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Continental hydrosystem modelling: the concept of nested stream–aquifer interfaces

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Abstract

Recent developments in hydrological modelling are based on a view of the interface being a single continuum through which water flows. These coupled hydrological-hydrogeological models, emphasising the importance of the stream–aquifer interface, are more and more used in hydrological sciences for pluri-disciplinary studies aiming at investigating environmental issues. This notion of a single continuum, which is accepted by the hydrological modellers, originates in the historical modelling of hydrosystems based on the hypothesis of a homogeneous media that led to the Darcy law. There is then a need to first bridge the gap between hydrological and eco-hydrological views of the stream–aquifer interfaces, and, secondly, to rationalise the modelling of stream–aquifer interface within a consistent framework that fully takes into account the multi-dimensionality of the stream–aquifer interfaces. We first define the concept of nested stream–aquifer interfaces as a key transitional component of continental hydrosystem. Based on a literature review, we then demonstrate the usefulness of the concept for the multi-dimensional study of the stream–aquifer interface, with a special emphasis on the stream network, which is identified as the key component for scaling hydrological processes occurring at the interface. Finally we focus on the stream–aquifer interface modelling at different scales, with up-to-date methodologies and give some guidances for the multi-dimensional modelling of the interface using the innovative methodology MIM (Measurements-Interpolation-Modelling), which is graphically developed, scaling in space the three pools of methods needed to fully understand stream–aquifer interfaces at various scales. The outcome of MIM is the localisation in space of the stream–aquifer interface types that can be studied by a given approach. The efficiency of the method is demonstrated with two approaches from the local (~ 1 m) to the continental ($< 10\,\mathrm{M\,km^2}$) scale.

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1 Introduction

The emergence of a systemic view of the hydrological cycle led to the concept of continental hydrosystem (Dooge, 1968; Kurtulus et al., 2011), which "is composed of storage components where water flows slowly (e.g. aquifers) and conductive components, where large quantities of water flow relatively quickly (e.g. surface water)" (Flipo et al., 2012, p. 1). This concept merges surface and ground waters into the same hydrological system through the stream–aquifer interface. As a key transitional component characterised by a high spatio-temporal variability in terms of physical and biogeochemical processes (Brunke and Gonser, 1997; Krause et al., 2009b), this interface requires further consideration for characterising the hydrogeological behaviour of basins (Hayashi and Rosenberry, 2002), and therefore continental hydrosystem functioning (Saleh et al., 2011).

The dynamics of water exchanges at the stream–aquifer interface is complex and mainly depends on geomorphological, hydrogeological, and climatological factors (Sophocleous, 2002; Winter, 1998). Recent eco-hydrological publications, dedicated to stream–aquifer interfaces claim the recognition of the multi-dimensionality and the complexity of the processes taking place in the interface (Ellis et al., 2007; Hancock et al., 2005; Poole et al., 2008; Stonedahl et al., 2012). Also modern landscape typologies, emerging from eco-hydrological concepts based on functionalities of morphological units, highlight the multi-dimensionality of the stream–aquifer interfaces (Bertrand et al., 2012; Dahl et al., 2007). Behind the multi-dimensionality is the notion of scales, which structures the definition, the behaviour and the functionality of the stream–aquifer interface.

Paradoxically, recent developments in hydrological modelling are based on a view of the interface being a single continuum through which water flows (Jones et al., 2006, 2008; Kollet and Maxwell, 2006; Panday and Huyakorn, 2004; VanderKwaak and Loague, 2001; Werner et al., 2006). On the one hand, this notion of a single continuum, which is accepted by the hydrological modellers, originates in the historical modelling of hydrosystems based on the hypothesis of an homogeneous media that led to the Darcy law. On the other hand, coupled hydrological-hydrogeological models, emphasising the importance of the stream–aquifer interface, are more and more used in hydrological sciences for pluri-disciplinary studies aiming at investigating environmental issues (Ebel et al., 2009). However, these models do not explicitly consider the multi-dimentionality of stream–aquifer interfaces, as formerly highlighted by the eco-hydrological community. There is then a need to first bridge the gap between hydrological and eco-hydrological views of the stream–aquifer interfaces, and, second, to rationalise the modelling of stream–aquifer interface within a consistent framework that fully accounts for the multi-dimensionality of the stream–aquifer interfaces (Marmonier et al., 2012).

Following the attempt of Mouhri et al. (2013) aiming at rationalising the design of stream–aquifer interfaces sampling system, we first define the concept of nested stream–aquifer interfaces as a key transitional component of continental hydrosystem. Based on a literature review, we then demonstrate the usefulness of the concept for the multi-dimensional study of the stream–aquifer interface, with a special emphasis on the stream network which is identified as the key component for scaling hydrological processes occurring at the interface. Finally the paper focuses on the stream–aquifer interface modelling at various scales, with up-to-date methodologies, and gives some guidance for the multi-dimensional modelling of the interface using the MIM (Measurements-Interpolation-Modelling) methodology, which is illustrated with two examples. The first one analyses stream–aquifer interface processes from the local (~ 1 m) to the watershed ($\sim 1000\,\mathrm{km}^2$) scale. The second one evaluates the potential of the future space borne SWOT mission for further understanding of stream–aquifer interfaces at the regional and continental scales, which are the scales of interest for stakeholders and practitioners.

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2 The concept of nested stream–aquifer interfaces

Many hydrosystem models have been developed, and especially coupled surface–subsurface hydro(geo)logical models (Loague and VanderKwaak, 2004), with no special emphasis on stream–aquifer interfaces. Based on 171 references reviewed by Flipo (2013), Table 1 synthesises practical applications of the most used Distributed Physically-Based Models (DPBMs), with a special emphasis on their spatio-temporal sizes.

During the 1970's and 1980's, the first sedimentary bassin' DPBMs were developed based on the finite differences numerical scheme (Abbott et al., 1986; Freeze, 1971; Harbaugh et al., 2000; Ledoux et al., 1989; de Marsily et al., 1978; McDonald and Harbaugh, 1988; Parkin et al., 1996; Refsgaard and Knudsen, 1996). In this type of approach, the hydrosystem is divided into compartments, which exchange through interfaces.

Since the late 1990's, new models based on finite elements numerical schemes have been developed (Bixio et al., 2002; Goderniaux et al., 2009; Kolditz et al., 2008; Kollet and Maxwell, 2006; Li et al., 2008; Panday and Huyakorn, 2004; Therrien et al., 2010; VanderKwaak and Loague, 2001; Weill et al., 2009). These models allow the simulation of the pressure head in 3-D instead of the former pseudo 3-D modelling of the piezometric head. However, it is not yet possible to straightforwardly simulate large hydrosystems (> 10 000 km^2) with a high spatio-temporal resolution for long periods of time (a few decades) (Flipo et al., 2012). This is due to the large number of elements required to simulate such hydrosystems (Gunduz and Aral, 2005), which imposes the usage of heavily parallelised codes for simulating these systems with such a spatio-temporal resolution. Only a proof of concept has recently been published by Kollet et al. (2010), who have simulated a 1000 km^2 basin with a high spatio-temporal resolution.

Contrarily to the atmosphere–groundwater interface (mostly the soil and the vadose zone), which was intensively studied through experimental (even with satellites facilities) and modelling approaches up to a project of a 1 km × 1 km distributed modelling of the earth hydrological cycle (Beven and Cloke, 2012; Wood et al., 2011, 2012), the stream–aquifer interfaces have only been intensively surveyed for broadly two decades (Fleckenstein et al., 2006; Marmonier et al., 2012). Its study by the eco-hydrological community led to a re-conceptualisation of its nature from the river being seen as an impervious drain that collects the effective rainfall and transfers it to the ocean, toward a more subtle view that integrates more spatio-temporal processes in the hydrosystem functioning. Indeed, the stream–aquifer interface is now conceptualised as a filter through which water flows many times over various spatial (from centimetres to kilometres) and temporal scales (from seconds to months) before to reach the sea (Datry et al., 2008). One of the main challenges is to understand the role of the stream–aquifer interfaces in the hydro(geo)logical functioning of basins (Hayashi and Rosenberry, 2002). The multi-dimensionality of the problem at hand imposes to define the scales of interest.

The five commonly recognised scales (scale is used here for the size of the studied objects) are the local, the reach, the catchment, the regional, and the continental ones (Blöschl and Sivapalan, 1995; Dahl et al., 2007; Gleeson and Paszkowski, 2013), being defined as:

- local scale (or the experimental site scale) [10 cm–~ 10 m]: this scale concerns the riverbed or the hyporheic zone (HZ, see Sect. 3.2 for more details);
- intermediate or reach scale [100 m–~ 10 km]: it concerns the river reach, a pound or a small lake;
- catchment–Watershed scale [10 km^2–~ 1000 km^2]: this scale connects the stream network to its surface watershed and more broadly to the hydrosystem. This is the scale from which surface-ground water exchanges are linked with the hydrological cycle and the hydrogeological processes;
- regional scale [10 000 km^2–~ 1 M km^2]: this is the scale of water resources management, and the one for which the least is known about stream–aquifer exchange dynamics. For a conceptual analysis of the stream–aquifer interfaces,

the watershed and the regional scales can be merged into a single category referred to as the regional scale (Mouhri et al., 2013). Merging these two scales is consistent with the fact that a regional basin is a collection of smaller watersheds. The distinction between the two categories is only necessary to conceptualise the scaling of processes as discussed in the final section of this paper;

– continental scale [$> 10\,\mathrm{M\,km^2}$]: this scale is a collection of regional scale basins. The difference with the regional scale is that there is a broader range of hydro-climatic conditions, which imposes to take into account climatic circulations.

From a conceptual point of view, stream–aquifer exchanges are driven by two main factors: the hydraulic gradient and the geological structure. The hydraulic gradient defines the water pathways (Winter, 1998), whereas the geological structure defines the conductive properties of the stream–aquifer interface (White, 1993; Dahm et al., 2003). These two factors are fundamental for hydrogeologists, who derive from those subsurface flow velocities and transfer times. The time scale to be considered also varies depending on the studied object (HZ itself or a sedimentary basin functioning) (Harvey, 2002). Estimating the stream–aquifer exchanges at a sedimentary basin scale then requires the combination of various processes with different characteristic times or periods covering a wide range of temporal orders of magnitude (Blöschl and Sivapalan, 1995; Flipo et al., 2012; Massei et al., 2010): hour-day for river flow, year-decade for effective rainfall, decade-century for subsurface transit time. To address this, models are used as spatio-temporal interpolators. The final choice of model, which can be either conceptual, statistical, process-based or hybrid, is a trade off between a number of factors, such as the required accuracy, type and availability of data, available computational facilities, temporal and spatial scale. The rationale for selecting a particular stream–aquifer modelling technique is a function of the application's objective and of the model's suitability for modelling key aspects of the problem at hand (Saleh et al., 2011).

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Mouhri et al. (2013) proposed a multi-scale framework to study stream–aquifer interfaces. Their approach is based on the observation that the two main hydrosystem components are the surface and groundwater components, which are connected by nested interfaces (Fig. 1). Stream–aquifer interfaces consist in alluvial plain at the regional and watershed scales (Fig. 1a and b), while within the alluvial plain, they consist in riparian zone at the reach scale (Fig. 1d). Within the riparian zone, they consist in the hyporheic zone at the local scale (Fig. 1c), and so on until the water column–benthos interface within the river itself (Fig. 1f). Before further developing the multi-scale framework, the various descriptions of stream–aquifer interfaces are outlined.

3 Multi-dimensionality of the stream–aquifer interface

A literature review of process-based modelling of stream–aquifer interfaces' functioning is presented in Table 2, which synthesises 42 references. The majority of them focuses on the local scale (21), while only four consider the regional and continental scales. The remaining mostly focuses on the local-intermediate (9) and intermediate scales (7).

3.1 A multi-scale issue structured around the intermediate scale – the river

The river network is identified as being the location where flow paths mix at all scales, and therefore the location of hydrological process scaling.

Near river groundwater flow paths are mainly controlled by regional flow paths in aquifer systems (Malard et al., 2002). Indeed, the groundwater component of hydrosystem controls the regional flows towards the alluvial plains and the rivers. Such flow paths define the total amount of water that flows in the stream–aquifer interface (Cardenas and Wilson, 2007b; Frei et al., 2009; Kalbus et al., 2009; Rushton, 2007; Storey et al., 2003). This is not a new concept as the river network corresponds to drains collecting regional groundwater (Fig. 1a), which sustain the network during low flow period (Ellis et al., 2007; Pinder and Jones, 1969; Tóth, 1963). These large scale structural heterogeneities can also generate local conditions that favour local re-infiltration of river water towards the aquifer system (Boano et al., 2010; Cardenas, 2009a, b; Fleckenstein et al., 2006). These re-infiltrations (Fig. 1b and c) can even constitute the main recharge of some peculiar local aquifer systems, as for instance some alluvial plain (Krause and Bronstert, 2007; Krause et al., 2007).

In second instance, the spatial distribution of the stream bed permeabilities controls the dynamics of stream–aquifer exchanges within the alluvial plain, and therefore the near-river piezometric head distribution (Calver, 2001; Fleckenstein et al., 2006; Frei et al., 2009; Genereux et al., 2008; Hester and Doyle, 2008; Kalbus et al., 2009; Käser et al., 2009; Rosenberry and Pitlick, 2009). Finally the longitudinal morphology of the river and the topography of the river bed, consisting in a pluri-metric succession of pools and riffles (Fig. 1e), also impact the stream–aquifer exchanges (Cardenas et al., 2004; Crispell and Endreny, 2009; Frei et al., 2010; Gooseff et al., 2006; Harvey and Bencala, 1993; Kasahara and Wondzell, 2003; Kasahara and Hill, 2006; Krause et al., 2012a; Stonedahl et al., 2010; Storey et al., 2003; Tonina and Buffington, 2007), as well as the depth of the alluvial aquifer (Koch et al., 2011; Marzadri et al., 2010; Whiting and Pomeranets, 1997) and the river hydraulic regime (Cardenas and Wilson, 2007a; Munz et al., 2011; Saenger et al., 2005). Ultimately a very fine scale process (~ cm–dm), due to the in-stream non hydrostatic flow induced by bedform micro-topography (Fig. 1f), also increases the absolute value of the total stream–aquifer exchanges (Cardenas and Wilson, 2007a; Cardenas and Wilson, 2007b; Endreny et al., 2011; Janssen et al., 2012; Käser et al., 2013; Krause et al., 2012b; Sawyer and Cardenas, 2009; Stonedahl et al., 2010).

It is therefore important to study the stream–aquifer exchanges in the dual perspective of regional and local exchanges; the former being controlled by regional recharge and structural heterogeneities, the later by the longitudinal distribution of stream bed heterogeneities and the river morphology (Schmidt et al., 2006). These two types of controlling factors may also generate water loops within the stream–aquifer interfaces, the river corridor being the location where these processes merge.

Ellis et al. (2007) confirmed this statement with the investigation of the spatio-temporal relevance of both data sampling density and models from the intermediate scale to the local one. They concluded that stream–aquifer exchange distributions are submitted to multi-scale controls, which influence the thickness of the HZ and the patterns of groundwater flow through the riverbed.

3.2 The stream–aquifer interface at the local scale – the hyporheic zone

At the local scale (plot, river cross section), the stream–aquifer interface consists in a hyporheic zone (HZ), which corresponds to an ecotone, whose extent varies dynamically in space and time. This ecotone is at the interface between two more uniform, yet contrasted ecological systems (Brunke and Gonser, 1997): the river and the aquifer. In a broad sense, the HZ is "the saturated transition zone between surface water and groundwater bodies that derives its specific physical (e.g. water temperature) and biogeochemical (e.g. steep chemical gradients) characteristics from active mixing of surface and groundwater to provide a habitat and refugia for obligate and facultative species" (Krause et al., 2009a, p. 2103). White (1993) also indicates that the HZ is located beneath the stream bed and in the stream banks that contain infiltrated stream water. Furthermore, Malard et al. (2002) identified five generic HZ configurations, that depend on the structure of the subsurface media, and especially on the location of the impervious substratum:

1. No HZ: the stream flows directly on the impervious substratum. A perennial lateral HZ can appear in the zone of significant longitudinal curvature of the stream, for instance in the case of meanders (Boano et al., 2009; Cardenas, 2009a; Revelli et al., 2008).

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2. No aquifer unit: a HZ can appear due to the infiltration of the stream water towards the substratum or through the stream banks. In the former case, the substratum is located near to the stream bed sediments.

3. Existence of a HZ in a connected stream–aquifer system: the HZ is created by advective water from both the stream and the aquifer unit. The impervious substratum is located beneath the aquifer unit.

4. Existence of a HZ in a disconnected stream–aquifer system: a distinct porous media lies in between the stream bed and the aquifer unit. This porous media would not be saturated if the stream bed were impervious. In this configuration, two subcategories are to be found:

   a. the vertical infiltration of stream water towards the top of the aquifer unit generates a zone of mixing waters at the top of the aquifer unit, far enough below the stream bed to be disconnected from it,

   b. a perched HZ is formed below the stream bed due to the infiltration of stream water. In this particular case, the porous media below the stream bed is either very thick or its conductive properties are so poor that the surface water may not reach the aquifer unit.

The extent of the HZ, which depends on the hydrological settings, varies from centimetres to hundreds of meters (Brunke and Gonser, 1997; Woessner, 2000; Wroblicky et al., 1998). Even in a specific configuration, the extent and the nature of the stream–aquifer interface vary through time, depending on the hydro(geo)logical context. For instance, Conant (2004) and Storey et al. (2003) reported that the HZ is affected by the regional flow of the aquifer system, whereas Wroblicky et al. (1998) indicate that the variation of the head difference between aquifer and stream modifies the extent of the HZ.

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3.3 The stream–aquifer interfaces at the regional and continental scales – the alluvial plains

The interaction between surface and subsurface waters has also been identified at the basin scale, where geological heterogeneities control the stream–aquifer exchanges, which in return can control the near river piezometric head distribution in the case of an alluvial aquifer (Boano et al., 2010; Cardenas, 2009a, b; Fleckenstein et al., 2006).

Although the usage of DPBM covers a broad range of spatial scales, only 19 publications among 183 (Tables 1 and 3) concern large river basins (> 10 000 km^2) (Abu-El-Sha's and Rihani, 2007; Andersen et al., 2001; Bauer et al., 2006; Boukerma, 1987; Christiaens et al., 1995; Etchevers et al., 2001; Golaz-Cavazzi et al., 2001; Gomez et al., 2003; Habets et al., 1999; Hanson et al., 2010; Henriksen et al., 2008; Kolditz et al., 2012; Ledoux et al., 2007; Lemieux and Sudicky, 2010; Monteil, 2011; Park et al., 2009; Saleh et al., 2011; Scibek et al., 2007) and except Monteil (2011), Pryet et al. (2013) and Saleh et al. (2011), none of them focuses on stream–aquifer exchanged water flux. Moreover, among DPBMs dedicated to stream–aquifer exchanges, no application was carried out at the regional scale (Table 3).

At this scale, most of the hydro(geo)logical models are limited to take into account local processes as the effect of near river pumping, or storage in the hyporheic zone, because they require a very fine spatial discretisation, which can be incompatible with the resolution of the model or, at most, drastically decreases the efficiency and precision of the model. Moreover, the usage of regional models to solve local issues, as well as the reverse, leads to equifinality problems (Beven, 1989; Beven et al., 2011; Ebel and Loague, 2006; Klemes, 1983; Polus et al., 2011), boundary conditions inconsistencies (Noto et al., 2008), or computational burdens (Jolly and Rassam, 2009). The usage of local models to solve regional issues also leads to the same effects (Aral and Gunduz, 2003, 2006; Wondzell et al., 2009). Moreover, neither a too simple model, nor a too complex one can provide relevant answers (Hill, 2006; Smith et al., 2004; Wondzell et al., 2009). Therefore alternative ways of modelling are needed to properly simulate

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the behaviour of stream–aquifer interfaces at the regional scale (Werner et al., 2006), especially that for a given reach of river the direction of stream–aquifer exchanges can vary longitudinally (Bencala et al., 2011).

According to Krause et al. (2011) the knowledge on processes occurring in the stream–aquifer interface and the need for knowledge by water resources managers is first inversely correlated, and second not much is known about the role of stream–aquifer interfaces at the regional scale, which is the scale of interest for practitioners. There is therefore is a crucial need to develop inovative methodologies for assessing stream–aquifer exchanges at the regional scale.

4 Modelling stream–aquifer exchanges

4.1 Models to simulate stream–aquifer interface

Surface water groundwater exchanges, mostly through the soil or the stream–aquifer interface, are simulated with two different models (Ebel et al., 2009; Kollet and Maxwell, 2006; LaBolle et al., 2003; Furman, 2008), whatever the number of simulated spatial dimensions (Tables 2 and 3):

- A conductance model or first order exchange coefficient, for which the interface is described with a water conductivity value. The exchanged water flux is then calculated as the product of the conductivity by the difference of piezometric heads between the aquifer and the surface water body. Depending on the model, the difference of pressures can also be used. This model implicitly formulates the hypothesis of a vertical water flux between surface water and groundwater whatever the mesh size. This is the most common model for simulating stream–aquifer exchanges. There are diverse conductance's formulations, especially in the case of disconnected aquifers and streams (Osman and Bruen, 2002). Irvine et al. (2012) advocate for the usage of the conductance model if the stream bed heterogeneities are well described, which is usually critical (Genereux et al., 2008).

However the conductance coefficient depends on the temperature because it implicitly integrates the fluid viscosity (Engeler et al., 2011). Moreover, the validity of the first order law is critical in case of a flood when water expends in the flood plain (Engeler et al., 2011).

– Continuity of pressures and fluxes at the interface. This boundary condition requires an iterative or a sequential computation, although the iterative one is more precise (Sulis et al., 2010). Sometimes the iterative process also leads to a discontinuity of the tangential component of the water velocity at the interface with the stream bed (Discacciati et al., 2002; Miglio et al., 2003; Urquiza et al., 2008). This is not a problem as this discontinuity can be interpreted as representative of the stream bed load.

Recent numerical developments allow for solving the coupled surface and subsurface equations at once with a matricial system. This method is called coupled in Tables 2 and 3, and can be used with whatever selected stream–aquifer interface model. One of the main drawbacks of this method is that it is computationally demanding and usually requires a parallelised model in order to simulate real hydrosystem.

From a conceptual point of view, the conductance model permits to better understand the hydrological processes occurring at the stream–aquifer interface (Delfs et al., 2012; Ebel et al., 2009; Liggett et al., 2012; Nemeth and Solo-Gabriele, 2003) and is equivalent to the continuity one in the case of a highly conductive interface.

4.2 Temperature as a tracer of the flow – the local scale

The study of heat propagation is a powerful tool for assessing stream–aquifer exchanges (Anderson, 2005; Constantz, 2008; Mouhri et al., 2013) based on the temperature used as a tracer of the flow. Coupled with in situ measurements, two methods, based on heat transport governing equations, are used to quantify stream–aquifer exchanges (Anderson, 2005):

1. Analytical models (Stallman, 1965; Anderson, 2005) are widely used to inverse temperature measurements solving the 1-D heat transport equation analytically under simplifying assumptions (sinusoidal or steady boundary conditions and homogeneity of hydraulic and thermal properties) (Anibas et al., 2009; Anibas et al., 2012; Becker et al., 2004; Hatch et al., 2006; Jensen and Engesgaard, 2011; Keery et al., 2007; Lautz et al., 2010; Luce et al., 2013; Rau et al., 2010; Schmidt et al., 2007; Swanson and Cardenas, 2011).

2. Numerical models which couple water flow equation in porous media with the heat transport equation in 2-D or 3-D. These models are divided in two categories based on the numerical scheme: finite differences (Anderson et al., 2011; Anibas et al., 2009; Constantz et al., 2002, 2013; Constantz, 2008; Ebrahim et al., 2013; Lewandowski et al., 2011; Mutiti and Levy, 2010; Rühaak et al., 2008; Schornberg et al., 2010) or finite elements (Kalbus et al., 2009; Mouhri et al., 2013). These models have the advantage of calculating spatio-temporal stream–aquifer exchanges with the capability of accounting for the heterogeneities under transient hydrodynamical and thermal conditions.

Eventually the two approaches provide estimates of the conductance coefficient that best represents the stream–aquifer interface at the local scale.

4.3 The conductance model at the regional scale

To the authors' knowledge, very few DPBMs have been applied to assess stream–aquifer exchanges at the regional scale ($> 10\,000\,\mathrm{km}^2$) (see Sect. 3.3). These applications exclusively use the conductance model, for which the longitudinal distribution of the conductance along the stream network has to be calibrated (Pryet et al., 2013). To provide accurate estimates, the conductance model has to be constrained by the piezometric head below the river and the surface water elevation. Former applications used a fixed water level throughout the simulation period (Flipo et al., 2007; Gomez et al., 2003; Monteil, 2011; Thierion et al., 2012). Saleh et al. (2011) showed that this

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methodology not only leads to biased assessments of stream–aquifer exchanges, but also to biased estimates of the near river piezometric head distributions.

The simulation of surface water levels is therefore of primary importance for the estimation of distributed stream–aquifer exchanges along the stream network at regional scale (Pryet et al., 2013; Saleh et al., 2011). Saleh et al. (2013) recommend the usage of local 1-D Saint-Venant based hydraulic models to build rating curves for every cell of a coarser regional model (Saleh et al., 2011) that uses simpler in-stream water routing models as RAPID (David et al., 2011). Such models are then coupled with the conductance model to simulate stream–aquifer exchanges at the regional scale along thousands of kilometres of river networks with a 1 km spatial discretisation (see for instance Pryet et al., 2013 for such an application along 4000 km of the Paris basin river network).

4.4 Conceptual needs at the continental scale

Russell and Miller (1990) achieved the first runoff calculation based on a $4^{\circ} \times 5^{\circ}$ grid mesh coupled with a Land Surface Model (LSM) and an Atmospheric Global Circulation Model (AGCM). It appears that even at this scale the river networks play an important role in the circulation models and water transfer time. Since then, few models have been developed to simulate the main river basins in the AGCMs with a grid mesh of $\sim 1^{\circ} \times 1^{\circ}$, which roughly corresponds to a 100 km × 100 km resolution (Oki and Sud, 1998). Geographical Information Systems (GISs) were used to derive the river networks from Digital Elevation Models (Oki and Sud, 1998). Jointly RRMs (River Routing Models) have been developed with simple transfer approaches, assuming either a steady uniform water velocity at the global scale or a variable water velocity based on simple geomorphological laws and the Manning Formula (Arora and Boer, 1999).

Decharme and Douville (2007) implemented the approach with a constant in-river water velocity (assumed to be 0.5 $m\,s^{-1}$) within the LSM, today referred to as SURFEX (Masson et al., 2013). Step by step the description of stream–aquifer exchanges was improved with:

- The introduction of a variable in-river water velocity (Decharme et al., 2008).
- A transfer time delay due to the stream–aquifer interface (Decharme et al., 2012).
- The explicit simulation with a DPBM of the worldwide largest aquifer systems coupled with the explicit simulation the river networks draining surface basins larger than 50 000–100 000 km^2 (Vergnes and Decharme, 2012).
- The explicit simulation of stream–aquifer exchanges based on the conductance model on a $0.5^\circ \times 0.5^\circ$ grid mesh (Vergnes et al., 2012; Vergnes and Decharme, 2012) in agreement with the continental scale transfer time delay of 30 days introduced by Decharme et al. (2012).

As expected given the numerical experiments of Maxwell and Miller (2005), accounting for groundwater kinetics improves the global hydrological mass balance (Decharme et al., 2010; Alkama et al., 2010; Yeh and Eltahir, 2005). Although the explicit simulation of stream–aquifer exchanges with the conductance model slightly improves the models' performances in terms of spatio-temporal discharge and real evapotranspiration assessments (Vergnes et al., 2012; Vergnes and Decharme, 2012), the global calibration of the conductance parameter has to take into account the multi-scale structure of the stream–aquifer interfaces, which means that a better assessment, not only of simple DEM derived river networks, but also of the transfer time in the stream–aquifer interfaces is required as well as the subgrid definition of dendritic river networks. Coupled with proper scaling procedures (see next section) these approaches seem to be less computationally demanding than the one proposed by Wood et al. (2011) and slightly less over parametrised, which should permit to better resolve the estimation of stream–aquifer exchanges at the continental scale.

4.5 Up and downscaling stream–aquifer exchanges

The conductance model historically assumes vertical fluxes at the stream–aquifer interface (Krause et al., 2012a; Sophocleous, 2002), so that it seems to be a proper

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framework for determining up and down scaling properties of stream–aquifer interfaces (Boano et al., 2009; Engdahl et al., 2010). However this hypothese becomes less valid at regional scale when the grid mesh is getting coarser (Mehl and Hill, 2010; Rushton, 2007). Indeed, in heterogeneous media modelling, the transmissivity field and the associated piezometric heads are highly mesh size dependent (Renard, 1997). Furthermore, in many models the calculated piezometric head corresponds to a volumetric average on the grid cells (Bear, 1972; de Marsily, 1986; Ledoux et al., 1989). In the case of a coarse grid, the calculated piezometric head at the stream–aquifer interface does not represent the piezometric head beneath the river itself (Fig. 2). The averaging process can then induce uncertainties in the assessment of the conductance parameter, which becomes scale dependent (Vermeulen et al., 2006).

The hypothesis of vertical fluxes is discussed by Rushton (2007) based on numerical experiments that showed its limit. Indeed, at the regional scale, stream–aquifer exchanges seem to be more controlled by the horizontal permeability of the aquifer unit than by the equivalent vertical permeabilities of both the river bed and the aquifer unit. Recently, this new formulation of the drivers of stream–aquifer exchanges proved to be suitable for the calibration of a regional modelling of stream–aquifer exchanges (Pryet et al., 2013).

As formulated by Rushton (2007), Pryet et al. (2013) calibrated a correction factor. To properly scale the conductance model, the correction factor should be defined analytically by linking the conductance to the vertical permeabilities of the stream bed and the aquifer unit (through the anisotropy of the near stream aquifer unit) (Morel-Seytoux, 2009). Coupled to the scaling of the conductance, proper distribution of piezometric heads has to be estimated (Vermeulen et al., 2006). A potential methodology could consist in a near stream interpolation of the regional piezometric head, which should consider the local variability of the transmissivity field (Chen and Durlofsky, 2006), verify the integrity of the regional flux (Mehl and Hill, 2002) and take into account the geometrical change of boundary conditions (Panday and Langevin, 2012).

Coupling these up and downscaling procedures of both parameters and state variables is critical for the explicit formulation of the nested stream–aquifer interface concept in a modelling framework structured around the river network, where the computational power needs to be concentrated.

5 The MIM methodology: from concepts to practice

The methodology of Mouhri et al. (2013) is hereby graphically developed, scaling in space the three pools of methods (measurements-interpolation-modelling) needed to fully understand stream–aquifer interfaces at various scales. The outcome is the MIM (Measurement-Interpolation-Modelling) methodological tool, which localises in space the type of stream–aquifer interface that can be studied by a given approach (see the five scales of interest in Fig. 3: local, reach, watershed, regional and continental scales).

5.1 Coupled in situ-modelling approaches: from local to watershed scale

Figure 4 displays the types of stream–aquifer interfaces that can be studied by the multi-scale sampling system developed by Mouhri et al. (2013), based on LOcal MOnitoring Stations (LOMOS) distributed along a 6 km river network covering a 40 km^2 watershed. As illustrated in Fig. 4, a single LOMOS allows the monitoring, based on water pressure and temperature measurements, of stream cross-sections ranging from 0.1–$\sim$ 10 m. LOMOS data are used with coupled thermo-hydro models to determine the properties of the aquifer units and the river beds (Mouhri et al., 2013), which can be used to assess the value of the conductance at the watershed scale (Mehl and Hill, 2002; Morel-Seytoux, 2009; Vermeulen et al., 2006; Rushton, 2007). Assuming that it is possible to distribute multiple LOMOS data, and the associated conductance values, along a stream network (for instance using FO-DTS – Fiber Optic Distributed Thermal Sensors), local in situ data become the basis of a broader surface–subsurface modelling at the watershed scale (Table 1). It thus appears in the MIM space that the upscaling is structured around stream cross-sections of ~ 1–10 m (Fig. 4).

5.2 Space borne approaches: regional and continental scales

At the regional and continental scales, stream–aquifer interfaces can be observed, at least partially, using satellite measurements (Fig. 4). Current satellite platforms do not allow for accurate observation of stream–aquifer exchanges, but they should be able to provide valuable information in the near future (Alsdorf et al., 2007). Indeed, total water storage (e.g. surface waters and ground waters) variations can be estimated from the Gravity Recovery and Climate Experiment (GRACE) mission, launched in 2002 (Tapley et al., 2004). Ramillien et al. (2008) present an extensive review of large-scale hydrological use of the first years of GRACE data. However, these data have low spatial (300–400 km) and temporal resolution (from 10 days to 1 month) (Ramillien et al., 2012), limiting their use for continental scales. Moreover, these data have to be coupled with ancillary information to distinguish between surface waters and ground waters variations. For instance, surface water variations can be estimated by combining multi sensors measurements. Optical or Radar images are used to compute water extent (Cretaux et al., 2011) and can be combined with Digital Elevation Model (DEM) or with water elevation measurements from NADIR altimeters (Calmant et al., 2008) to derive storage changes and fluxes (Neal et al., 2009; Gao et al., 2012). The mismatch between acquisition time, repeatability, and spatial coverage of such data implies that it is difficult to use them for the assessment of stream–aquifer exchanges at the continental scale.

To overcome these issues a new space-borne mission, the Surface Water and Ocean Topograpy (SWOT) mission, is currently being developed by NASA, CNES (French Spatial Agency) and CSA (Canadian Space Agency), for a planned launch around 2020. SWOT will provide maps of distributed water elevations, water extents and water slopes on two swaths of 50 km coverage each. It will enable the observation of rivers wider than 100 m and surface areas larger than 250 m × 250 m (Rodríguez, 2012).

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Accuracies on water elevation and water slope will be around 10 cm and 1 cm km^{-1}, respectively, after averaging over 1 km^2 water area (Rodríguez, 2012). From these requirements, Biancamaria et al. (2010) estimated that SWOT should be able to provide useful information to compute discharge for river reaches with drainage areas above 70 000 km^2. This preliminary assessment was recently refined by Andreadis et al. (2013), who estimate that rivers with a bank full width of 100 m have drainage area ranging from 1050 to 50 000 km^2. Although the database contains errors (reported errors on river width range from 8 to 62 %), it provides the order of magnitude of minimum drainage area that should be sampled by SWOT. Thanks to the two swaths and its ∼ 20 day repeat orbit, the instrument will observe almost all continental surfaces in between 78° S and 78° N, allowing the sampling of all drainage areas above 50 000 km^2. Therefore SWOT is a valuable tool to localise in the MIM space (Fig. 4). SWOT data consist of raw cloud data, which appear on the measurement axis, and reach averaged data to reduce uncertainties (see the Interpolation axis in Fig. 4). Both products can be coupled with regional or continental hydrosystem models. To achieve such coupled applications, it will be necessary to use downscaling methods (Aires et al., 2013) and/or assimilate SWOT observations in stream–aquifer interface models like the one used by Pryet et al. (2013), Saleh et al. (2011) and Vergnes and Decharme (2012).

5.3 Further challenges

Albeit being a breakthrough in terms of surface coverage SWOT requirements impose restrictions on observable stream–aquifer interfaces, which can be visualised in the MIM space (Fig. 4). Unfortunately, it appears in the MIM space that SWOT applications do not completely overlap other methodologies as the one proposed to scale processes between the local and the watershed scales. To overcome this issue, an incoming airborne campaign, called AirSWOT, with a main payload similar to the one of SWOT, but with higher spatial resolution (metric), will (i) help to determine whether regular airborne campaigns can provide a valuable tool to connect the watershed scale to the regional/continental one with the help of multi-scale modelling tools (cf. Sect. 4.5) and (ii) permit to design new in situ monitoring stations derived from the LOMOS defined by Mouhri et al. (2013) but dedicated to the watershed/regional scale, which means for river cross-sections larger than a few decametres.

6 Conclusions

The systemic view of hydrosystems makes us reformulate the stream–aquifer interface as a cascade of nested objects. These nested objects depend on the scale of interest. At the watershed, regional and continental scales, they consist in alluvial plains, while within the alluvial plan itself (intermediate-reach scale), they consist in riparian zones. Within the riparian zone (local scale), they consist in HZ, and so on until the water column–benthos interface within the river itself.

Estimating stream–aquifer exchanges therefore requires to combine the modelling of various processes with different characteristic times. Depending on the refinement of the modelling at the regional scale (i.e. number of processes taken into account), the estimation of stream–aquifer exchanges may vary significantly. As stakeholders need more detailed information at the regional scale, which is the scale of water resources management, it is crucial to develop modelling tools which can precisely simulate stream–aquifer exchanges at the reach scale within a regional basin. These innovative modelling tools should be multi-scale modelling platforms, which implement the concept of nested stream–aquifer interfaces as the core of the coupling between regional and local models: the former simulating the basin, the latter the alluvial plains. To achieve this, it was shown that processes scaling should be performed around the river network.

To fully estimate stream–aquifer exchanges, this multi-scale modelling tool has to be coupled with observation devices. The MIM methodology provides a powerful framework to jointly develop observation infrastructures and modelling tools, allowing the localisation of the global structure in the scale space. The main result of the first analysis is that airborne campaigns, as well as regional in situ systems, will have to be rationalised to connect the watershed to the regional and continental scales, which will be sampled by the SWOT mission.

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References

Abbott, M., Bathurst, J., Cunge, J., O'Connell, P., and Rasmussen, J.: An introduction to the European Hydrological System, 1. History and philosophy of a physically based distributed modelling system, J. Hydrol., 87, 45–59, 1986. 455

Abu-El-Sha's, W. and Rihani, J.: Application of the high performance computing techniques of ParFlow simulator to model groundwater flow at Azraq basin, Water Resour. Manag., 21, 409–425, doi:10.1007/s11269-006-9023-5, 2007. 462

Aires, F., Prigent, C., Papa, F., and Cretaux, J.-F.: Downscaling of the inundation extent over the Niger delta using a combination of multi-wavelength and Modis retrievals, J. Hydrometeorol., doi:10.1175/JHM-D-13-032.1, in press, 2013. 471

Alkama, R., Decharme, B., Douville, H., Becker, M., Cazenave, A., Sheffield, J., Voldoire, A., Tyteca, S., and Moigne, P. L.: Global evaluation of the ISBA-TRIP continental hydrological system, Part I: Comparison to GRACE terrestrial water storage estimates and in situ river discharges, J. Hydrometeorol., 11, 583–600, 2010. 467

Alsdorf, D., Rodríguez, E., and Lettermaier, D.: Measuring surface water from space, Rev. Geophys., 45, RG2002, doi:10.1029/2006RG000197, 2007. 470

Andersen, J., Refsgaard, J., and Jensen, K.: Distributed hydrological modelling of the Senegal River Basin – model construction and validation, J. Hydrol., 247, 200–214, 2001. 462

Anderson, M. P.: Heat as a ground water tracer, Ground Water, 43, 951–968, doi:10.1111/j.1745-6584.2005.00052.x, 2005. 464, 465

Anderson, W. P., Storniolo, R. E., and Rice, J. S.: Bank thermal storage as a sink of temperature surges in urbanized streams, J. Hydrol., 409, 525–537, doi:10.1016/j.jhydrol.2011.08.059, 2011. 465

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11, 451–500, 2014

Nested stream–aquifer interfaces

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Andreadis, K., Schumann, G., and Pavelsky, T.: A simple global river bankfull width and depth database, Water Resour. Res., 49, 7164–7168, doi:10.1002/wrcr.20440, 2013. 471

Anibas, C., Fleckenstein, J., Volze, N., Buis, K., Verhoeven, R., Meire, P., and Batelaan, O.: Transient or steady-state? Using vertical temperature profiles to quantify groundwater-surface water exchange, Hydrol. Process., 23, 2165–2177, doi:10.1002/hyp.7289, 2009. 465

Anibas, C., Verbeiren, B., Buis, K., Chormański, J., De Doncker, L., Okruszko, T., Meire, P., and Batelaan, O.: A hierarchical approach on groundwater-surface water interaction in wetlands along the upper Biebrza River, Poland, Hydrol. Earth Syst. Sci., 16, 2329–2346, doi:10.5194/hess-16-2329-2012, 2012. 465

Aral, M. and Gunduz, O.: Scale effects in large scale watershed modeling, in: International Conference on Water and Environment, edited by: Singh, V. and Yadava, R., Allied Publishers, India, 37–51, 2003. 462

Aral, M. and Gunduz, O.: Large-scale hybrid watershed modeling, in: Watershed Models, edited by: Singh, V. P. and Frevert, D. K., Taylor & Francis, Boca Raton, 75–95, 2006. 462

Arora, V. and Boer, G.: A variable velocity flow routing algorithm for GCMs, J. Geophys. Res., 104, 30965–30979, 1999. 466

Bauer, P., Gumbricht, T., and Kinzelbach, W.: A regional coupled surface water/groundwater model of the Okavango Delta, Botswana, Water Resour. Res., 42, W04403, doi:10.1029/2005WR004234, 2006. 462

Bear, J.: Dynamics of Fluids in Porous Media, American Elsevier Publishing Co., New York, 1972. 468

Becker, M., Georgian, T., Ambrose, H., Siniscalchi, J., and Fredrick, K.: Estimating flow and flux of ground water discharge using water temperature and velocity, J. Hydrol., 296, 221–233, doi:10.1016/j.jhydrol.2004.03.025, 2004. 465

Bencala, K., Gooseff, M., and Kimball, B.: Rethinking hyporheic flow and transient storage to advance understanding of stream-catchment connections, Water Resour. Res., 47, W00H03, doi:10.1029/2010WR010066, 2011. 463

Bertrand, G., Goldscheider, N., Gobat, J.-M., and Hunkeler, D.: Review: from multi-scale conceptualization to a classification system for inland groundwater-dependent ecosystems, Hydrogeol. J., 20, 5–25, doi:10.1007/s10040-011-0791-5, 2012. 453

Beven, K.: Changing ideas in hydrology, The case of physically-based model, J. Hydrol., 105, 157–172, 1989. 462

Beven, K. and Cloke, H.: Comment on "Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water" by Wood et al., Water Resour. Res., 48, W01801, doi:10.1029/2011WR010982, 2012. 456

Beven, K., Smith, P. J., and Wood, A.: On the colour and spin of epistemic error (and what we might do about it), Hydrol. Earth Syst. Sci., 15, 3123–3133, doi:10.5194/hess-15-3123-2011, 2011. 462

Biancamaria, S., Andreadis, K., Durand, M., Clark, E., Rodriguez, E., Mognard, N., Alsdorf, D., Lettenmaier, D., and Oudin, Y.: Preliminary characterization of SWOT hydrology error budget and global capabilities, IEEE J. Sel. Top. Appl., 3, 6–19, doi:10.1109/JSTARS.2009.2034614, 2010. 471

Bitteli, M., Tomei, F., Pistocchi, A., Flury, M., Boll, J., Brooks, E., and Antolini, G.: Development and testing of a physically based, three-dimensional model of surface and subsurface hydrology, Adv. Water Resour., 33, 106–122, doi:10.1016/j.advwatres.2009.10.013, 2010. 496

Bixio, A., Gambolati, G., Paniconi, C., Putti, M., Shestopalov, V., Bublias, V., Bohuslavsky, A., Kasteltseva, N., and Rudenko, Y.: Modeling groundwater-surface water interactions including effects of morphogenetic depressions in the Chernobyl exclusion zone, Environ. Geol., 42, 162–177, doi:10.1007/s00254-001-0486-7, 2002. 455

Blöschl, G. and Sivapalan, M.: Scale issues in hydrological modelling: a review, Hydrol. Process., 9, 251–290, 1995. 456, 457

Boano, F., Revelli, R., and Ridolfi, L.: Quantifying the impact of groundwater discharge on the surface–subsurface exchange, Hydrol. Process., 23, 2108–2116, doi:10.1002/hyp.7278, 2009. 460, 468

Boano, F., Camporeale, C., and Revelli, R.: A linear model for coupled surface–subsurface flow in meandering stream, Water Resour. Res., 46, W07535, doi:10.1029/2009WR008317, 2010. 459, 462

Boukerma, B.: Modélisation des écoulements superficiels et souterrains dans le sud-ouest de la France: approche du bilan hydrique, Ph. D. thesis, ENSMP, Paris, 1987. 462

Brunke, M. and Gonser, T.: The ecological significance of exchange processes between rivers and groundwater, Freshwater Biol., 37, 1–33, doi:10.1046/j.1365-2427.1997.00143.x, 1997. 453, 460, 461

Brunner, P., Cook, P., and Simmons, C.: Hydrogeologic controls on disconnection between surface water and groundwater, Water Resour. Res., 45, W01422, doi:10.1029/2008WR006953, 2009a. 495

Brunner, P., Simmons, C., and Cook, P.: Spatial and temporal aspects of the transition from connection to disconnection between rivers, lakes and groundwater, J. Hydrol., 376, 159–169, doi:10.1016/j.jhydrol.2009.07.023, 2009b. 495

Brunner, P., Simmons, C., Cook, P., and Therrien, R.: Modeling surface water-groundwater interaction with MODFLOW: some considerations, Ground Water, 48, 174–180, doi:10.1111/j.1745-6584.2009.00644.x, 2010. 495

Calmant, S., Seyler, F., and Cretaux, J.-F.: Monitoring continental surface waters by satellite altimetry, Surv. Geophys., 29, 247–269, 2008. 470

Calver, A.: Riverbed permeabilities: information from pooled data, Ground Water, 39, 546–553, doi:10.1111/j.1745-6584.2001.tb02343.x, 2001. 459

Cardenas, M.: Stream–aquifer interactions and hyporheic exchange in gaining and losing sinuous streams, Water Resour. Res., 45, W06469, doi:10.1029/2008WR007651, 2009a. 459, 460, 462, 495

Cardenas, M.: A model for lateral hyporheic flow based on valley slope and channel sinuosity, Water Resour. Res., 45, W01501, doi:10.1029/2008WR007442, 2009b. 459, 462

Cardenas, M. and Wilson, J.: Hydrodynamics of coupled flow above and below a sediment–water interface with triangular bedforms, Adv. Water Resour., 30, 301–313, doi:10.1016/j.advwatres.2006.06.009, 2007a. 459

Cardenas, M. and Wilson, J.: Dunes, turbulent eddies, and interfacial exchange with permeable sediments, Water Resour. Res., 43, W08412, doi:10.1029/2006WR005787, 2007b. 458, 459, 495

Cardenas, M. and Wilson, J.: Exchange across a sediment–water interface with ambient groundwater discharge, J. Hydrol., 346, 69–80, doi:10.1016/j.jhydrol.2007.08.019, 2007c. 495

Cardenas, M., Wilson, J., and Zlotnik, V.: Impact of heterogeneity, bed forms, and stream curvature on subchannel hyporheic exchange, Water Resour. Res., 40, W08307, doi:10.1029/2004WR003008, 2004. 459, 495

Chen, X. and Chen, X.: Sensitivity analysis and determination of streambed leakance and aquifer hydraulic properties, J. Hydrol., 284, 270–284, 2003. 495

Chen, Y. and Durlofsky, L.: Adaptive local-global upscaling for general flow scenarios in heterogeneous formations, Transport Porous Med., 62, 157–185, 2006. 468

Christiaens, K., Vanclooster, M., Mallants, D., Xevi, E., and Feyen, J.: Modelling of the water and nutrient cycle at the catchment scale using the European Hydrological System SHE 2: nitrogen balance, Water, 81, Water number: 81-maart/april 1995, 1995. 462
Conant, B.: Delineating and quantifying ground water discharge zones using streambed temperatures, Ground Water, 42, 243–257, 2004. 461
Constantz, J.: Heat as a tracer to determine streambed water exchanges, Water Resour. Res., 44, 1–20, doi:10.1029/2008WR006996, 2008. 464, 465
Constantz, J., Stewart, A., Niswonger, R., and Sarma, L.: Analysis of temperature profiles for investigating stream losses beneath ephemeral channels, Water Resour. Res., 38–12, 1316, doi:10.1029/2001WR001221, 2002. 465
Constantz, J., Eddy-Miller, C., Wheeler, J., and Essaid, H.: Streambed exchanges along tributary streams in humid watersheds, Water Resour. Res., 49, 2197–2204, doi:10.1002/wrcr.20194, 2013. 465
Cretaux, J.-F., Berge-Nguyen, M., Leblanc, M., Rio, R. A. D., Delclaux, F., Mognard, N., Lion, C., Pandey, R.-K., Tweed, S., Calmant, S., and Maisongrande, P.: Flood mapping inferred from remote sensing data, Int. Water Technol. J., 1, 48–62, 2011. 470
Crispell, J. and Endreny, T.: Hyporheic exchange flow around constructed in-channel structures and implications for restoration design, Hydrol. Process., 23, 1158–1168, doi:10.1002/hyp.7230, 2009. 459
Dahl, M., Nilsson, B., Langhoff, J., and Refsgaard, J.: Review of classification systems and new multi-scale typology of groundwater–surface water interaction, J. Hydrol., 344, 1–16, 2007. 453, 456
Dahm, C., Baker, M., Moore, D., and Thibault, J.: Coupled biogeochemical and hydrological responses of streams and rivers to drought, Freshwater Biol., 48, 1219–1231, doi:10.1046/j.1365-2427.2003.01082.x, 2003. 457
Datry, T., Dole-Olivier, M., Marmonier, P., Claret, C., Perrin, J., Lafont, M., and Breil, P.: La zone hyporhéique, une composante à ne pas négliger dans l'état des lieux et la restauration des cours d'eau, Ingénieries – E A T, 54, 3–18, 2008. 456
David, C., Habets, F., Maidment, D., and Yang, Z.-L.: RAPID applied to the SIM-France model, Hydrol. Process., 25, 3412–3425, doi:10.1002/hyp.8070, 2011. 466
Dawson, C.: A continuous/discontinuous Galerkin framework for modeling coupled subsurface and surface water flow, Comput. Geosci., 12, 451–472, doi:10.1007/s10596-008-9085-y, 2008. 496

HESSD
11, 451–500, 2014
Nested stream–aquifer interfaces
N. Flipo et al.

de Marsily, G.: Quantitative Hydrogeology – Groundwater Hydrology for Engineers, Academic Press, London, 1986. 468
de Marsily, G., Ledoux, E., Levassor, A., Poitrinal, D., and Salem, A.: Modelling of large multi-layered aquifer systems: theory and applications, J. Hydrol., 36, 1–34, 1978. 455
Decharme, B., Douville, H., Prigent, C., Papa, F., and Aires, F.: A new river flooding scheme for global climate applications: off-line evaluation over South America, J. Geophys. Res., 113, D11110, doi:10.1029/2007JD009376, 2008. 467
Decharme, B., Alkama, R., Douville, H., Becker, M., and Cazenave, A.: Global evaluation of the ISBA-TRIP continental hydrological system, Part II: Uncertainties in river routing simulation related to flow velocity and groundwater storage, J. Hydrometeorol., 11, 601–617, doi:10.1175/2010JHM1212.1, 2010. 467
Decharme, B., Alkama, R., Papa, F., Faroux, S., Douville, H., and Prigent, C.: Global off-line evaluation of the ISBA-TRIP flood model, Clim. Dynam., 38, 1389–1412, doi:10.1007/s00382-011-1054-9, 2012. 467
Decharme, R. and Douville, H.: Global validation of the ISBA sub-grid Hydrology, Clim. Dynam., 29, 21–37, doi:10.1007/s00382-006-0216-7, 2007. 466
Delfs, J.-O., Blumensaat, F., Wang, W., Krebs, P., and Kolditz, O.: Coupling hydrogeological with surface runoff model in a Poltva case study in Western Ukraine, Environ. Earth. Sci., 65, 1439–1457, doi:10.1007/s12665-011-1285-4, 2012. 464
Discacciati, M., Miglio, E., and Quarteroni, A.: Mathematical and numerical models for coupling surface and groundwater flows, Appl. Numer. Math., 43, 57–74, 2002. 464, 495
Dooge, J.: The hydrologic cycle as a closed system, International Association of Scientific Hydrology, Bulletin, 13, 58–68, doi:10.1080/02626666809493568, 1968. 453
Ebel, B. A. and Loague, K.: Physics-based hydrologic-response simulation: seeing through the fog of equifinality, Hydrol. Process., 20, 2887–2900, 2006. 462
Ebel, B. A., Mirus, B. B., Heppner, C. S., VanderKwaak, J. E., and Loague, K.: First-order exchange coefficient coupling for simulating surface water-groundwater interactions: parameter sensitivity and consistency with a physics-based approach, Hydrol. Process., 23, 1949–1959, doi:10.1002/hyp.7279, 2009. 454, 463, 464, 495
Ebrahim, G., Hamonts, K., van Griensven, A., Jonoski, A., Dejonghe, W., and Mynett, A.: Effect of temporal resolution of water level and temperature inputson numerical simulation of groundwater-surface water flux exchange in a heavily modified urban river, Hydrol. Process., 27, 1634–1645, doi:10.1002/hyp.9310, 2013. 465

Ellis, P., Mackay, R., and Rivett, M.: Quantifying urban river-aquifer fluid exchange processes: a multi-scale problem, J. Contam. Hydrol., 91, 58–80, 2007. 453, 459, 460
Endreny, T., Lautz, L., and Siegel, D.: Hyporheic flow path response to hydraulic jumps at river steps: flume and hydrodynamic models, Water Resour. Res., 47, W02517, doi:10.1029/2009WR008631, 2011. 459
Engdahl, N., Volger, E., and Weissmann, G.: Evaluation of aquifer heterogeneity effects on river flow loss using a transition probability framework, Water Resour. Res., 46, W01506, doi:10.1029/2009WR007903, 2010. 468
Engeler, I., Hendricks Franssen, H., Müller, R., and Stauffer, F.: The importance of coupled modelling of variably saturated groundwater flow-heat transport for assessing river-aquifer interactions, J. Hydrol., 397, 295–305, doi:10.1016/j.jhydrol.2010.12.007, 2011. 464, 495
Etchevers, P., Golaz, C., and Habets, F.: Simulation of the water budget and the river flows of the Rhone basin from 1981 to 1994, J. Hydrol., 244, 60–85, 2001. 462
Fleckenstein, J., Niswonger., R., and Fogg, G.: River–aquifer interactions, geologic heterogeneity, and low-flow management, Ground Water, 44, 837–852, doi:10.1111/j.1745-6584.2006.00190.x, 2006. 456, 459, 462, 495
Flipo, N.: Modélisation des Hydrosystèmes Continentaux pour une Gestion Durable de la Ressource en Eau, Ph.D. thesis, Université Pierre et Marie Curie, Paris VI, available at: http://tel.archives-ouvertes.fr/docs/00/87/94/49/PDF/flipo2013_hdr.pdf (last access: January 2014), Habilitation thesis, 2013. 455, 494
Flipo, N., Even, S., Poulin, M., Théry, S., and Ledoux, E.: Modelling nitrate fluxes at the catchment scale using the integrated tool CaWaQS, Sci. Total Environ., 375, 69–79, doi:10.1016/j.scitotenv.2006.12.016, 2007. 465
Flipo, N., Monteil, C., Poulin, M., de Fouquet, C., and Krimissa, M.: Hybrid fitting of a hydrosystem model: long term insight into the Beauce aquifer functioning (France), Water Resour. Res., 48, W05509, doi:10.1029/2011WR011092, 2012. 453, 455, 457
Freeze, R.: Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin, Water Resour. Res., 7, 347–366, 1971. 455
Frei, S., Fleckenstein, J., Kollet, S., and Maxwell, R.: Patterns and dynamics of river-aquifer exchange with variably-saturated flow using a fully-coupled model, J. Hydrol., 375, 383–393, doi:10.1016/j.jhydrol.2009.06.038, 2009. 458, 459, 495

HESSD
11, 451–500, 2014

Nested stream–aquifer interfaces

N. Flipo et al.

Frei, S., Lischeid, G., and Fleckenstein, J.: Effects of micro-topography on surface–subsurface exchange and runoff generation in a virtual riparian wetland – a modeling study, Adv. Water Resour., 33, 1388–1401, doi:10.1016/j.advwatres.2010.07.006, 2010. 459, 495

Furman, A.: Modeling coupled surface–subsurface flow processes: a review, Vadose Zone J., 7, 741–756, doi:10.2136/vzj2007.0065, 2008. 463

Gao, H., Birkett, C., and Lettenmaier, D.: Global monitoring of large reservoir storage from satellite remote sensing, Water Resour. Res., 48, W09504, doi:10.1029/2012WR012063, 2012. 470

Genereux, D. P., Leahy, S., Mitasova, H., Kennedy, C. D., and Corbett, D. R.: Spatial and temporal variability of streambed hydraulic conductivity in West Bear Creek, North Carolina, USA, J. Hydrol., 358, 332–353, doi:10.1016/j.jhydrol.2008.06.017, 2008. 459, 463

Gleeson, T. and Paszkowski, D.: Perceptions of scale in hydrology: what do you mean by regional scale?, Hydrolog. Sci. J., 59, 1–9, doi:10.1080/02626667.2013.797581, 2013. 456

Goderniaux, P., Brouyère, S., Fowler, H., Blenkinsop, S., Therrien, R., Orban, P., and Dassargues, A.: Large scale surface–subsurface hydrological model to assess climate change impacts on groundwater reserves, J. Hydrol., 373, 122–138, 2009. 455

Golaz-Cavazzi, C., Etchevers, P., Habets, F., Ledoux, E., and Noilhan, J.: Comparison of two hydrological simulations of the Rhône basin, Phys. Chem. Earth, 26, 461–466, 2001. 462

Gomez, E., Ledoux, E., Viennot, P., Mignolet, C., Benoît, M., Bornerand, C., Schott, C., Mary, B., Billen, G., Ducharne, A., and Brunstein, D.: Un outil de modélisation intégrée du transfert des nitrates sur un système hydrologique: Application au bassin de la Seine, Houille Blanche, 3, 38–45, 2003. 462, 465

Gooseff, M., Anderson, J., Wondzell, S., LaNier, J., and Haggerty, R.: A modelling study of hyporheic exchange pattern and the sequence, size, and spacing of stream bedforms in mountain stream networks, Oregon, USA, Hydrol. Process., 20, 2443–2457, doi:10.1002/hyp.6349, 2006. 459, 495

Gunduz, O. and Aral, M.: River networks and groundwater flow: a simultaneous solution of a coupled system, J. Hydrol., 301, 216–234, doi:10.1016/j.jhydrol.2004.06.034, 2005. 455, 496

Habets, F., Noilhan, J., Golaz, C., Goutorbe, J., Lacarrère, P., Leblois, E., Ledoux, E., Martin, E., Ottlé, C., and Vidal-Madjar, D.: The ISBA surface scheme in a macroscale hydrological model applied to the Hapex-Mobilhy area Part I: Model and database, J. Hydrol., 217, 75–96, 1999. 462

HESSD
11, 451–500, 2014

Nested stream–aquifer interfaces

N. Flipo et al.

Hancock, P., Boulton, A., and Humphreys, W.: Aquifers and hyporheic zones: towards an ecological understanding of groundwater, Hydrogeol. J., 13, 98–111, doi:10.1007/s10040-004-0421-6, 2005. 453

Hanson, R., Schmid, W., Faunt, C., and Lockwood, B.: Simulation and analysis of conjunctive use with MODFLOW's farm process, Ground Water, 48, 674–689, doi:10.1111/j.1745-6584.2010.00730.x, 2010. 462

Harbaugh, A., Banta, E., Hill, M., and McDonald, M.: MODFLOW-2000, the US Geological Survey modular ground-water model: user guide to modularization concepts and the ground-water flow process, Tech. Rep. 00-92, USGS, Kentucky, USA, 2000. 455

Harvey, A.: Effective timescales of coupling within fluvial systems, Geomorphology, 44, 175–201, 2002. 457

Harvey, J. and Bencala, K.: The effect of streambed topography on surface–subsurface water exchange in mountain catchments, Water Resour. Res., 29, 89–98, 1993. 459

Hatch, C., Fisher, A., Revenaugh, J., Constantz, J., and Ruehl, C.: Quantifying surface water–groundwater interactions using time series analysis of streambed thermal records: method development, Water Resour. Res., 42, 10410–10424, 2006. 465

Hayashi, M. and Rosenberry, D.: Effects of ground water exchange on the hydrology and ecology of surface water, Ground Water, 40, 309–316, 2002. 453, 456

Henriksen, H., Troldborg, L., Hojberg, A., and Refsgaard, J.: Assessment of exploitable groundwater resources of Denmark by use of ensemble resource indicators and a numerical groundwater–surface water model, J. Hydrol., 348, 224–240, 2008. 462

Hester, E. and Doyle, M.: In-stream geomorphic structures as drivers of hyporheic exchange, Water Resour. Res., 44, W03417, doi:10.1029/2006WR005810, 2008. 459, 495

Hill, M.: The practical use of simplicity in developing ground water models, Ground Water, 44, 775–781, 2006. 462

Hussein, M. and Schwartz, F.: Modeling of flow and contaminant transport in coupled stream–aquifer systems, J. Contam. Hydrol., 65, 41–64, doi:10.1016/S0169-7722(02)00229-2, 2003. 496

Irvine, D., Brunner, P., Hendricks Franssen, H.-J., and Simmons, G.: Heterogeneous or homogeneous? Implications of simplifying heterogeneous streambeds in models of losing streams, J. Hydrol., 424–425, 16–23, doi:10.1016/j.jhydrol.2011.11.051, 2012. 463, 495

Janssen, F., Cardenas, M., Sawyer, A., Dammrich, T., Krietsch, J., and de Beer, D.: A comparative experimental and multiphysics computational fluid dynamics study of

coupled surface–subsurface flow in bed forms, Water Resour. Res., 48, W08514, doi:10.1029/2012WR011982, 2012. 459
Jensen, J. and Engesgaard, P.: Nonuniform groundwater discharge across a streambed: heat as a tracer, Vadose Zone J., 10, 98–109, doi:10.2136/vzj2010.0005, 2011. 465
Jolly, I. and Rassam, D.: A review of modelling of groundwater-surface water interactions in arid/semi-arid floodplains, in: 18th World IMACS/MODSIM Congress, Cairns, Australia, 2009. 462
Jones, J., Sudicky, E., Brookfield, A., and Park, Y.-J.: An assessment of the tracer-based approach to quantifying groundwater contributions to streamflow, Water Resour. Res., 42, W02407, doi:10.1029/2005WR004130, 2006. 453
Jones, J., Sudicky, E., and McLaren, R.: Application of a fully-integrated surface–subsurface flow model at the watershed-scale: a case study, Water Resour. Res., 44, W03407, doi:10.1029/2006WR005603, 2008. 453
Kalbus, E., Schmidt, C., Molson, J. W., Reinstorf, F., and Schirmer, M.: Influence of aquifer and streambed heterogeneity on the distribution of groundwater discharge, Hydrol. Earth Syst. Sci., 13, 69–77, doi:10.5194/hess-13-69-2009, 2009. 458, 459, 465, 495
Kasahara, T. and Hill, A.: Hyporheic exchange flows induced by constructed riffles and steps in lowland streams in southern Ontario, Canada, Hydrol. Process., 20, 4287–4305, doi:10.1002/hyp.6174, 2006. 459, 495
Kasahara, T. and Wondzell, S.: Geomorphic controls on hyporheic exchange flow in mountain streams, Water Resour. Res., 39, 1005, doi:10.1029/2002WR001386, 2003. 459, 495
Käser, D., Binley, A., Heathwaite, A., and Krause, S.: Spatio-temporal variations of hyporheic flow in a riffle-step-pool sequence, Hydrol. Process., 23, 2138–2149, doi:10.1002/hyp.7317, 2009. 459
Käser, D., Binley, A., and Heathwaite, A.: On the importance of considering channel microforms in groundwater models of hyporheic exchange, River Res. Appl., 29, 528–535, doi:10.1002/rra.1618, 2013. 459
Keery, J., Binley, A., Crook, N., and Smith, J.: Temporal and spatial variability of groundwater-surface water fluxes: development and application of an analytical method using temperature time series, J. Hydrol., 336, 1–16, doi:10.1016/j.jhydrol.2006.12.003, 2007. 465
Kim, J., Warnock, A., Ivanov, V., and Katopodes, N.: Coupled modeling of hydrologic and hydrodynamic processes including overland and channel flow, Adv. Water Resour., 37, 104–126, doi:10.1016/j.advwatres.2011.11.009, 2012. 496

HESSD
11, 451–500, 2014

Nested stream–aquifer interfaces

N. Flipo et al.

Klemes, V.: Conceptualization and scale in hydrology, J. Hydrol., 65, 1–23, 1983. 462
Koch, J., McKnight, D., and Neupauer, R.: Simulating unsteady flow, anabranching, and hyporheic dynamics in a glacial meltwater stream using a coupled surface water routing and groundwater flow model, Water Resour. Res., 47, W05530, doi:10.1029/2010WR009508, 2011. 459, 495
Kolditz, O., Delfs, J., Bürger, C., Beinhorn, M., and Parkee, C.: Numerical analysis of coupled hydrosystems based on an object-oriented compartment approach, J. Hydroinform., 10, 227–244, 2008. 455
Kolditz, O., Bauer, S., Beyer, C., Böttcher, N., Dietrich, P., Görke, U.-J., Kalbacher, T., Park, C.-H., Sauer, U., Schütze, C., Shao, H., Singh, A., Taron, J., Wang, W., and Watanabe, N.: A systematic benchmarking approach for geologic CO_2 injection and storage, Environ. Earth. Sci., 67, 613–632, doi:10.1007/s12665-012-1656-5, 2012. 462
Kollet, S. J. and Maxwell, R. M.: Integrated surface-groundwater flow modeling: a free-surface overland flow boundary condition in a parallel groundwater flow model, Adv. Water Resour., 29, 945–958, 2006. 453, 455, 463
Kollet, S. J., Maxwell, R. M., Woodward, C., Smith, S., Vanderborght, J., Vereecken, H., and Simmer, C.: Proof of concept of regional scale hydrologic simulations at hydrologic resolution utilizing massively parallel computer, Water Resour. Res., 46, W04201, doi:10.1029/2009WR008730, 2010. 455
Krause, S. and Bronstert, A.: The impact of groundwater-surface water interactions on the water balance of a mesoscale lowland river catchment in northeastern Germany, Hydrol. Process., 21, 169–184, doi:10.1002/hyp.6182, 2007. 459, 495
Krause, S., Bronstert, A., and Zehe, E.: Groundwater-surface water interactions in a North German lowland floodplain – implications for the river discharge dynamics and riparian water balance, J. Hydrol., 347, 404–417, doi:10.1016/j.jhydrol.2007.09.028, 2007. 459, 495
Krause, S., Hannah, D., and Fleckenstein, J.: Hyporheic hydrology: interactions at the groundwater-surface water interface, Hydrol. Process., 23, 2103–2107, doi:10.1002/hyp.7366, 2009a. 460
Krause, S., Heathwaite, L., Binley, A., and Keenan, P.: Nitrate concentration changes at the groundwater-surface water interface of a small Cumbrian River, Hydrol. Process., 23, 2195–2211, doi:10.1002/hyp.7213, 2009b. 453

Krause, S., Hannah, D. M., Fleckenstein, J. H., Heppell, C. M., Kaeser, D., Pickup, R., Pinay, G., Robertson, A. L., and Wood, P. J.: Inter-disciplinary perspectives on processes in the hyporheic zone, Ecohydrology, 4, 481–499, doi:10.1002/eco.176, 2011. 463

Krause, S., Blume, T., and Cassidy, N. J.: Investigating patterns and controls of groundwater up-welling in a lowland river by combining Fibre-optic Distributed Temperature Sensing with observations of vertical hydraulic gradients, Hydrol. Earth Syst. Sci., 16, 1775–1792, doi:10.5194/hess-16-1775-2012, 2012a. 459, 467

Krause, S., Munz, M., Tecklenburg, C., and Binley, A.: The effect of groundwater forcing on hyporheic exchange: reply to comment on "Reducing monitoring gaps at the aquifer–river interface by modelling groundwater-surfacewater exchange flow patterns" by Munz et al., Hydrol. Process., 26, 1589–1592, doi:10.1002/hyp.9271, 2012b. 459

Kurtulus, B., Flipo, N., Goblet, P., Vilain, G., Tournebize, J., and Tallec, G.: Hydraulic head interpolation in an aquifer unit using anfis and Ordinary Kriging, Stud. Comp. Intell., 343, 265–273, doi:10.1007/978-3-642-20206-3_18, 2011. 453

LaBolle, E., Ahmed, A., and Fogg, G.: Review of the Integrated Groundwater and Surface-Water Model (IGSM), Ground Water, 41, 238–46, 2003. 463

Lautz, L. and Siegel, D.: Modeling surface and ground water mixing in the using MODFLOW and MT3D, Adv. Water Resour., 29, 1618–1633, doi:10.1016/j.advwatres.2005.12.003, 2006. 495

Lautz, L., Kranes, N., and Siegel, D.: Heat tracing of heterogeneous hyporheic exchange adjacent to in-stream geomorphic features, Hydrol. Process., 24, 3074–3086, doi:10.1002/hyp.7723, 2010. 465

Ledoux, E., Girard, G., de Marsily, G., Villeneuve, J., and Deschenes, J.: Spatially distributed modeling: conceptual approach, coupling surface water and groundwater, in: Unsaturated Flow in Hydrologic Modeling – Theory and Practice, Springer, NATO Science Series, Massachusset, USA, 435–454, 1989. 455, 468

Ledoux, E., Gomez, E., Monget, J., Viavattene, C., Viennot, P., Ducharne, A., Benoit, M., Mignolet, C., Schott, C., and Mary, B.: Agriculture and groundwater nitrate contamination in the Seine basin, The STICS-MODCOU modelling chain, Sci. Total Environ., 375, 33–47, 2007. 462

Lemieux, J. and Sudicky, E.: Simulation of groundwater age evolution during the Wisconsinian glaciation over the Canadian landscape, Environ. Fluid Mech., 10, 91–102, 2010. 462

Lewandowski, J., Angermann, L., Nützmann, G., and Fleckenstein, J.: A heat pulse technique for the determination of small-scale flow directions and flow velocities in the streambed of sand-bed streams, Hydrol. Process., 25, 3244–3255, doi:10.1002/hyp.8062, 2011. 465

Li, Q., Unger, A., Sudicky, E., Kassenaar, D., Wexler, E., and Shikaze, S.: Simulating the multi-seasonal response of a large-scale watershed with a 3D physically-based hydrologic model, J. Hydrol., 357, 317–336, 2008. 455

Liang, D., Falconer, R., and Lin, B.: Coupling surface and subsurface flows in a depth averaged flood wave model, J. Hydrol., 337, 147–158, doi:10.1016/j.jhydrol.2007.01.045, 2007. 496

Liggett, J., Werner, A., and Simmons, C.: Influence of the first-order exchange coefficient on simulation of coupled surface–subsurface flow, J. Hydrol., 414–415, 503–515, doi:10.1016/j.jhydrol.2011.11.028, 2012. 464

Loague, K. and VanderKwaak, J.: Physics-based hydrologic response: platinium bridge, 1958 Edsel, or useful tool, Hydrol. Process., 18, 2949–2956, 2004. 455

Luce, C., Tonina, D., Gariglio, F., and Applebee, R.: Solutions for the diurnally forced advection-diffusion equation to estimate bulk fluid velocity and diffusivity in streambeds from temperature time series, Water Resour. Res., 49, 1–19, doi:10.1029/2012WR012380, 2013. 465

Malard, F., Tockner, K., Dole-Olivier, M.-J., and Ward, J. V.: A landscape perspective of surface–subsurface hydrological exchanges in river corridors, Freshwater Biol., 47, 621–640, 2002. 458, 460

Marmonier, P., Archambaud, G., Belaidi, N., Bougon, N., Breil, P., Chauvet, E., Claret, C., Cornut, J., Datry, T., Dole-Olivier, M., Dumont, B., Flipo, N., Foulquier, A., Gérino, M., Guilpart, A., Julien, F., Maazouzi, C., Martin, D., Mermillod-Blondin, F., Montuelle, B., Namour, P., Navel, S., Ombredane, D., Pelte, T., Piscart, C., Pusch, M., Stroffek, S., Robertson, A., Sanchez-Pérez, J., Sauvage, S., Taleb, A., Wantzen, M., and Vervier, P.: The role of organisms in hyporheic processes: gaps in current knowledge, needs for future research and applications, Ann. Limnol.-Int. J. Lim., 48, 253–266, 2012. 454, 456

Marzadri, A., Tonina, D., Bellin, A., Vignoli, G., and Tubino, M.: Semianalytical analysis of hyporheic flow induced by alternate bars, Water Resour. Res., 46, W07531, doi:10.1029/2009WR008285, 2010. 459, 495

Marzadri, A., Tonina, D., and Bellin, A.: A semianalytical three-dimensional process-based model for hyporheic nitrogen dynamics in gravel bed rivers, Water Resour. Res., 47, W11518, doi:10.1029/2011WR010583, 2011. 495

Massei, N., Laignel, B., Deloffre, J., Mesquita, J., Motelay, A., Lafite, R., and Durand, A.: Long-term hydrological changes of the Seine River flow (France) and their relation to the North Atlantic Oscillation over the period 1950–2008, Int. J. Climatol., 30, 2146–2154, doi:10.1002/joc.2022, 2010. 457

Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., Belamari, S., Barbu, A., Boone, A., Bouyssel, F., Brousseau, P., Brun, E., Calvet, J.-C., Carrer, D., Decharme, B., Delire, C., Donier, S., Essaouini, K., Gibelin, A.-L., Giordani, H., Habets, F., Jidane, M., Kerdraon, G., Kourzeneva, E., Lafaysse, M., Lafont, S., Lebeaupin Brossier, C., Lemonsu, A., Mahfouf, J.-F., Marguinaud, P., Mokhtari, M., Morin, S., Pigeon, G., Salgado, R., Seity, Y., Taillefer, F., Tanguy, G., Tulet, P., Vincendon, B., Vionnet, V., and Voldoire, A.: The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes, Geosci. Model Dev., 6, 929–960, doi:10.5194/gmd-6-929-2013, 2013. 466

Maxwell, R. and Miller, N.: Development of a coupled land surface and groundwater model, J. Hydrometeorol., 6, 233–247, 2005. 467

McDonald, M. and Harbaugh, A.: MODFLOW, a modular three-dimensional finite-difference ground-water flow model, in: Technique of Water Ressources Investigations of the US Geological Survey, US Geological Survey, USGS Federal Center, Denver, Colorado, p. 586, 1988. 455

Mehl, S. and Hill, M.: Developement and evaluation of a local grid refinement method forblock-centred finite-difference groundwater models using shared nodes, Adv. Water Resour., 25, 497–511, 2002. 468, 469

Mehl, S. and Hill, M.: Grid-size dependence of Cauchy boundary conditon used to simulate stream–aquifer interactions, Adv. Water Resour., 33, 430–442, 2010 468

Miglio, E., Quarteroni, A., and Saleri, F.: Coupling of free surface and groundwater flows, Comput. Fluids, 32, 73–83, 2003. 464, 495

Monteil, C.: Estimation de la contribution des principaux aquifères du bassin-versant de la Loire au fonctionnement hydrologique du fleuve à l’étiage, Ph.D. thesis, MINES-ParisTech, Paris, 2011. 462, 465

Morel-Seytoux, J.: The turning factor in the estimation of stream aquifer seepage, Ground Water, 42, 205–212, 2009. 468, 469

Mouhri, A., Flipo, N., Rejiba, F., de Fouquet, C., Bodet, L., Goblet, P., Kurtulus, B., Ansart, P., Tallec, G., Durand, V., and Jost, A.: Designing a multi-scale sampling system of stream–aquifer interfaces in a sedimentary basin, J. Hydrol., 504, 194–206, doi:10.1016/j.jhydrol.2013.09.036, 2013. 454, 457, 458, 464, 465, 469, 472, 495

Munz, M., Krause, S., Tecklenburg, C., and Binley, A.: Reducing monitoring gaps at the aquifer–river interface by modelling groundwater–surface water exchange flow patterns, Hydrol. Process., 25, 3547–3562, doi:10.1002/hyp.8080, 2011. 459, 495

Mutiti, S. and Levy, J.: Using temperature modeling to investigate the temporal variability of riverbed hydraulic conductivity during storm events, J. Hydrol., 388, 321–334, 2010. 465

Neal, J., Schumann, G., Bates, P., Buytaert, W., Matgen, P., and Pappenberger, F.: A data assimilation approach to discharge estimation from space, Hydrol. Process., 23, 3641–3649, doi:10.1002/hyp.7518, 2009. 470

Nemeth, M. and Solo-Gabriele, H.: Evaluation of the use of reach transmissivity to quantify exchange between groundwater and surface water, J. Hydrol., 274, 145–159, doi:10.1016/S0022-1694(02)00419-5, 2003. 464

Noto, L., Ivanov, V., Bras, R., and Vivoni, E.: Effects of initialization on response of a fully-distributed hydrologic model, J. Hydrol., 352, 107–125, doi:10.1016/j.jhydrol.2007.12.031, 2008. 462

Oki, T. and Sud, Y.: Design of total runoff integrating pathways (TRIP), A global river channel network, Earth Interact., 2, 1–36, 1998. 466

Osman, Y. and Bruen, M.: Modelling stream–aquifer seepage in an alluvial aquifer: an improved loosing-stream package for MODFLOW, J. Hydrol., 264, 69–86, 2002. 463, 495

Panday, S. and Huyakorn, P. S.: A fully coupled physically-based spatially-distributed model for evaluating surface/subsurface flow, Adv. Water Resour., 27, 361–382, doi:10.1016/j.advwatres.2004.02.016, 2004. 453, 455

Panday, S. and Langevin, C. D.: Improving sub-grid scale accuracy of boundary features in regional finite-difference models, Adv. Water Resour., 41, 65–75, 2012. 468

Park, Y.-J., Sudicky, E., Panday, S., and Matanga, G.: implicit subtime stepping for solving nonlinear flow equations in an integrated surface–subsurface system, Vadose Zone J., 8, 825–836, doi:10.2136/vzj2009.0013, 2009. 462

Parkin, G., O'Donnell, G., Ewen, J., Bathurst, J., O'Connell, P., and Lavabre, J.: Validation of catchment models for predicting land-use and climate change impacts, 2. Case study for a Mediterranean catchment, J. Hydrol., 175, 595–613, 1996. 455

Peyrard, D., Sauvage, S., Vervier, P., Sanchez-Perez, J., and Quintard, M.: A coupled vertically integrated model to describe lateral exchanges between surface and subsurface in large alluvial floodplains with a fully penetrating river, Hydrol. Process., 22, 4257–4273, doi:10.1002/hyp.7035, 2008. 495, 496

Pinder, G. and Jones, J.: Determination of the groundwater component of peak discharge from the chemistry of total run-off, Water Resour. Res., 5, 438–445, 1969. 459

Polus, E., Flipo, N., de Fouquet, C., and Poulin, M.: Geostatistics for assessing the efficiency of distributed physically-based water quality model., Application to nitrates in the Seine River, Hydrol. Process., 25, 217–233, doi:10.1002/hyp.7838, 2011. 462

Poole, G., O'Daniel, J., Jones, K., Woessner, W., Bernhardt, E., Helton, A., Stanford, J., Boer, B., and Beechie, T.: Hydrologic spiralling: the role of multiple interactive flow paths in stream ecosystems, River Res. Appl., 24, 1018–1031, doi:10.1002/rra.1099, 2008. 453

Pryet, A., Labarthe, B., Saleh, F., Akopian, M., and Flipo, N.: Quantification of stream–aquifer flow distribution at the regional scale with a distributed process-based model, Water Resour. Manag., submitted, 2013. 462, 465, 466, 468, 471, 495

Qu, Y. and Duffy, C.: A semidiscrete finite volume formulation for multiprocess watershed simulation, Water Resour. Res., 43, W08419, doi:10.1029/2006WR005752, 2007. 496

Ramillien, G., Famiglietti, J., and Wahr, J.: Detection of continental hydrology and glaciology signals from GRACE: a review, Surv. Geophys., 29, 361–374, doi:10.1007/s10712-008-9048-9, 2008. 470

Ramillien, G., Seoane, L., Frappart, F., Biancale, R., Gratton, S., Vasseur, X., and Bourgogne, S.: Constrained regional recovery of continental water mass time-variations from GRACE-based geopotential anomalies over South America, Surv. Geophys., 33, 887–905, doi:10.1007/s10712-012-9177-z, 2012. 470

Rau, G., Andersen, M., McCallum, A., and Acworth, R.: Analytical methods that use natural heat as a tracer to quantify surface water-groundwater exchange, evaluated using field temperature records, Hydrogeol. J., 18, 1093–1110, 2010. 465

Refsgaard, J. and Knudsen, J.: Operational validation and intercomparison of different types of hydrological models, Water Resour. Res., 32, 2189–2202, 1996. 455

Renard, P.: Calculating equivalent permeability: a review, Adv. Water Resour., 20, 253–278, 1997. 468

Revelli, R., Boano, F., Camporeale, C., and Ridolfi, L.: Intra-meander hyporheic flow in alluvial rivers, Water Resour. Res., 44, W12428, doi:10.1029/2008WR007081, 2008. 460, 495

HESSD
11, 451–500, 2014

Nested stream–aquifer interfaces

N. Flipo et al.

Rodríguez, E.: SWOT Science Requirements Document, Second Release (v. 1.1), Tech. rep., JPL, available at: http://swot.jpl.nasa.gov/files/swot/SWOT_science_reqs_release2_v1.14.pdf (last access: January 2014), 2012. 470, 471

Rosenberry, D. and Pitlick, J.: Local-scale variability of seepage and hydraulic conductivity in a shallow gravel-bed river, Hydrol. Process., 23, 3306–3318, doi:10.1002/hyp.7433, 2009. 459

Rühaak, W., Rath, V., Wolf, A., and Clauser, C.: 3D finite volume groundwater and heat transport modeling with non-orthogonal grids, using a coordinate transformation method, Adv. Water Resour., 31, 513–524, 2008. 465

Rushton, K.: Representation in regional models of saturated river–aquifer interaction for gaining/losing rivers, J. Hydrol., 334, 262–281, doi:10.1016/j.jhydrol.2006.10.008, 2007. 458, 468, 469, 495

Russell, G. and Miller, J.: Global river runoff calculated from a global atmospheric general circulation model, J. Hydrol., 117, 241–254, 1990. 466

Saenger, N., Kitanidis, P., and Street, R.: A numerical study of surface–subsurface exchange processes at a riffle-pool pair in the Lahn River, Germany, Water Resour. Res., 41, W12424, doi:10.1029/2004WR003875, 2005. 459, 495

Saleh, F., Flipo, N., Habets, F., Ducharne, A., Oudin, L., Viennot, P., and Ledoux, E.: Modeling the impact of in-stream water level fluctuations on stream–aquifer interactions at the regional scale, J. Hydrol., 400, 490–500, doi:10.1016/j.jhydrol.2011.02.001, 2011. 453, 457, 462, 465, 466, 471, 495

Saleh, F., Ducharne, A., Flipo, N., Oudin, L., and Ledoux, E.: Impact of river bed morphology on discharge and water levels simulated by a 1D Saint-Venant hydraulic model at regional scale, J. Hydrol., 476, 169–177, doi:10.1016/j.jhydrol.2011.02.001, 2013. 466

Sawyer, A. and Cardenas, M.: Hyporheic flow and residence time distributions in heterogeneous cross-bedded sediment, Water Resour. Res., 45, W08406, doi:10.1029/2008WR007632, 2009. 459, 495

Schmidt, C., Bayer-Raich, M., and Schirmer, M.: Characterization of spatial heterogeneity of groundwater-stream water interactions using multiple depth streambed temperature measurements at the reach scale, Hydrol. Earth Syst. Sci., 10, 849–859, doi:10.5194/hess-10-849-2006, 2006. 459

Schmidt, C., Conant, B., Bayer-Raich, M., and Schirmer, M.: Evaluation and field-scale application of an analytical method to quantify groundwater discharge using mapped streambed temperatures, J. Hydrol., 347, 292–307, doi:10.1016/j.jhydrol.2007.08.022, 2007. 465

HESSD
11, 451–500, 2014

Nested stream–aquifer interfaces

N. Flipo et al.

Schornberg, C., Schmidt, C., Kalbus, E., and Fleckenstein, J.: Simulating the effects of geologic heterogeneity and transient boundary conditions on streambed temperatures – implications for temperature-based water flux calculations, Adv. Water Resour., 33, 1309–1319, doi:10.1016/j.advwatres.2010.04.007, 2010. 465

Scibek, J., Allen, D., Cannon, A., and Whitfield, P.: Groundwater–surface water interaction under scenarios of climate change using a high-resolution transient groundwater model, J. Hydrol., 333, 165–181, doi:10.1016/j.jhydrol.2006.08.005, 2007. 462

Shen, C. and Phanikumar, M.: A process-based, distributed hydrologic model based on a large-scale method for surface–subsurface coupling, Adv. Water Resour., 33, 1524–1541, doi:10.1016/j.advwatres.2010.09.002, 2010. 496

Singh, V. and Bhallamudi, S.: Conjunctive surface–subsurface modeling of overland flow, Adv. Water Resour., 21, 567–579, 1998. 496

Smith, M., Seo, D.-J., Koren, V., Reed, S., Zhang, Z., Duan, Q., Moreda, F., and Cong, S.: The distributed model intercomparison project (DMIP): motivation and experiment design, J. Hydrol., 298, 4–26, doi:10.1016/j.jhydrol.2004.03.040, 2004. 462

Sophocleous, M.: Interactions between groundwater and surface water: the state of the science, Hydrogeol. J., 10, 52–67, doi:10.1007/s10040-002-0204-x, 2002. 453, 467

Spanoudaki, K., Stamou, A., and Nanou-Giannarou, A.: Development and verification of a 3-D integrated surface water-groundwater model, J. Hydrol., 375, 410–427, doi:10.1016/j.jhydrol.2009.06.041, 2009. 496

Stallman, R.: Steady one-dimensional fluid flow in a semi-infinite porous medium with sinusoidal surface temperature, J. Geophys. Res., 70, 2821–2827, doi:10.1029/JZ070i012p02821, 1965. 465

Stonedahl, S., Harvey, J., Wörman, A., Salehin, M., and Packman, A.: A multiscale model for integrating hyporheic exchange from ripples to meanders, Water Resour. Res., 46, W12539, doi:10.1029/2009WR008865, 2010. 459, 497

Stonedahl, S., Harvey, J., Detty, J., Aubeneau, A., and Packman, A.: Physical controls and predictability of stream hyporheic flow evaluated with a multiscale model, Water Resour. Res., 48, W10513, doi:10.1029/2011WR011582, 2012. 453

Storey, R. G., Howard, K., and Williams, D.: Factors controlling riffle-scale hyporheic exchange flows and their seasonal changes in a gaining stream: a three-dimensional groundwater flow model, Water Resour. Res., 39, 1034, doi:10.1029/2002WR001367, 2003. 458, 459, 461, 495

Sulis, M., Meyerhoff, S., Paniconi, C., Maxwell, R., Putti, M., and Kollet, S.: A comparison of two physics-based numerical models for simulating surface water-groundwater interactions, Adv. Water Resour., 33, 456–467, doi:10.1016/j.advwatres.2010.01.010, 2010. 464, 495

Swanson, T. and Cardenas, M.: Ex-Stream: a MATLAB program for calculating fluid flux through sediment–water interfaces based on steady and transient temperature profiles, Comput. Geosci., 37, 1664–1669, doi:10.1016/j.cageo.2010.12.001, 2011. 465

Tapley, B., Bettadpur, S., Ries, J., Thompson, P., and Watkins., M.: GRACE measurements of mass variability in the Earth system, Science, 305, 503–505, 2004. 470

Therrien, R., McLaren, R., Sudicky, E., and Panday, S.: HydroGeoSphere: a Three-Dimensionnal Numerical Model Describing Fully-integrated Subsurface and Surface Flow and Solute Transport, Tech. rep., Université Laval and University of Waterloo, 2010. 455

Thierion, C., Longuevergne, L., Habets, F., Ledoux, E., Ackerer, P., Majdalani, S., Leblois, E., Lecluse, S., Martin, E., Queguiner, S., and Viennot, P.: Assessing the water balance of the Upper Rhine Graben hydrosystem, J. Hydrol., 424–425, 68–83, doi:10.1016/j.jhydrol.2011.12.028, 2012. 465

Tonina, D. and Buffington, J. M.: Hyporheic exchange in gravel bed rivers with pool-riffe morphology: laboratory experiments and three-dimensional modelling, Water Resour. Res., 43, W01421, doi:10.1029/2005WR004328, 2007. 459, 495

Tóth, J.: A theoretical analysis of groundwater flow in small drainage basins, J. Geophys. Res., 68, 4795–4812, 1963. 459

Urquiza, J., N'Dri, D., Garon, A., and Delfour, M.: Coupling Stokes and Darcy equations, Appl. Numer. Math., 58, 525–538, doi:10.1016/j.apnum.2006.12.006, 2008. 464, 495

VanderKwaak, J. E. and Loague, K.: Hydrologic-response simulations for the R-5 catchment with a comprehensive physics-based model, Water Resour. Res., 37, 999–1013, 2001. 453, 455

Vergnes, J.-P. and Decharme, B.: A simple groundwater scheme in the TRIP river routing model: global off-line evaluation against GRACE terrestrial water storage estimates and observed river discharges, Hydrol. Earth Syst. Sci., 16, 3889–3908, doi:10.5194/hess-16-3889-2012, 2012. 467, 471, 495

Vergnes, J.-P., Decharme, B., Alkama, R., Martin, E., Habets, F., and Douville, H.: A simple groundwater scheme for hydrological and climate applications: description and offline evaluation over France, J. Hydrometeorol., 13, 1149–1171, doi:10.1175/JHM-D-11-0149.1, 2012. 467, 495

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Nested stream–aquifer interfaces

N. Flipo et al.

Vermeulen, P., te Stroet, C., and Heemink, A.: Limitations to upscaling of groundwater Flow models dominated by surface water interaction, Water Resour. Res., 42, W10406, doi:10.1029/2005WR004620, 2006. 468, 469
Weill, S., Mouche, E., and Patin, J.: A generalized Richards equation for surface/subsurface flow modelling, J. Hydrol., 366, 9–20, 2009. 455
Werner, A., Gallagher, M., and Weeks, S.: Regional-scale, fully coupled modelling of stream–aquifer interaction in a tropical catchment, J. Hydrol., 328, 497–510, doi:10.1016/j.jhydrol.2005.12.034, 2006. 453, 463
White, D. S.: Perspectives on defining and delineating hyporheic zones, J. N. Am. Benthol. Soc., 12, 61–69, 1993. 457, 460
Whiting, P. and Pomeranets, M.: A numerical study of bank storage and its contribution to streamflow, J. Hydrol., 202, 121–136, 1997. 459
Winter, T.: Relation of streams, lakes, and wetlands to groundwater flow systems, Hydrogeol. J., 7, 28–45, 1998. 453, 457
Woessner, W. W.: Stream and fluvial plain ground water interactions: rescaling hydrogeologic thought, Ground Water, 38, 423–429, doi:10.1111/j.1745-6584.2000.tb00228.x, 2000. 461
Wondzell, S., LaNier, J., and Haggerty, R.: Evaluation of alternative groundwater flow models for simulating hyporheic exchange in a small mountain stream, J. Hydrol., 364, 142–151, doi:10.1016/j.jhydrol.2008.10.011, 2009. 462, 495
Wood, E., Roundy, J., Troy, T., van Beek, L., Bierkens, M., Blyth, E., de Roo, A., Döll, P., Ek, M., Famiglietti, J., Gochis, D., van de Giesen, N., Houser, P., Jaffé, P., Kollet, S., Lehner, B., Lettenmaier, D., Peters-Lidard, C., Sivapalan, M., Sheffield, J., Wade, A., and Whitehead, P.: Hyperresolution global land surface modeling: meeting a grand challenge for monitoring Earth's terrestrial water, Water Resour. Res., 47, W05301, doi:10.1029/2010WR010090, 2011. 456, 467
Wood, E., Roundy, J., Troy, T., van Beek, L., Bierkens, M., Blyth, E., de Roo, A., Döll, P., Ek, M., Famiglietti, J., Gochis, D., van de Giesen, N., Houser, P., Jaffé, P., Kollet, S., Lehner, B., Lettenmaier, D., Peters-Lidard, C., Sivapalan, M., Sheffield, J., Wade, A., and Whitehead, P.: Reply to comment on "Hyperresolution global land surface modeling: meeting a grand challenge for monitoring Earth's terrestrial water" by: Keith, J. et al., Water Resour. Res., 48, W01802, doi:10.1029/2011WR011202, 2012. 456

Wroblicky, G., Campana, M., Valett, H., and Dahm, C.: Seasonal variation in surface–subsurface water exchange and lateral hyporheic area of two stream–aquifer systems, Water Resour. Res., 34–3, 317–328, doi:10.1029/97WR03285, 1998. 461

Yeh, P. and Eltahir, E.: Representation of water table dynamics in a land surface scheme, Part II: Subgrid variability, J. Climate, 18, 1881–1901, 2005. 467

Yuan, D., Lin, B., and Falconer, R.: Simulating moving boundary using a linked groundwater and surface water flow model, J. Hydrol., 349, 524–535, doi:10.1016/j.jhydrol.2007.11.028, 2008. 496

Table 1. Coupled surface–subsurface hydrological DPBM. References to be found in Flipo (2013).

Model	SW	GW	Cg	Δx	Δt
CATHY	Muskingum-Cunge 1-D FD	RE 3-D FE	P	0.01 ha–690 km^2	hours–decades
CaWaQS	SV [m] 1-D FD	DE pseudo 3-D FD	K	2500 km^2	decades
EauDyssée[b]	Muskingum RC + 1-D FD	DE pseudo 3-D FD	K	1000 km^2–100 000 km^2	days–century
HydroGeoSphere[a]	DW [dw] 2-D FE	RE 3-D FE	K	1 m^2–25 M km^2	hours–300 000 yr
InHM	DW[m] 2-D FE	RE 3-D FE	K	15 m^2–100 km^2	hours–century
MIKE SHE	SV 1-D FD	BE 3-D FD	K	10 km^2–375 000 km^2	hours–decades
MODCOU	isochronism	DE pseudo 3-D FD	K	100 km^2–100 000 km^2	days–century
MODFLOW	Coupling dependent	BE pseudo 3-D FD	K	0.02 ha–30 000 km^2	hours–century
MODHMS	DW[dw] 2-D FD	RE 3-D VF	K	0.8 km^2–3200 km^2	hours–decades
OpenGeoSys[a]	SV 1-D FD	BE 3-D FE	K	3 ha–20 000 km^2	hours–century
ParFlow[a]	KW[m] 2-D FE	RE 3-D FE	P	3 ha–13 000 km^2	hours–decades
SHE	SV 1-D FD	BE 3-D FD	K	5 ha–16 000 km^2	days–years
SHETRAN	DW 1-D FD	BE 3-D FD	K	3 ha–2000 km^2	hours–millenium

SW: Surface water; GW: Groundwater; Cg: Coupling DE: Diffusivity Equation; BE: Boussinesq Equation; RE: Richards Equations SV: Saint-Venant; DW: Diffusive Wave; KW: Kinematic Wave; RC: Rating Curves FD: Finite Differences; FE: Finite Elements; K: Conductance model; P: Pressure continuity,
[a] Parallelised code,
[b] Can be parallelised by tasks,
[m] Friction is calculated with the Manning formulae,
[dw] Friction is calculated with the Darcy–Weisbach formulae.

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Table 2. Physically-based modelling of stream–aquifer exchanges.

Ref	exch	Spec	Resolution		Scale	CS
			Δx	Δt		
Brunner et al. (2009a, b)	K	2-D V LAT	[1–100] m · [≤ 0.05] m	perm	loc-int	S
Brunner et al. (2010)	K	2-D V LAT	[1–10] m · [0.1–10] m	perm	loc-int	S
Cardenas et al. (2004)	K	3-D	0.25 m · 0.25 m · 0.04 m	perm	loc	S
Cardenas and Wilson (2007b); Cardenas and Wilson (2007c)	P	2-D V LON	0.01 m · 0.01 m [a]	perm	loc	S
Cardenas (2009a)	P	2-D H	NS (80 m · 45 m)	perm	loc	S
Chen and Chen (2003)	K	3-D	[3–6] m · [3–6] m · [6.7–7.6] m	min	loc-int	R
Discacciati et al. (2002)	P	3-D	[0.5–5] m · [0.5–5] m · [0.3–1.5] m [a]	perm	loc	S
Ebel et al. (2009)	K	3-D	[1–20] m · [1–20] m · [0.05–0.25] m	adapt	loc-int	R
Engeler et al. (2011)	K	3-D	[1–50] m · [1–50] m · [1.6–40] m	900 s	int	R
Fleckenstein et al. (2006)	K	3-D	200 m · 100 m · [5–40] m	3 h	int	R
Frei et al. (2009)	P	3-D	20 m × 50 m × 0.5 m	min	int	S
Frei et al. (2010)	K	3-D	0.1 m × 0.1 m × 0.1 m	adapt	loc	S
Gooseff et al. (2006)	K	2-D V LON	0.20 m · [0.3–0.5] m	perm	loc	S
Hester and Doyle (2008)	K	2-D V LON	3 m · [0.1–0.25] m	perm	loc	S
Irvine et al. (2012)	K	3-D	0.5 m · [0.5–2.6] m · [0.03–0.7] m	perm	loc	S
Kalbus et al. (2009)	K	2-D V LON	1 m · [0.05–0.2] m	perm	loc	S
Kasahara and Wondzell (2003)	K	3-D	[0.3–0.5] m · [0.3–0.5] m · [0.15–0.3] m	perm	loc-int	R
Kasahara and Hill (2006)	K	3-D	[0.6–3.5] m · [0.2–0.5] m · 0.15 m	perm	loc	R
Koch et al. (2011)	K	3-D	NS (1.7 km · 200 m · 0.5 m)	1 h	int	R
Krause and Bronstert (2007)	K	2-D H	[25–50] m · [25–50] m	1 h	int	R
Krause et al. (2007)	K	2-D H	[25–250] m · [25–250] m	1 h	int-rég	R
Lautz and Siegel (2006)	K	3-D	0.5 m · 0.5 m · [0.6–2] m	perm	loc-int	R
Marzadri et al. (2010)	K	3-D	[0.19–1.88] m · [0.06–0.5] m · [0.1] m	perm	loc-int	S
Marzadri et al. (2011)	K	3-D	NS (16.9 m · 2.6 m · 1.6 m)	perm	loc	S
Miglio et al. (2003)	P	3-D	[0.2–0.5] m · [0.2 · 0.5] m · [0.05–0.15] m [a]	600 s	loc	S
Mouhri et al. (2013)	P	2-D V	[0.01–0.1] m · [0.01 · 0.1] m	min	loc	R
Munz et al. (2011)	K	3-D	0.5 m · 0.5 m · [0.1–2.48] m	1 h [†]	loc	R
Osman and Bruen (2002)	K	2-D V LAT	NS (360 m · 21 m)	perm	loc	S
Peyrard et al. (2008)	P	2-D H	[10–40] m · [10–40] m	adapt	int	R
Pryet et al. (2013)	K	2-D H	1 km · 1 km	1d	reg	R
Revelli et al. (2008)	K	2-D H	NS ([0.22–4.4] km · [0.19–3.8] km)	perm	int	S
Rushton (2007)	K	2-D V LAT	20 m · 0.2 m	perm	loc-int	S
Saenger et al. (2005)	K	V LON	0.1 m · 0.02 m	perm	loc	R
Saleh et al. (2011)	K	2-D H	[1–4] km · [1–4] km · [–] m	1 j	reg	R
Sawyer and Cardenas (2009)	P	2-D V LON	0.01 m · 0.005 m [‡]	perm	loc	L
Storey et al. (2003)	K	3-D	[1–8] m · [1–8] m · [0.25–0.42] m	perm	loc	R
Sulis et al. (2010)	K,P	3-D	[1–80] m · [1–80] m · [0.0125–0.5] m	adapt	loc-int	S
Tonina and Buffington (2007)	P	3-D	0.03 m · 0.03 m · 0.03 m	perm	loc	L
Urquiza et al. (2008)	P	2-D V LON	1 m · 1 m	perm	loc	S
Vergnes et al. (2012)	K	2-D V LON	0.5° · 0.5° · [–] m	1 d	reg	R
Vergnes and Decharme (2012)	K	2-D V LON	0.5° · 0.5° · [–] m	1 d	con	R
Wondzell et al. (2009)	K	3-D	[0.125–2] m · [0.125–2] m · [0.16–0.4] m	perm	loc	R

Exch (stream–aquifer exchanges' model): K: conductance model; P: Pressure continuity; V: vertical; LAT: lateral; LON: longitudinal; H: horizontal.
Resolution: NS: not specified (total extension between parenthesis); [a] cell size not specified in the paper.
Spec (Specificities) Δx (spatial); Δt (temporal): perm: steady state; adapt: adaptative time step.
Scale: loc: local; int: intermediate; reg: regional; con: continental.
CS (Case Study): S: synthetical; L: lab experiment; R: real.

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Table 3. Other DPBMS for intermediate and watershed scales – complementary with Table 1.

Reference	Model SW	Model GW	Cg	Sg	Spatial Size	Time Period
Bitteli et al. (2010)	DW 2-D FD	RE 3-D FD	K	seq	3 ha	1 yr
Dawson (2008)	NS 1-D FE	RE 2-D FE	P	seq	2-D vertical	30 min
Gunduz and Aral (2005)	SV 1-D FD	DE 2-D FE	L	sim	1800 km^2	3 months
Hussein and Schwartz (2003)	KW 1-D FD	DE 3-D FD	P	seq	256 km^2	100 yr
Kim et al. (2012)	SV 2-D FV	DE 3-D FE	K	seq	64 km^2	200 h
Liang et al. (2007)	NS 2-D	BE 2-D	L	sim	8–40 ha	2–3 min
Peyrard et al. (2008)	SV 2-D FE	BE 2-D FE	P	sim	36 km^2	5 yr
Qu and Duffy (2007)	DW 2-D FV	RE 2-D FV	K	sim	0.2 ha	1 month
Spanoudaki et al. (2009)	NS 3-D FD	RE 3-D FD	K	sim	2.5 ha–25 km^2	30 h
Shen and Phanikumar (2010)	DW 2-D FV	DE 3-D FD[a]	K	seq	12 ha–1169 km^2	5 h–7 yr
Singh and Bhallamudi (1998)	SV 1-D FD	RE 2-D FD	P	seq	0.6 m^2	15 min
Yuan et al. (2008)	NS 2-D FD	BE 2-D FD	P	sim	160 km^2	30 min

SW: Surface water; GW: Groundwater; Cg: Coupling; Sg: Solving; DW: Diffusive Wave; KW: Kinematic Wave; NS: Navier–Stokes; SV: Saint-Venant; RE: Richards Equations; BE: Boussinesq Equation; DE: Diffusivity Equation; FD: Finite Differences; FE: Finite Elements; FV: Finite Volumes; K: conductance model; P: Pressure continuity; L: Horizontal Darcy law; sim/seq: The system of equations is solved simultaneously/sequentially; [a]: pseudo 3-D.

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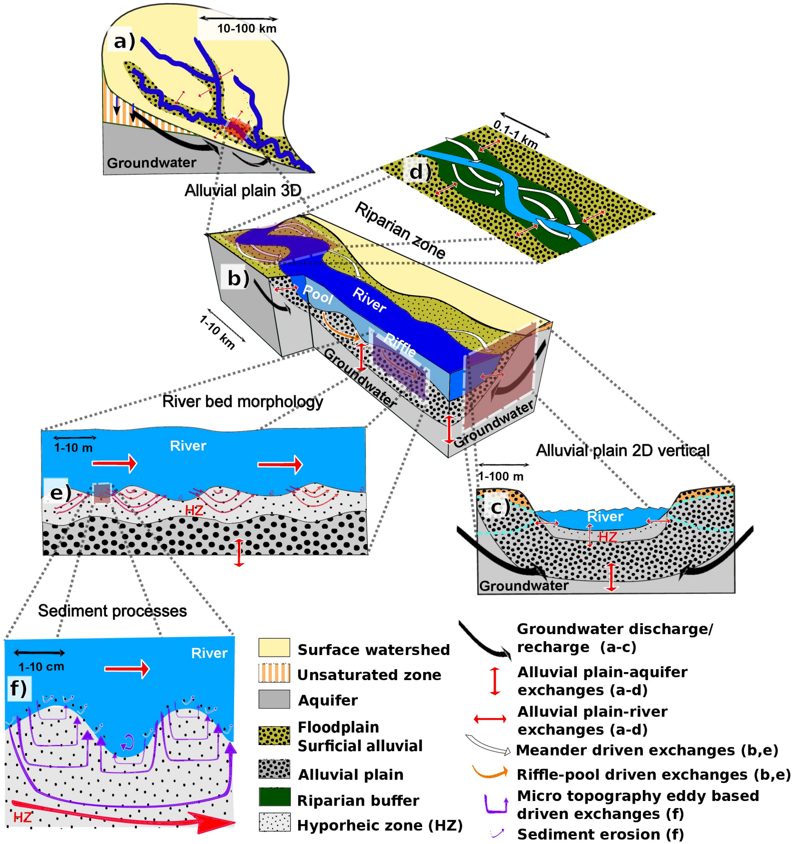

Fig. 1. Nested stream–aquifer interfaces: **(a)** watershed-basin scale **(b)** intermediate-reach scale in an alluvial plain **(c)** cross section of the stream–aquifer interface **(d)** meandered reach scale **(e)** longitudinal river-HZ exchanges **(f)** water column-sediment scale. Inspired by Stonedahl et al. (2010).

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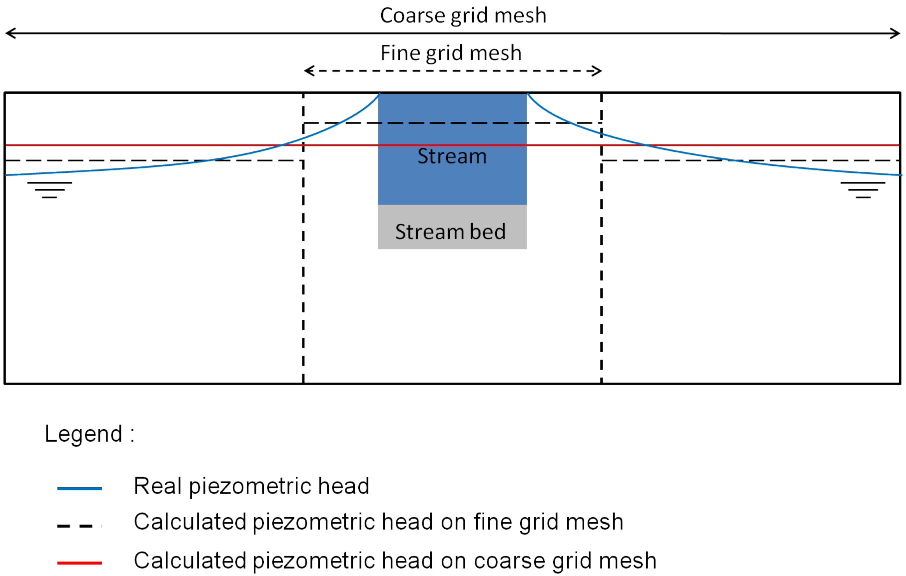

Fig. 2. Scaling effects on averaged near river piezometric heads.

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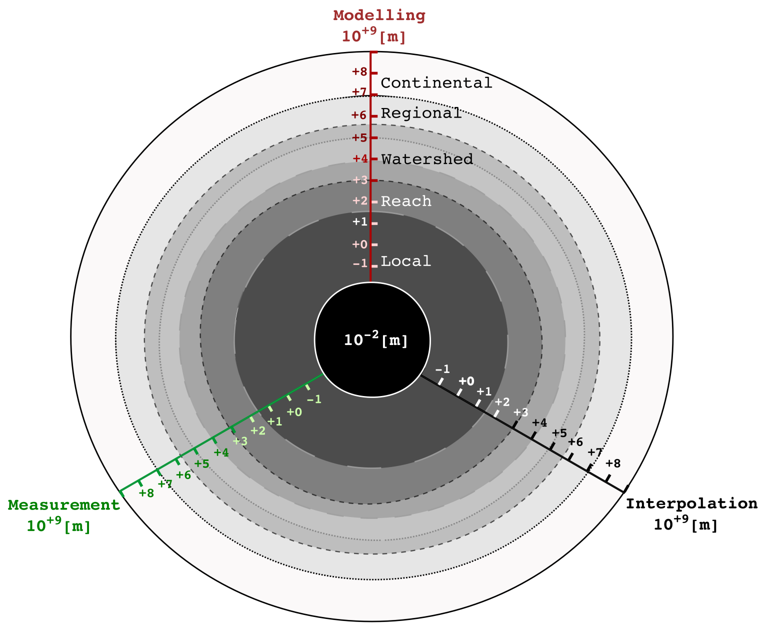

Fig. 3. MIM methodological space. Axis in logarithmic scale.

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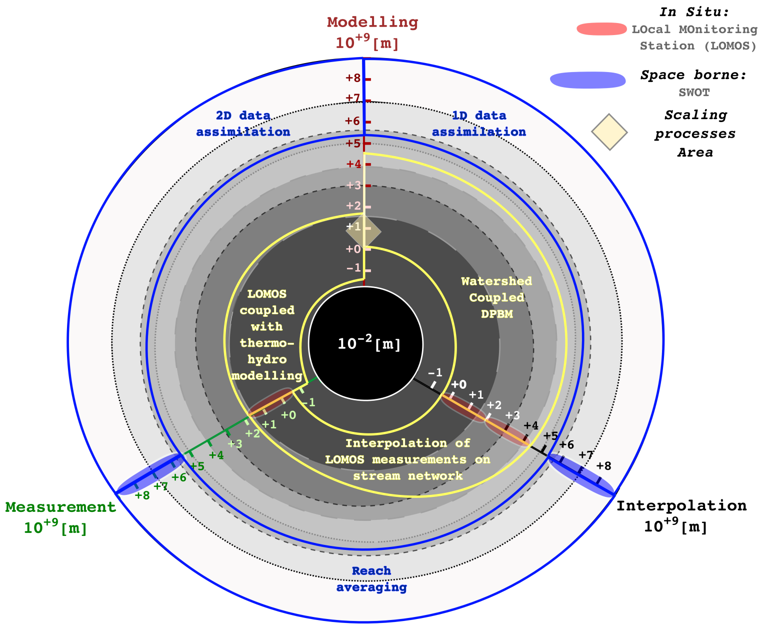

Fig. 4. Localisation of two approaches in the MIM methodological space. In yellow: upscaling methodology from the local to the watershed scale based on LOMOS coupled with DPBM. In blue: regional to continental scales covered by the SWOT space borne approach. Axis in logarithmic scale.

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