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Spatially distributed modelling of surface water-groundwater exchanges during overbank flood events – a case study at the Garonne River

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ABSTRACT

Exchanges between surface water (SW) and groundwater (GW) are of considerable importance to floodplain ecosystems and biogeochemical cycles. Flood events in particular are important for riparian water budget and element exchanges and processing. However SW-GW exchanges present complex spatial and temporal patterns and modelling can provide useful knowledge about the processes involved at the scale of the reach and its adjacent floodplain. This study used a physically-based, spatially-distributed modelling approach for studying SW-GW exchanges. The modelling in this study is based on the MOHID Land model, combining the modelling of surface water flow in 2D with the Saint-Venant equation and the modelling of unsaturated groundwater flow in 3D with the Richards' equation. Overbank flow during floods was also integrated, as well as water exchanges between the two domains across the entire floodplain. Conservative transport simulations were also performed to study and validate the simulation of the mixing between surface water and groundwater. The model was applied to the well-monitored study site of Monbéqui (6.6 km^2) in the Garonne floodplain (south-west France) for a five-month period and was able to represent the hydrology of the study area. Infiltration (SW to GW) and exfiltration (SW to GW) were characterised over the five-month period. Results showed that infiltration and exfiltration exhibited strong spatiotemporal variations, and infiltration from overbank flow accounted for 88% of the total simulated infiltration, corresponding to large flood periods. The results confirmed that overbank flood events played a determinant role in floodplain water budget and SW-GW exchanges compared to smaller (below bankfull) flood events. The impact of floods on water budget appeared to be similar for flood events exceeding a threshold corresponding to the five-year return period event due to the study area's topography. Simulation of overbank flow during flood events was an important feature in the accurate assessment of exchanges between surface water and groundwater in floodplain areas, especially when considering large flood events.

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1. Introduction

Exchanges at the interface between surface water (SW) and groundwater (GW) are known to play a key role in floodplain ecosystems (Amoros and Bornette, 2002, Sophocleous, 2002, Thoms, 2003). Areas of mixing between SW and GW are regions of intensified biogeochemical activity (Grimm and Fisher, 1984, McClain et al., 2003). These processes include denitrification, which has been recognised as the most important nitrate removal process in GW (Rivett et al., 2008) and can lead to significantly reduced nitrate concentrations in aquifers supporting agricultural activities (Sánchez-Pérez and Tremolières, 1997, Correll et al., 1992). Denitrification is known to be influenced by hydrological connectivity between SW and GW, and denitrification hotspots have been related to activation of the processes through the organic matter flux coming from surface water (Sánchez-Pérez et al., 2003, Bernard-Jannin et al., 2016). This natural mitigation process is reinforced by the dilution of contaminant concentrations due to the mixing between SW and GW (Pinay et al., 1998, Baillieux et al., 2014). In floodplains, flood events are an important feature for ecosystems. The pulsing of river discharge is the major driving

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force determining the exchange processes of organic matter and organisms across river-floodplain gradients (Junk et al., 1989, Tockner et al., 1999). Furthermore it is recognised that the overbank flow component has to be included in SW-GW exchanges for a comprehensive water balance assessment (Rassam et al., 2008). An accurate quantification and description of SW-GW exchanges, including overbank floods, is therefore a key factor when dealing with water quality in alluvial aquifers as it can help assess the patterns of activation of natural mitigation biogeochemical processes and dilution effects. However SW-GW interactions often present complex spatial and temporal patterns (Sophocleous, 2002, Krause et al., 2007) and a study at the scale of the stream and its adjacent floodplain (Woessner, 2000) is required to understand them fully.

As they allow characteristics of the environment to be taken into consideration on a detailed scale, physically-based, spatially-distributed models are valuable tools for improving knowledge of SW-GW exchanges and assessing the three-dimensional nature of the problem (Sophocleous, 1998, Bradford and Acreman, 2003). Numerous studies featuring distributed models and including SW-GW exchanges in floodplain areas have been carried out, encompassing SW-GW exchange patterns and biogeochemical zonation induced by meander sinuosity (Boano et al., 2006, Boano et al., 2010), heat transport (Brookfield et al., 2009, Horritt et al., 2006), 3D-flow patterns in relation to river level variations (Derx et al., 2010, Nützmann et al., 2013), hydrofacies heterogeneity impact on SW-GW exchanges (Frei et al., 2009), SW-GW exchange impact on floodplain water balance (Krause et al., 2007, Krause and Bronstert, 2007, Weng et al., 2003), solute transport through riparian areas (Weng et al., 2003, Hoffmann et al., 2006, Peyrard et al., 2008) and contribution of GW to stream water (Partington et al., 2011). While all these modelling studies integrate a surface and subsurface component as well as SW-GW exchanges, overbank flood events have not been included in the analysis. This can present a problem for assessing SW-GW exchanges in the floodplain accurately, especially during large flood events where infiltration from surface runoff can occur across the floodplain (Bates et al., 2000) and inundated areas can drive aquifer recharge patterns (Helton et al., 2014). Although overbank flood infiltration is not considered important when the river and aquifer are disconnected (Morin et al., 2009), it is recognised that the lack of an overbank flow component in models leads to an underestimation of infiltration of river water into the aquifer (Doppler et al., 2007, Engeler et al., 2011). In another study, overbank flow during flooding has been simulated to study floodplain contamination, but only vertical infiltration has been taken into account to evaluate pollutant deposition and subsurface flows have not been simulated (Stewart et al., 1998). In this case it is the simulation of subsurface flow returning to the river that is lacking in order to provide a comprehensive representation of SW-GW exchanges.

Overbank flood events are known to be very important for element processing and water budget in floodplain areas, but to the authors' knowledge they are not usually included in SW- GW studies. The main objective of this study was to assess the importance of overbank flood events on SW-GW interactions in a floodplain area. Using a distributed model, two domains – SW and GW – were simulated and coupled through infiltration/exfiltration processes. These processes were simulated across the entire floodplain area in order to include the impact of overbank flood events on SW-GW exchange dynamic. The model was applied to a well-monitored study site, providing a strong dataset for model validation, where SW-GW exchanges were analysed. A transport model was also included and the model was then used to evaluate SW-GW exchanges spatially and temporally for different flood conditions in the study area. This study is also a prerequisite for future work involving the simulation of biogeochemical processes such as denitrification in floodplain areas.

2. Materials and methods

2.1. Modelling approach

The modelling strategy for a complete surface-subsurface flow system should include surface and subsurface components and the coupling between them (Furman, 2008). Numerous models belong to this category that differ in terms of the formulation of the component governing equations (including dimensionality) and their coupling strategy and technical solution (Maxwell et al., 2014). For subsurface flow, most of the models solve the Richards' equation (one, two or three dimensions) and solve a formulation of the Saint-Venant equation (kinematic, diffusive or dynamic wave in one or two dimensions) for the surface component (Furman, 2008). The models differ in terms of their coupling strategy involving asynchronous linking (Condon and Maxwell, 2013), sequential iteration (Dagès et al., 2012) or a globally implicit scheme (Kollet and Maxwell, 2006), and the technical solution involving boundary conditions (BC) switching (Dagès et al., 2012), first-order exchange (Panday and Huyakorn, 2004) or pressure continuity (Maxwell et al., 2014, Kollet and Maxwell, 2006). In a study comparing seven models with the different characteristics described above, it was found that the models demonstrate the same qualitative agreement although they use different approaches (Maxwell et al., 2014).

Out of the open-source models able to simulate SW-GW exchanges, MOHID Land was applied in this study. This model includes all features required to simulate impact of flood events on SW-GW exchanges. Subsurface flow was computed with the three-dimensional Richard's equation needed to represent spatial variability of the flow in the unsaturated media of the floodplain area in detail. Surface flow was computed with the two-dimensional dynamic wave formulation of the Saint-Venant equation, allowing the correct representation of the rapidly changing stream stages during flooding. The coupling between the two components was produced through asynchronous linking and first-order exchange and realised across the entire modelled domain (*i.e.* not limited to the riverbed location). In addition, the model included a transport module. While these features are shared by several models, the novelty of the approach is to apply this type of model to simulate floodplain hydrology.

2.1.1. Overview of the MOHID model

MOHID Land is a part of the MOHID Water Modelling System (Neves et al., 2013) (www.mohid.com). It is a physically-based, spatially-distributed model designed to simulate the water cycle in hydrographic basins, including SW-GW interactions. It uses an object-oriented approach to facilitate the integration of different processes and modules, and a finite volume approach with a flux-driven strategy to facilitate the coupling of processes and verify the conservation of mass and momentum (Trancoso et al., 2009, Braunschweig et al., 2004, Brito et al., 2015).

Although it was originally designed to model river network systems and watersheds (Trancoso et al., 2009), the modularity of MOHID Land allows the model to meet the specific features of a floodplain area. The model set-up used in this study consisted of two domains: the surface water (SW) domain and the porous media (PM) domain (Fig. 1). The hydrology of the SW domain was calculated according to the two-dimensional Saint-Venant equation (dynamic wave). The river geometry was included in the SW domain to ensure the continuity of surface runoff simulation over the floodplain during overbank flood events. Water fluxes in the PM domain were calculated in three dimensions for saturated and unsaturated media using the Buckingham-Darcy equation. The spatially-distributed structure allowed interactions between the two domains – infiltration from SW to PM and exfiltration from

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