Groundwater

Issue Paper/

Channel Representation in Physically Based Models Coupling Groundwater and Surface Water: Pitfalls and How to Avoid Them

by Daniel Käser[1,2], Tobias Graf[3], Fabien Cochand[3], Rob McLaren[4], René Therrien[3], and Philip Brunner[2]

Abstract

Recent models that couple three-dimensional subsurface flow with two-dimensional overland flow are valuable tools for quantifying complex groundwater/stream interactions and for evaluating their influence on watershed processes. For the modeler who is used to defining streams as a boundary condition, the representation of channels in integrated models raises a number of conceptual and technical issues. These models are far more sensitive to channel topography than conventional groundwater models. On all spatial scales, both the topography of a channel and its connection with the floodplain are important. For example, the geometry of river banks influences bank storage and overbank flooding; the slope of the river is a primary control on the behavior of a catchment; and at the finer scale bedform characteristics affect hyporheic exchange. Accurate data on streambed topography, however, are seldom available, and the spatial resolution of digital elevation models is typically too coarse in river environments, resulting in unrealistic or undulating streambeds. Modelers therefore perform some kind of manual yet often cumbersome correction to the available topography. In this context, the paper identifies some common pitfalls, and provides guidance to overcome these. Both aspects of topographic representation and mesh discretization are addressed. Additionally, two tutorials are provided to illustrate: (1) the interpolation of channel cross-sectional data and (2) the refinement of a mesh along a stream in areas of high topographic variability.

Introduction

Physically based integrated (PBI) hydrological models offer a promising tool to simulate groundwater-stream interactions (GSI) (see Box 1). By allowing surface water (SW) to flow freely over the entire topography and exchange with the subsurface in a fully coupled way, PBI models have the potential to simulate complex feedbacks between groundwater (GW) and streams, predict inundated areas during flood events, or evaluate the implications of management strategies on GW and SW bodies. PBI models have been successfully used to understand basic hydrological processes within simplified conceptual frameworks (Brunner et al. 2009; Frei et al. 2009; Irvine et al. 2012), and are increasingly applied to real catchments (see Rossman and Zlotnik 2013). The ability to simulate stream flow without defining *a priori* the channel's position is a key-strength of PBI models. As a result, these are inherently more sensitive to topography than conventional GW models: for example, simulated SW bodies may not match their observed position and extent. It is therefore important that aspects of channel-representation are not overlooked, or else the absence of a fit-to-purpose digital elevation model (DEM) and numerical mesh will undermine the credibility of PBI models.

The conceptualization of the drainage network may ultimately affect the simulation of important watershed

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[1] Corresponding author: Centre for Hydrogeology and Geothermics, 11 rue Emile-Argand, Neuchâtel 2000, Switzerland; +41 (0) 32 718 26 22; fax: +41 (0) 32 718 26 03; daniel.kaeser@unine.ch

[2] Centre d'Hydrogéologie et de Géothermie, Université de Neuchâtel, 11 rue Emile-Argand, Neuchâtel, 2000, Switzerland.

[3] Département de Géologie et de Génie Géologique, Université Laval, 1065 Avenue de la Médecine, Québec, G1V 0A6, Canada.

[4] Golder Associates Limited, 50 Crimea St, Guelph, ON N1H, Canada.

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functions: channel morphology is a primary control on fine-scale hyporheic exchange, wider patterns of GW recharge/discharge, and riparian GW levels. These aspects, in turn, play a critical role in the generation of stream flow, the functioning of aquatic ecosystems and the transport of contaminants (Winter et al. 1998; Sophocleous 2002; Brunke and Gonser 1997; Jones and Mulholland 2000; Hayashi and Rosenberry 2002). Technicalities of channel-representation may therefore profoundly influence the outputs of PBI models. In practise, the challenges are associated with the DEM and the numerical mesh. At both levels common issues are related to: the occurrence of spurious pits and dams along the river, the connectivity of the channel and the floodplain, and the representation of in-channel morphology. Issues specific to the mesh include the parameterization of surface roughness, and the minimization of nodes along the drainage network. Our purpose here is to identify the implications of methodological choices on GSI simulations, and provide some guidance to overcome potential pitfalls.

The paper starts with identifying important issues of channel-representation in the context of GSI modeling, and follows with some strategies for addressing these in terms of DEM processing and mesh generation. Numerically, the focus is upon the “two-dimensional depth-averaged” conceptualization of overland flow. Most issues discussed, however, pertain also to one- and three-dimensional approaches. The vertical discretization beneath the channel is of course a crucial aspect of physically-based models, but this paper does not touch this issue. It discusses hyporheic exchange but not the specific aspect of upscaling, which remains a challenge. Note that two tutorials illustrating channel-meshing are provided in the Supporting Information.

Box 1

Physically Based Integrated (PBI) Models

Hydrological PBI models partition rainfall inputs into key components of the water cycle in a fully distributed way and according to physical laws. Their essential feature is the coupling of 2D overland flow with 3D subsurface flow at each time step (for a review of numerical coupling approaches, see Furman 2008). While some PBI models offer a 1D conceptualization of the stream network, this paper is primarily concerned with models that allow streams to emerge “naturally,” that is, the channel needs not be imposed a priori (Brunner and Simmons 2012). In this case, characteristics of simulated streams are highly dependent on the quality of the DEM. Such models differ from GW models coupled with a *predefined* 1D conceptualization of the drainage network (e.g., MODFLOW-SFR1 code). Well-known PBI codes include, for example, *ParFlow* (Kollet and Maxwell 2006), *HydroGeoSphere* (see Brunner and Simmons 2012), and *OpenGeoSys* (Delfs et al. 2012).

Channel-Representation Issues

The Digital Elevation Model

The influence of DEMs on hydrological modeling has been discussed previously in the modeling community, (e.g., Li et al. [2008]; Milzow and Kinzelbach [2010]). If DEMs were perfectly accurate and available at any resolution, representing channels would be straightforward. Problems arise either as a result of a DEM’s relative coarseness, of errors inherent to the measurement device (instrument noise), or of methodological limitations. For example, LiDAR measurements may be affected by vegetation or water (see Hilldale and Raff 2008). Problems of coarseness and inaccuracies typically result in unrealistic and ’noisy’ slopes along the drainage network, which affect in turn GSI. Geometric properties include the wetted area of the channel, the water depth, the slope and breaks-in-slope of the stream surface. Coarseness must be understood here in a relative sense, as the issue crosses the spectrum of scale. Even fine-scale DEMs may represent incorrectly the narrow drainage features that control the patterns of surface flow and GSI (Figure 1a and 1b). Coarseness obviously impedes the simulation of fine-scale GSI driven by morphological features that are poorly or not captured by a DEM. For example, breaks-in-slope of the stream surface are major drivers of hyporheic exchange, yet these areas are generally associated with the largest errors in DEMs (Heritage et al. 2009; Schäppi et al. 2010).

In models relying on a crude conceptualization of the channel, problems of inaccuracy and coarseness manifest themselves typically as spurious “pits” (lows) and “dams”

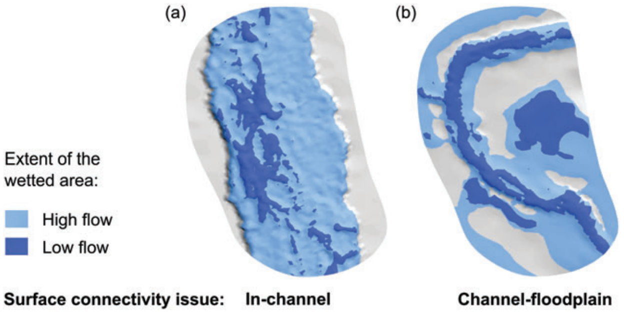

Figure 1. Wetted area in two flow conditions for two river-types (a: braided; b: meandering) depicting some effects of topography on the wetted area and hence on GSI. Small topographic features, spurious or real, control the connectivity of SW, especially in low flows (a) and in the aftermath of flow events (b). Such patterns of connectivity may induce complex feedbacks between GW and SW. Data: (a) DEM courtesy of Guillaume Pirot; (b) DEM of River Leith, UK (data collection supported by Environment Agency grant SC030155 to L. Heathwaite, Lancaster Environment Centre).

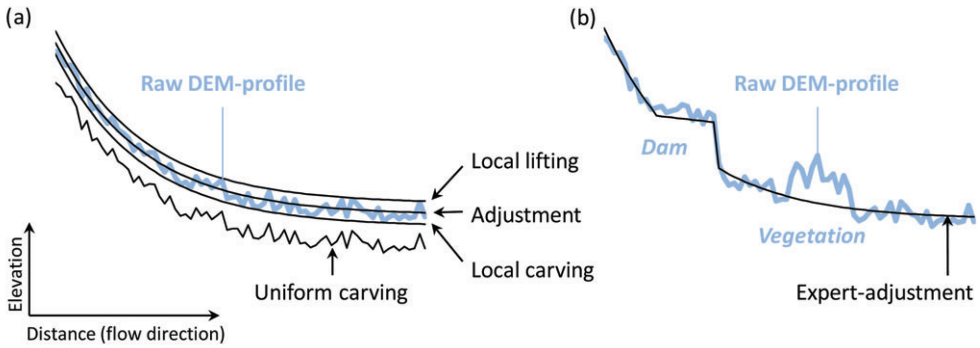

Figure 2. DEM profile along a channel prior to corrections (raw DEM: thick blue line) and the following corrections (thin black lines): (a) "simple" corrective approaches; (b) DEM adjustment based on expert rules and/or external data (modified after Yamazaki et al. 2012).

(highs), which must be removed to obtain a continuous downstream slope (Merwade et al. 2008; Yamazaki et al. 2012) (Figure 2). Failing to do so may cause strong deviations of a stream's course, especially in flatter terrains. As channels are represented more realistically, such deviations become less of an issue, but the modeler is required to make an increasing number of choices that may affect GSI. To discuss the 3-D and transient impacts of channel representation on GSI (Box 2), it is useful to distinguish "in-channel" and "channel-riparian" aspects.

In-channel geomorphology refers to the bed and banks of a channel, often represented in GW models by a rectangular cross-section. Such a simplification is generally assumed to have a minor effect on model outputs, given the high uncertainty surrounding the estimation of streambed permeability. This, however, should not conceal the various influences of in-channel topography on GSI. A major control is the relationship between stream flow and the wetted area (i.e., the area of overland-flow). For example, any deviation from a vertical representation of banks will increase the area of exchange during a stream flow event (Doble et al. 2012), and possibly the area adjacent to the unsaturated zone, which tends to slow down the propagation of a flood wave in the shallow subsurface (McCallum et al. 2010) (see Figure 3a). As stream flow recedes, smaller bedforms increasingly affect the surface flow field (Horritt et al. 2006; Casas et al. 2010b; Legleiter et al. 2011) (Figure 3b). If sections of a stream become disconnected from each other, bedforms may shape the disconnection pattern (Figure 3e). At the finest scale, the simulation of hyporheic exchange is naturally highly sensitive to the representation of morphological complexity: these flows are driven by centimeter-scale bedforms, sharp breaks-in-slope of the water-surface, and high stream velocity (Figure 3c).

Another in-channel issue is related to the inaccuracy of bed elevation, and its effects on GW heads and river discharge. Bed levels in a DEM are commonly lowered to prevent spurious overbank flooding (stream carving/burning). In this case, a "bed-level tradeoff" issue is likely to arise (Figure 3d): either an accurate stream flow is maintained by adjusting stream-depth, and SW heads are therefore underestimated, or the consistency between GW and SW heads is maintained, and stream flow is therefore overestimated (Yamazaki et al. 2012). In addition, lowering the riverbed to prevent spurious overbank flooding may lower GW levels in the floodplain, and subsequently reduce riparian GW evapotranspiration or dry out riparian SW bodies. Although trivial in appearance, this problem may prove extremely difficult to handle over large regions (Figure 1a). In summary and from the standpoint of GSI, key aspects of in-channel morphology include the: longitudinal connectivity of SW, bank representation, relationship between stream surface elevation and wetted area, channel-depth below floodplain, and the representation of bedforms (e.g., bars, riffles, and steps).

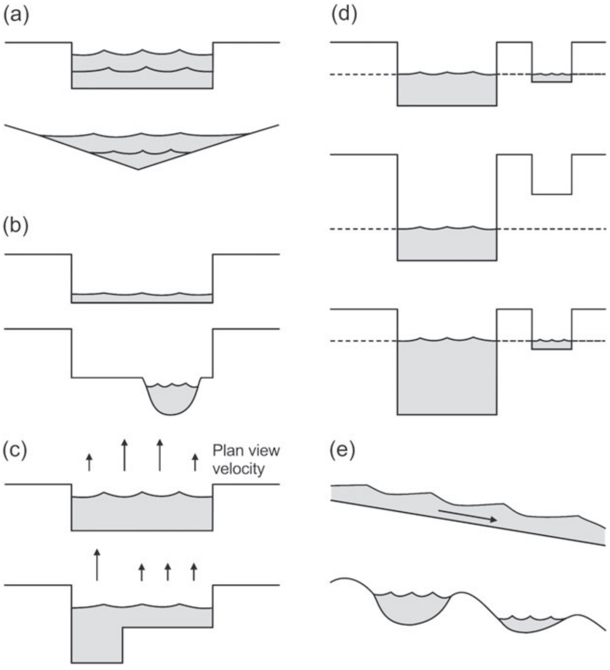

Figure 3. Potential effects of the representation of channel topography on: (a) the stream stage/wetted perimeter relationship; (b) the location of the wetted perimeter during low flows; (c) the surface-flow velocity field; (d) groundwater levels in the floodplain and river discharge; and (e) stream-flow connectivity along a channel.

The *channel-riparian* interface has a major influence on overbank flooding. As these events constitute a mechanism of aquifer recharge, especially in flat regions, their extent and duration are important for GSI predictions. The challenge for modelers is to control the seemingly minor topographic inaccuracies that may dramatically impact the simulation of overbank floods (Marks and Bates 2000; Hunter et al. 2007; Merwade et al. 2008). Inaccuracies are commonly caused by: (1) elevation discrepancies resulting from a mismatch of channel-riparian boundaries; (2) DEM errors in the channel and the floodplain, for example, owing to the presence of vegetation; and (3) a DEM that is too coarse to represent tributaries and lateral breaches in the embankments. For example, breaches that are narrower than the DEM resolution will cause the elevation of low points to be overestimated. As a result, channel-riparian connectivity is reduced, thus diminishing the extent of inundation, and in the aftermath of floods, "trapping" SW in the floodplain during long periods (Yamazaki et al. 2012) (Figure 4). Because the wetted area expands to the floodplain during overbank floods, the representation of floodplain topography also becomes crucial. As pointed out by Hardy et al. (1999), the floodplain friction may have a far greater effect on overland flow predictions than channel friction. Additionally, the complex patterns of surface flow may be impossible to reproduce without meter-resolution (Bates et al. 2003; Nicholas and Mitchell 2003; Cook and Merwade 2009) or even centimeter-resolution DEMs of the floodplain (Frei et al. 2010). Hence, to ensure appropriate simulations of surface storage and drainage, it is important to evaluate prior to the model design: (1) the extent of the largest wetted area that will be simulated; and (b) within this perimeter which processes require explicit topographic representation, and which ones can be defined implicitly through parameterization of surface roughness or flow obstacles. In summary, common issues related to the channel-riparian interface include: the misrepresentations of the stream-riparian connectivity, and the representation of riparian topography.

Box 2

GSI Are Three-Dimensional and Transient

The impacts of channel-representation in PBI models can be usefully conceptualized in a 3D transient framework. For example: (1) longitudinally, DEM-artifacts may alter the river course, or generate surface ponding in areas where it does not occur; (2) laterally, the hydraulic connection between the channel and its floodplain affects the spatial extent of a flood. Similarly, lateral topographic variability within the channel influences the wetted perimeter; (3) vertically, the elevation of the streambed relative to the floodplain may control the depth of the GW table, and therefore the access of riparian vegetation to GW; and (4) such processes must be considered in a dynamic context. Thus, any approach to channel representation has temporal and spatial aspects that may potentially impact the overall water flow budget, the exchange budget between GW and SW, and other characteristics such as spatial exchange patterns, residence times, etc.

The Numerical Mesh

The design of the numerical mesh reflects a number of key decisions made by the modeler; for example: What scale and what type of processes does the model represent? Whatever the meshing approach, the design must at least be consistent with: (1) the level of terrain detail required by the model objectives; and (2) the strategy of parameterization of roughness. Both aspects will ultimately determine the relationship between stream flow and water level. Surface roughness may not appear as a problem to those who consider it an effective calibration parameter. However, parameterizing roughness through calibration has a limitation: roughness in a single mesh-element may have to vary with stream flow to satisfy calibration requirements (Lane 2005), and may therefore not be valid under conditions that are out of the calibration range.

The influence of mesh resolution on 2D surface-hydrodynamic simulations is well discussed by Hardy et al. (1999), who mention three key points: (1) the impact of resolution can be at least as important as typical calibration parameters; (2) although it is often assumed that higher resolution enables a better estimation of the "true" hydraulic solution, there are no means of telling how close to this solution the mesh is; and (3) defining the element size based either on (a) the coarsest resolution at which numerical convergence is achieved, or on (b) the appreciation of a length scale of the modeled phenomena, are two approaches that cannot be generalized.

Fundamentally, coarse elements tend to simplify hydraulic processes and impede model convergence as they decrease the topological integrity of the physical system (Hunter et al. 2007). Areas that are

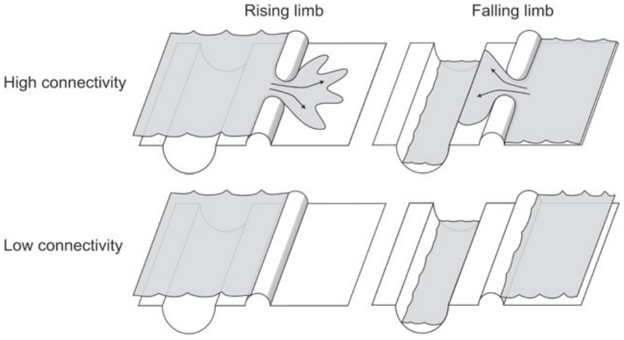

Figure 4. Influence of topographic connectivity between the channel and the floodplain upon overbank flooding and therefore groundwater/stream interactions.

sensitive to mesh resolution are generally related to sharp variations in space or in time (e.g., the water-surface next to channel weirs). Poor simulations of hydraulic processes caused by a coarse mesh may occur following the oversimplification of: (a) the terrain's geometry, (b) the roughness distribution, or (c) the mesh geometry. Meshes that simplify topography may affect the routing of flow, cause the displacement of the shoreline due to terrain distortion (Hardy et al. 1999; Horritt et al. 2006), the removal of local minima, which tends to increase the volume of static water that cannot be drained (Caviedes-Voullième et al. 2012), and the disappearance of flow variability (Horritt et al. 2006). Coarse meshes can also cause spurious zigzagging of the river course, and subsequently increase its length, thus delaying the arrival time of a peak flow (Lai 2005). At the catchment scale, coarse elements will tend to obliterate creeks and low-order streams, therefore reducing the surface area of exchange between and GW and SW. As to roughness parameterization, its simplification decreases the level of flow organization (Casas et al. 2010a); it leaves the possibility that the impact of hydraulically significant but small features (e.g., vegetation in floodplains) on flow routing and water depth will be reduced, because roughness is averaged out within the mesh element (Cobby et al. 2003). While some of these effects may have little influence on areas of GW recharge and discharge, they could be significant for simulations of fine-scale GSI such as hyporheic exchange.

Channel-Representation Strategies

Processing the DEM

Two approaches are commonly followed to improve channel topography in raw DEMs: either the DEM is corrected, or it is merged with another DEM generated specifically for the channel. Catchment-scale models that ignore in-channel morphology typically rely on corrections, whereas reach-scale models will likely require generating a specific DEM. Key aspects of these two approaches are presented hereafter.

Correcting a DEM

To represent a channel, the rougher but computationally more effective approach consists of using a DEM with a resolution similar to the channel width. In this case, spurious pits and dams are likely to occur. Techniques to remove these features seek either to (Figure 2): (1) lift the pits up, a technique referred to as pit-lifting or sink-filling (Soille and Ansoult 1990); (2) lower down the dams or the entire channel (Martz and Garbrecht 1999), a technique called stream-burning or -carving; or (3) optimize changes by applying both lifting and carving, a technique that may be referred to as DEM-adjustment (Soille 2004; Yamazaki et al. 2012). These corrections may require additional data such as maps of the drainage network. For a limited number of nodes, elevations along the drainage network may also be corrected manually or semi-automatically, for example using Geographic Information System techniques. In principle, the DEM-adjustment appears as the most appropriate approach to minimize the amount of modification, and thus prevent large local errors that could remain after conducting pit-lifting or stream-burning alone.

These corrective approaches are appealing for models covering large regions. There are two issues, however, related to scale and coarseness. The first and practical issue is the distinction between spurious features to remove, and natural ones to preserve (see Figure 2b). The interested reader is referred here to the algorithm proposed by Yamazaki et al. (2012) who implement expert rules in a decision-making process. The second issue, inherent to coarse DEMs, is the failure to represent explicitly subscale processes that potentially affect GSI. Steps and weirs are typical features that enhance and modify the spatial distribution of exchange, yet they are incompatible with a coarse representation of topography. Because most PBI models do not currently include such exchanges implicitly (i.e., through parameterization), the alternative is therefore to increase topographic resolution by conducting a topographic survey tailored to the needs of the model, as discussed next.

Generating a DEM

The quality of a DEM generated specifically for the channel depends on the topographic survey and the interpolation technique. Three types of channel-surveys may be distinguished: (1) grid-based, (2) cross-sectional, or (3) terrain-sensitive. The topography may then be interpolated through: (1) standard interpolation methods and/or (2) topographic reconstruction methods. Last, a strategy is required to merge the channel- and the regional-DEM into a continuous and consistent DEM. These steps and options are briefly discussed hereafter.

Grid-based surveys consist of elevation measurements following a regular grid. They may be time consuming or expensive, yet they favor repeatability and some consistency between different datasets. Potential limitations include the high data volume, which must be reduced to a manageable size (Mandlburger et al. 2009), and the poor representation of hydraulically significant steep slopes, despite seemingly small sampling intervals (Heritage et al. 2009).

Terrain-sensitive surveys are conducted by measuring elevations along characteristic landscape lines such as bar outlines and thalwegs. This approach seeks to reduce the number of measurements while favoring some spatial uniformity of elevation errors (Merwade et al. 2008; Heritage et al. 2009). In complex terrains, a useful approach is a triangular sampling pattern scaled to surface discontinuities, which can be efficiently converted to the numerical mesh (Vallé and Pasternack 2006).

Cross-sectional surveys involve the measurement of elevations across representative channel transects. This approach is widely used, partly because of its suitability for 1D hydraulic models. Errors in the interpolated DEM will typically increase with spacing between sections (Heritage et al. 2009), and even more so with spacing between points of a same section (Horritt et al. 2006). Legleiter and Kyriakidis (2008) observed a proportional relationship between section spacing and root mean square of the interpolated DEM. Although sampling density impacts the uncertainty of hydrodynamic predictions (Legleiter et al. 2011), there is no general rule regarding an optimum spacing. For example, Merwade et al. (2008) suggest that the interpolation is no longer realistic when the sections are separated by more than 10 to 15 channel widths. Legleiter et al. (2011) report that topographic uncertainty is minimal when sections are separated by less than a quarter of the wetted channel width. Horritt and Bates (2002) found that despite widely spaced cross sections (>15 channel widths), their models gave good predictions of bulk flow properties such as discharge and flow extent, failures resulting rather from the parameterization of roughness. Horritt et al. (2006) compared different DEMs based on a 0.5, 50, and 500 m section spacing, and found that this had only little influence on velocity compared with the effect of water-surface elevation. For an example of cross-section interpolation and projection onto a mesh, the reader is referred here to *Tutorial I* (see Supporting Information).

Standard interpolation techniques in channel environments are likely to benefit from approaches that: (1) operate in a curvilinear coordinate system; (2) represent anisotropy (i.e., the elongated nature of channel morphology); and (3) favor the representation of sharp boundaries and break lines. Especially useful in sinuous streams, the curvilinear system refers to the distance s along the stream's axis, and the lateral distance n (Merwade et al. 2006). Points can be surveyed directly in the s, n system, or derived from x, y coordinates (e.g., Goff and Nordfjord 2004; Merwade et al. 2005; Legleiter and Kyriakidis 2006). To represent anisotropy, kriging appears as one of the most suitable methods (Merwade et al. 2006; Casas et al. 2010b; Legleiter et al. 2011). It is also flexible enough to include cross-sectional asymmetry and topographical break lines, as shown by Legleiter and Kyriakidis (2008). Note that simpler procedures may also enable the representation of sharp breaks. Merwade et al. (2008), for example, represent gravel bars as prism-like features by incorporating polygonal vectors in a linear interpolation.

Topographic reconstruction is useful when a topographic survey does not capture explicitly the required level of detail, and is possible when some geostatistical description is availabe. This approach relies either on the delineation of characteristic zones (e.g., bars vs. channels), on rules that define spatial patterns, or on process based models of erosion/deposition (see Koltermann and Gorelick 1996). Examples of topographic reconstruction applied to channels are provided by Legleiter et al. (2011), Casas et al. (2010b), and in the context of GSI modeling, by Stonedahl et al. (2013).

Merging different DEMs commonly involves combining a channel with a regional DEM, or combining various datasets within the channel. The creation of a consistent elevation model based on a channel and a regional DEM is discussed by Merwade et al. (2008) who suggest that the two datasets be interpolated separately to prevent the mutual influence of floodplain and channel elevations. In overlapping areas, the dataset with the better accuracy must be honored, and the final DEM must then be smoothed to attenuate any remaining spurious discrepancies (Merwade et al. 2008). The combination of various datasets within a channel is illustrated Schäppi et al. (2010) who use both cross-sectional and aerial surveys to produce an optimal DEM.

Generating the Numerical Mesh

Refining the Mesh

Designing the mesh of a river network is generally a challenging optimization problem where the number of nodes must be minimized, while process representation and model convergence must be ensured (Mandlburger et al. 2009; Caviedes-Voullième et al. 2012). One approach is the examination of grid convergence. By running a model on successively finer meshes, the discretization error should asymptotically approach a minima. Accordingly, the adequate resolution is found when the results of a given mesh are near-identical to those of a slightly coarser one (Caviedes-Voulliéme et al. 2012). However, to ascertain thoroughly the overall model-response to spatial resolution, it may be preferable to test the model's sensitivity to the resolution of both the mesh and the topography. (Hardy et al. 1999; Horritt et al. 2006; Cook and Merwade 2009; Casas et al. 2010b).

The simplest representation of a channel is perhaps the "V-shape," which involves in its simplest form two cross-sectional elements. Providing this approach supports the model's purpose, the adequate mesh will require defining the size of these elements, and ensuring that the central segments match the channel axis (Figure 5). Adding a third element across a section allows capturing, even in a crude fashion, the bathymetry (Horritt 2000). If the mesh must represent in-channel structures, a reasonable starting point for defining the resolution is through the length-scale of key bed forms (Marks and Bates 2000). The variogram range or a visual inspection of the topography can provide a general criterion to select an initial mesh size, the key step being the discrimination between features that need to be explicitly incorporated into the model, and those that are implicitly expressed through parameterization (Bates et al. 2003). Reliable stream flow simulations can generally be achieved by elongating elements in the direction of flow (Mandlburger 2006; Mandlburger et al. 2009), while shortening them as a function of local curvature (Horritt 2000).

In addition to mesh requirements for finite element models (e.g., aspect-ratio, angle criterion, and expansion ratio), topographic constraints are being increasingly described in meshing approaches for hydrodynamic studies. For example, Cobby et al. (2003) refine the mesh in areas of significant variations of roughness. Bates

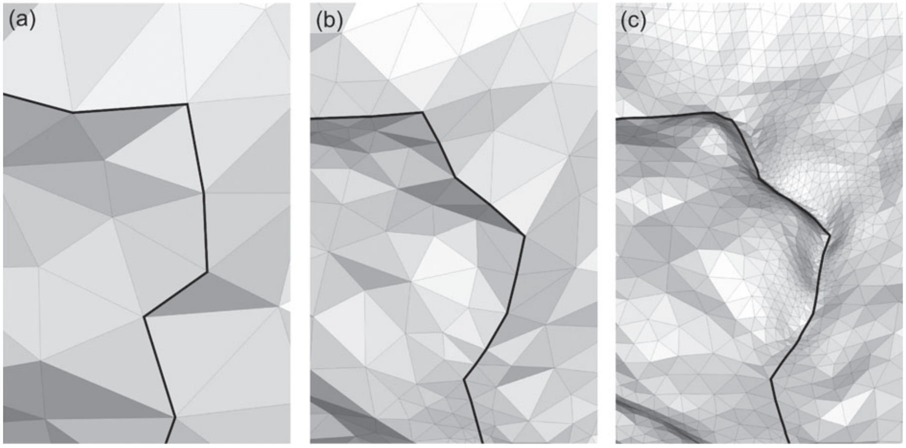

Figure 5. Terrain represented by a coarse- (a), medium- (b), and high-resolution (c) mesh exemplifying the influence of a simplified terrain on the channel's position (thick line) and cross-sectional profile.

et al. (2003) build an optimized mesh that incorporates "topographically significant points" and use, as Caviedes-Voullième et al. (2012), vertical curvature as an indicator of areas to refine. A methodology for generating a mesh and refining it according to slope is described here in *Tutorial II* (see Supporting Information), which also illustrates the removal of unnecessary close nodes (Horritt et al. 2006; Mandlburger et al. 2009). Such optimization approaches favor the representation of small structures such as levees and embankments, which can significantly affect the routing of flow (Cobby et al. 2003). Thus, a useful meshing algorithm is one that preserves relevant topographic features, while satisfying the mesh qualities required by the hydraulic model (e.g., Mandlburger et al. 2009).

Accounting for Roughness

Representing multi-scale topography involves fitting a mesh to available topographic data, and then parameterizing smaller features, for example through the roughness term (Lane et al. 2004). Commonly, the roughness parameter depends on the resolution of the mesh and the flow conditions, and is not readily transferable between different meshes (Hardy et al. 1999). Because it is not straightforward to derive its value from *in situ* measurements, roughness is often used as an effective calibration parameter. This approach, however, becomes less effective as the complexity of channel geometry increases (Fewtrell et al. 2011). To parameterize roughness, the modeler must decide whether external data will be incorporated (e.g., look-up tables, remote sensing, and field surveys). Three broad options are possible: (1) *non-informed calibration*, which means that no a priori roughness information is included; (2) *informed calibration*, which involves external data (e.g., a grain size map or a roughness distribution function) included through weights or rules; (3) *physical or empirical modeling* of roughness, which uses external data to estimate the friction factors objectively (e.g., Mason et al. 2003; Casas et al. 2010a). When the flow conditions of the calibration and the prediction periods are substantially different, physically-based estimates of roughness are preferable (see de Marsily 1994). For a full discussion on parameterization in environmental models, and hydraulic models in particular, the reader is referred to Grayson and Blöschl (2001) and Bates et al. (2003), respectively. Note that terrain roughness has also an effect on the routing of flow, as a result of blockage, with sometimes dramatic impacts on flow patterns. To reflect the effect of subscale obstacles, without defining unrealistic roughness values, additional parameters such as "numerical porosity" have been proposed (Olsen and Stokseth 1995; Lane 2005).

Tutorials

Two tutorials are provided as Supplementary Information to illustrate the meshing of channels and to exemplify procedures for those who are unfamiliar with these techniques. The tutorials were developed in the context of PBI modeling but are also applicable to conventional GW modeling. *Tutorial I* exemplifies the interpolation of cross-sections, the combination of channel and floodplain topography, and the subsequent projection onto a mesh, using the software GridBuilder™. The example relies on the following input data: (1) a line along the stream defined by its x, y coordinates; (2) cross-sectional bathymetric data, including the sections' positions along this line, and pairs of coordinates representing "depths beneath floodplain elevation" and "lateral distances from the stream's centre line"; and (3) a regional DEM. After creating a 2D mesh, the user interpolates the cross-sectional data in a curvilinear coordinate system, and merges the result with a regional DEM. It is worth mentioning here the tutorials referred to by Merwade et al. (2008; 2005), which also illustrates the interpolation of cross-sections in a curvilinear coordinate system, and the subsequent integration of channel- and floodplain-topography. The methodology is similar to *Tutorial I*, but uses a different software package and is restricted to regular grids. Merwade's documents are available at the current date of publication through the author's website.[5,6]

Tutorial II describes a semi-automated procedure for optimizing a mesh according to the drainage network. It shows how to refine areas of high topographic variability, and to filter unnecessary nodes. The example requires ArcGIS™ and the following input data: (1) a DEM; (2) the drainage network in vector format; and (3) the model domain boundary in vector format. The user starts by defining a discretization interval for the river network and model boundaries. A mesh triangulation is then conducted using the freely available software Triangle™ to create a Delaunay mesh that conforms to the predefined inner- and outer-boundary nodes. Based on this first mesh, a semiautomated procedure is performed to remove unnecessary nodes, and refine the mesh as a function of the topographic slope.

Conclusions

The representation of channel topography plays a critical role in PBI simulations of groundwater-stream interactions. Various strategies exist to improve the representation of channels in both the DEM and the numerical mesh. To create a suitable DEM, one may distinguish: (1) approaches that correct a relatively coarse DEM to obtain a continuous downstream slope along the drainage network; and (2) approaches that focus on the finer representation of in-channel morphology. Devising the appropriate method requires evaluating the influence of channel representation on GSI in three dimensions, in time and across scales. To refine a mesh, several criteria may be accounted for, such as the slope and curvature of the topography. The examination of grid convergence is a key optimization step. However, a mesh that satisfies convergence criteria does not necessarily represent GSI at the appropriate scale. It is therefore recommended that modelers analyze, to some extent at least, the sensitivity of simulated GSI to the representation of channels.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Two documents discussed in Section "Tutorial" may be found in the online version of this article: Tutorial I ("Design and run a simple channel-floodplain model") and Tutorial II ("3D mesh generation and refinement as a function of topographic slope"). The python scripts required by Tutorial II are also provided.

Appendix S1. Design and run a simple channel-floodplain model with *GridBuilder* and *HydroGeoSphere*.

Appendix S2. 3D mesh generation and mesh refinement as a function of the topographic slope.

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[5] Creating river bathymetry from cross sections: http://web.ics.purdue.edu/~vmerwade/research/terrain_tutorial.pdf

[6] Representation of river channels: http://www.crwr.utexas.edu/gis/gishydro03/Channel/Channels.htm

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