-aquifer exchanges are analyzed at pluri-annual and annual scales, as well as during short-term hydrological events.

The model simulates the spatio-temporal variability of in-stream water levels accurately, with Nash coefficients up to 0.96 for the Loire river. The river network mainly drains the aquifer system. The average net exchanged flow is $2 \cdot 10^{-2}\ m^3\ s^{-1}\ km^{-1}$, which corresponds to 12% of the averaged discharge at the outlet of the basin.

The assumption of constant river stages significantly impacts the total infiltration (−70%) and exfiltration (−10%) in the basin, whereas it has a negligible influence on the average net flux. The river fluctuations increase the time variability of the stream-aquifer exchanges and may determine flow reversals during flood events and also more frequently for river stretches at equilibrium with its nearby aquifer.

This study highlights the importance of accounting for river stage fluctuations in the modeling of regional hydrosystems. Moreover, a sensitivity analysis indicates that it is mandatory to develop new methodologies to better estimate the riverbed elevation at high resolution for a river network at regional scale. In a lesser extent, errors on Manning coefficient affect the timing of infiltration and exfiltration, leading to temporally localized discrepancies. However it does not affect the estimates of the global net exchanges significantly.

1. Introduction

The concept of hydrosystem (see, e.g., Dooge (1968), Kurtulus et al. (2011), Flipo et al. (2014)) reflects the need to consider the interactions between the different components of the water cycle in order to evaluate the water and solute fluxes properly. In particular, the stream-aquifer interface controls the interactions between surface water and groundwater. The evaluation of the water fluxes at this interface is then a primary task to correctly simulate the hydrosystem functioning (Fleckenstein et al., 2010; Saleh et al., 2011; Flipo et al., 2014) and predict its response to climatic and anthropogenic stresses (Scibek and Allen, 2006; Scibek et al., 2007; Zume and Tarhule, 2008; Zume and Tarhule, 2011; Waibel et al., 2013; Graham et al., 2015).

Stream-aquifer interfaces can be described at different scales (Flipo et al., 2014): local (10 cm to 10 m), intermediate or reach (10 m to 1 km), watershed (10–1000 km^2), regional (10,000 km^2 to 1 M km^2) and continental (>10 M km^2). The regional scale is of utmost importance since environmental regulatory frameworks, such as the european Water Framework Directive (EU Parliament, 2008), and water resource management plans (Pryet et al., 2015) are often set at this scale.

In their extensive literature review, Flipo et al. (2014) pointed out that, among 183 publications concerning the usage of distributed physically based hydrological-hydrogeological models,

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only 19 pertain to the regional scale. Except for Monteil (2011) and Pryet et al. (2015), none of these publications explicitly perform a distributed quantification of the stream-aquifer exchanges. Further work is then needed to improve the modeling of the stream-aquifer exchanges at the regional scale. The classical approach is a conductance model (Rushton and Tomlinson, 1979) assuming constant river stages over time. To the authors' knowledge, the only study taking into account water level fluctuations at the regional scale was carried out by Pryet et al. (2015).

Nevertheless, the effect of water level fluctuations on stream-aquifer exchanges was studied by a few authors at intermediate and watershed scale. At the intermediate scale, in-stream water level fluctuations may determine temporary reversals of the gaining or losing regime for some river reaches, particularly during flood events (Cloutier et al., 2014). Such reversals could have a major influence on the fluxes of contaminants (Zachara et al., 2013; Batlle-Aguilar et al., 2014). An accurate description of the river longitudinal water level distribution is also important to estimate groundwater residence times, as shown at reach scale by Diem et al. (2014).

At the watershed scale, in-stream water level fluctuations have a significant impact on the stream-aquifer exchanges and on the near-river piezometric head distribution (Saleh et al., 2011). Moreover, in-stream water level fluctuations slightly increase both the global exfiltration and the global infiltration in the basin, with a resulting negligible variation of the net stream-aquifer exchange (Saleh et al., 2011). At larger scales (regional or continental), the assessment of the impact of in-stream water level fluctuations on the stream-aquifer exchanges still needs to be developed.

The approach to account for river stage fluctuations in coupled hydrological-hydrogeological models depends on the scale of the modeled domain as well as on data availability. At the watershed scale, the methodology is generally based on the availability of river cross-section profiles. This is the case of the study published recently by Foster and Allen (2015) concerning a mountain to coast 930 km^2-watershed. The net and absolute fluxes were estimated taking into account the in-stream water level fluctuations by means of the diffusive wave approximation of the one-dimensional Saint-Venant equations.

In Saleh et al. (2011), a one-dimensional Saint-Venant model is employed to derive the rating curves to be used in the hydrogeological model to compute the water stages from the simulated discharge. This approach is successful to accurately simulate river stage variability and near-river piezometric head distribution with a rather low computational cost, as the hydraulic model is not coupled to the hydrogeological model, but it is used to construct the rating curves. However, this method is also based on the availability of surveyed cross-section, which is often not guaranteed for regional scale basins.

At the regional scale, Pryet et al. (2015) simulate in-stream water level fluctuations with a simplified Manning-Strickler approach, which requires as input data some basic morphological features (river width, riverbed elevation and longitudinal slope) as well as the Manning roughness coefficient. The geomorphological properties are estimated with a Digital Elevation Model (DEM), while the roughness coefficient is calibrated against observed discharge and river stages as in Saleh et al. (2011). This is an acceptable compromise for simulating river stages at the regional scale (Saleh et al., 2013).

The approach followed by Pryet et al. (2015) is suitable for regional hydrosystems where surveyed cross-sections are not available. However, the river network morphological parameters are difficult to estimate at the regional scale and the values derived from a DEM may be affected by significant errors. The question then arises whether such errors in the modeling of river stage variability may hinder a correct evaluation of the stream-aquifer exchanges.

In this context, the present work aims at answering two main questions. First of all, which are the effects of in-stream water level fluctuations on the stream-aquifer exchanges for a regional hydrosystem? The answer to this question has a practical application for hydrosystem modeling because it will determine whether a simpler model assuming constant river stages is reliable or not.

The second question is: which are the effects of the uncertainties related to the modeling of in-stream water level fluctuations on the stream-aquifer exchanges? In other words, does the answer to the first question depend on the uncertainties on input quantities like the DEM and the Manning roughness coefficient?

In order to address these questions, an integrated distributed surface-subsurface model, Eau-Dyssée (Flipo et al., 2012; Flipo, 2013), is applied to the Loire river basin (117,480 km^2), where the variability of in-stream water levels is taken into account following the approach of Pryet et al. (2015). The effects of river stage fluctuations on the stream-aquifer exchanges are assessed by performing a simulation with constant river stages. Moreover, a sensitivity analysis of the stream-aquifer exchanges on some of the parameters controlling the river stage variability, namely, the DEM, which is used to estimate the riverbed elevation, and the Manning coefficient, is performed.

2. The Eau-Dyssée platform for hydrosystem modeling

Eau-Dyssée is a distributed model that allows the simulation of the different components of the water cycle in a hydrosystem. Detailed descriptions of the model can be found in Flipo (2013), Flipo et al. (2012), Saleh et al. (2011) and Saleh (2010). Here, only the main features are briefly recalled.

Eau-Dyssée conceptually divides a hydrosystem into three interacting compartments: surface, unsaturated zone and saturated zone. Specifically, the model couples six modules which simulate the surface water mass balance, the runoff, the river flow, the in-stream water level fluctuations, the flow in the unsaturated zone, the flow in the saturated zone (Fig. 1).

The surface water balance module is a conceptual model that computes runoff, real evapotranspiration, soil storage and infiltration from the input data of precipitations and potential evapotranspiration. This model integrates information on land use and soil cover through a seven-parameter conceptual model (production function, Deschesnes et al. (1985)).

The surface runoff is routed to the river network by the ISO module, according to which the runoff reaches the river network with a delay that depends on topography and concentration time (Flipo et al., 2012).

Water reaching the river network is routed by the module RAPID (Routing Application for Parallel Computation of Discharge, see David et al. (2011a,b, 2013)), which is based on a one-dimensional Muskingum scheme.

Then, the QTOZ module (Saleh et al., 2011; Saleh, 2010) calculates the in-stream water level as a function of the discharge routed by the module RAPID. The module allows three options: fixed water levels, water levels estimated from a rating curve or water levels estimated using the Manning-Strickler equation.

Infiltrated water flows through the unsaturated zone before reaching the saturated zone. This is simulated in the conceptual model NONSAT by introducing a succession of reservoirs, whose number increases with the thickness of the unsaturated zone. This simplified description of the unsaturated zone simulates the delay between water infiltration and flow in the saturated zone.

The flow in the saturated zone is simulated by the module SAM, which is a physically-based distributed hydrogeological model for