AGU PUBLICATIONS

Reviews of Geophysics

REVIEW ARTICLE
10.1002/2016RG000530

Key Points:
- Complex feedback mechanisms exist between sedimentological processes and surface water-groundwater flow in streams
- There is currently no quantitative approach that allows exploration of these feedback mechanisms
- A blueprint of a mathematical model is suggested that allows coupling of sedimentology, hydrology, and hydrogeology in streambeds

Correspondence to:
D. Partington,
daniel.partington@flinders.edu.au

Citation:
Partington, D., R. Therrien, C. T. Simmons, and P. Brunner (2017), Blueprint for a coupled model of sedimentology, hydrology, and hydrogeology in streambeds, *Rev. Geophys.*, *55*, 287–309, doi:10.1002/2016RG000530.

Received 20 JUL 2016
Accepted 14 FEB 2017
Accepted article online 27 FEB 2017
Published online 11 APR 2017

Blueprint for a coupled model of sedimentology, hydrology, and hydrogeology in streambeds

Daniel Partington[1], Rene Therrien[2], Craig T. Simmons[1], and Philip Brunner[3]

[1]School of the Environment and National Centre for Groundwater, Research and Training, Flinders University, Adelaide, South Australia, Australia, [2]Department of Geology and Geological Engineering, Université Laval, Quebec, Quebec, Canada, [3]Centre of Hydrogeology and Geothermics, Neuchâtel, Switzerland

Abstract The streambed constitutes the physical interface between the surface and the subsurface of a stream. Across all spatial scales, the physical properties of the streambed control surface water-groundwater interactions. Continuous alteration of streambed properties such as topography or hydraulic conductivity occurs through erosion and sedimentation processes. Recent studies from the fields of ecology, hydrogeology, and sedimentology provide field evidence that sedimentological processes themselves can be heavily influenced by surface water-groundwater interactions, giving rise to complex feedback mechanisms between sedimentology, hydrology, and hydrogeology. More explicitly, surface water-groundwater exchanges play a significant role in the deposition of fine sediments, which in turn modify the hydraulic properties of the streambed. We explore these feedback mechanisms and critically review the extent of current interaction between the different disciplines. We identify opportunities to improve current modeling practices. For example, hydrogeological models treat the streambed as a static rather than a dynamic entity, while sedimentological models do not account for critical catchment processes such as surface water-groundwater exchange. We propose a blueprint for a new modeling framework that bridges the conceptual gaps between sedimentology, hydrogeology, and hydrology. Specifically, this blueprint (1) fully integrates surface-subsurface flows with erosion, transport, and deposition of sediments and (2) accounts for the dynamic changes in surface elevation and hydraulic conductivity of the streambed. Finally, we discuss the opportunities for new research within the coupled framework.

1. Introduction

Sustainable management of both surface water (SW) and groundwater (GW) resources and the environments they support requires a quantitative understanding of surface water-groundwater (SW-GW) interactions [*Boulton and Hancock*, 2006; *Gran and Paola*, 2001]. In a seminal paper, *Freeze and Harlan* [1969] described a blueprint for the simulation of catchment hydrology by proposing to fully couple climatic forcing with SW and GW flow in a single model. Their blueprint allows for the simulation of the main streamflow generation processes observed in a catchment and provides a quantitative framework for the sustainable management of water resources at the catchment scale. Several models spawned by this blueprint have and continue to be used to explore SW-GW interactions both through purely theoretical studies as well as applied studies of real systems [*Brunner and Simmons*, 2012].

Within this review, the term "SW-GW interaction" concerns stream-aquifer interactions, the streambed, and near-stream processes. A range of scales is made reference to throughout this review; scales with an indicative length or area are defined within this paper as bed form (centimeters), meander (meters to tens of meters), reach (hundreds of meters to thousands of meters), catchment (square kilometers), and regional (hundreds to thousands of square kilometers). In this review, "small scale" refers to the bed form and meander scales and "large scale" refers to the catchment and regional scales.

Although management of water resources often focuses on whole catchments, streambeds have long been a topic of great interest because they are the physical interface between surface flow in streams and subsurface flow in underlying aquifers [*Constantz*, 2016; *Sophocleous*, 2002]. They have been the focus of a large number of studies in the fields of geomorphology, hydrology, and ecology [*Wainwright et al.*, 2011]. The topography, hydraulic conductivity, and porosity of streambeds control water, mass, and energy fluxes between SW and GW [*Kasahara and Wondzell*, 2003]. The physical characteristics of the streambed also control hyporheic residence times, with major implications for stream ecology, biogeochemistry, and water quality (see Tutorial 1). From a global ecological perspective, increased sediment loads pose a threat to the health of stream ecosystems due to clogging and permeability reduction of benthic and hyporheic zones [*Hartwig and Borchardt*, 2015; *Mathers et al.*, 2014].

Tutorial 1: Why the Streambed Matters in Exchanges Between the Surface and Subsurface

Stream-aquifer exchange is driven by the hydraulic head gradient across the streambed. The hydraulic head at a given location in a streambed has hydrostatic and hydrodynamic components [*Boano et al.*, 2014]. The hydrostatic component is the sum of elevation and pressure heads, which corresponds to the hydraulic head commonly used in hydrogeology [*Freeze and Cherry*, 1979]. The hydrodynamic component is the sum of velocity head and hydrodynamic pressure head resulting from the flow field, which is important at bed form scales [*Sawyer and Cardenas*, 2009]. Using Darcy's law, the exchange fluid flux q (LT^{-1}), which is the volume of water flowing through a unit area of streambed per unit time, is obtained by multiplying the hydraulic head gradient ∇H (LL^{-1}) by the hydraulic conductivity of the streambed K (LT^{-1}):

$$q = K\nabla H$$

The magnitude of fluid exchange between the surface and subsurface is therefore directly proportional to the hydraulic conductivity of the streambed, defined as [*Freeze and Cherry*, 1979]

$$K = \frac{k\rho g}{\mu}$$

where k (L^2) is the intrinsic permeability of the streambed, ρ and μ are the density (ML^{-3}) and dynamic viscosity (ML^{-1}T^{-1}) of water, respectively, and g is the gravitational constant (LT^{-2}). Variations in the water temperature and salinity therefore affect the streambed hydraulic conductivity. For the sake of simplicity, we assume here constant water viscosity and density such that permeability and hydraulic conductivity are related by a constant.

The streambed permeability depends on the grain size distribution (GSD) of sediments within the streambed [*Agency*, 2009; *Arya et al.*, 1999b; *Rosas et al.*, 2015]. Also, there is a link between the GSD and porosity of a sediment mixture [*Ouchiyama and Tanaka*, 1986]. However, obtaining porosity from the GSD alone is challenging because porosity is also related to the geometrical arrangement, or packing, of the individual grains forming the sediment. Any changes to the sediment composition of the streambed will modify its permeability, and therefore its hydraulic conductivity, and affect the exchange through the streambed. In addition, the GSD influences the stability of the streambed [*Bartzke and Huhn*, 2015], which can promote its erosion.

The physical properties of the streambed, including the hydraulic conductivity and porosity, affect surface water-groundwater exchanges across different spatial scales, from the catchment ($>10^6$ m^2), stream reach (~10^6 m^2), and meanders (~10^3 m^2) down to the bed form dunes scale ($<10^{-1}$ m^2) [*Boano et al.*, 2014]. A considerable amount of research dedicated to small-scale controls of the hyporheic zone exists [e.g., *Harvey and Bencala*, 1993]. *Elliott and Brooks* [1997] presented a conceptual study of the drivers for small-scale hyporheic exchange, which they verified in flume experiments. They observed patterns of hyporheic exchange fluxes for different streambed topography types, including ripples and riffle-pool sequences. They show that water flowing around and over topographical obstacles generates high pressures upstream of the obstacle and low pressures downstream. The pressure difference across the obstacle creates a hydraulic gradient that induces hyporheic flow through the subsurface, which they labeled bed form induced pumping. The role of hydrologic variability in driving streamflow has also been recently examined by [*Schmadel et al.*, 2016], who conclude that spatial and temporal fluctuations of the hydraulic gradient in the hyporheic zone can be as important as the geomorphic features of streams in driving hyporheic flow.

Knowledge of the spatial and temporal variability of the streambed hydraulic conductivity is critical for quantifying variations in hyporheic exchange as well as stream-aquifer interactions at a larger scale. *Salehin et al.* [2004] showed in flume experiments that the heterogeneity of hydraulic conductivity increases the average hyporheic exchange flux but at the same time results in a shallower hyporheic zone. The heterogeneity of hydraulic conductivity in the streambed has been identified as a critical parameter for hyporheic exchange and stream ecology [*Boulton et al.*, 1998]. Therefore, the impetus for understanding spatiotemporal patterns of the streambed and the processes that drive them is clearly necessary for understanding surface-subsurface exchanges. The reader is referred to *Boano et al*. [2014] for a comprehensive review of hyporheic flow processes and a detailed discussion of the importance of streambed hydraulic conductivity on hyporheic exchange.

There is an intrinsic link between a streambed's hydraulic properties and its sedimentary composition. Transient and complex erosion and deposition processes shape the sedimentary composition of streambeds. These processes have received attention for the last century in the fields of fluvial geomorphology and sedimentology [*Garcia*, 2008]. Erosion and deposition are a function of the stream power and are therefore linked to streamflow generation and depletion processes (see Tutorial 2).

Given that the hydraulic properties of streambeds are of pivotal importance to SW-GW interactions, and that sedimentological processes control these properties, a holistic understanding of SW-GW interactions must include aspects of sedimentology. One would also expect close interactions and common conceptual models between studies of SW-GW interactions and studies of the dynamics of streambeds. However, as this review demonstrates, this is not currently the case.

In this review, we explore the feedback mechanisms between sedimentological processes and SW-GW interactions and critically review the current extent to which these fields of research interact and are coupled. We assess this interaction by reviewing the conceptual and numerical models in both fields. This review demonstrates that feedback and coupling between sedimentology, hydrology, and hydrogeology remain largely unexplored, poorly understood, underdeveloped, and semiquantitative or qualitative at best. We, therefore, propose a union of hydrological processes (including streamflow generation processes in the surface and subsurface) and stream morphological models as an extension of the *Freeze and Harlan* [1969] blueprint to both couple these disparate areas and to provide a critically needed quantitative basis for scientific analyses. The extensions proposed capture topographical and near-surface property dynamics of streambeds while accounting for the feedbacks with SW-GW exchanges. This paper focuses on the development of a conceptual blueprint framework for coupled modeling of sedimentology, hydrology, and hydrogeology in streambeds. To guide future model development, we provide one possible mathematical formulation for this coupled framework. The subsequent development, implementation, and application of the model itself remain a significant and detailed task in its own right. This is beyond the scope of the current review and framework formulation paper. This paper is therefore deliberately strategic and conceptual in nature and thus treats this topic at a higher philosophical level.

The newly proposed blueprint provides the conceptual and quantitative basis for numerous scientific and technical applications. As groundwater scientists working in SW-GW interaction studies, including model development and application, our primary motivation for this work was catalyzed by studies of SW-GW interaction at the regional scale. It is clear that many spatially distributed models are now available for studying SW-GW interaction at the regional scale. What is also readily apparent is that the treatment of the streambed—the ultimate connection between surface water in a stream and groundwater—is generally trivialized or simplified, poorly understood, or largely ignored. Quantifying the role of the streambed (and associated streambed dynamic processes) in coupled SW-GW interaction processes remains an open scientific question. To support this scientific understanding requires quantitative modeling tools capable of simulating the fully coupled sedimentological-hydrological-hydrogeological processes at appropriate (regional) scales. This in turn will provide a rigorous scientific basis for informing conceptual and numerical modeling choices—such as the level of simplicity or complexity required to provide answers to specific questions at specific spatial and temporal scales.

Such models are anticipated to have significant and wide-ranging applications across SW-GW interaction and streambed problems. For example, quantifying feedback mechanisms is expected to help in river restoration projects. In current engineering practice, river restoration focuses mainly on the horizontal dimension [*Boulton*, 2007] without adequately integrating the dynamics of the streambed. Another example is the transport and fate of contaminants. Fine sediments play a crucial role in the attenuation and transport of nutrients [*Owens et al*., 2005] and micropollutants [*Luo et al*., 2014]. Although numerous studies exist on the advective transport of pollutants and nutrients through GW and SW, there remain many open scientific questions about the implications of SW-GW exchange on fine sediments and the associated transport of nutrients and pollutants. At a catchment scale, the model can also provide important information on the partitioning of precipitation into SW and GW. While the small-scale processes at the interface between the subsurface and the surface are not important for a catchment's water balance on an annual basis, they are expected to be important for rainfall partitioning into SW and GW which has profound implications for water quality and the timing of the event hydrograph. The discussion provides an outline of further opportunities for the application of such a hydrological-hydrogeological-sedimentological model.

2. Streambed Dynamics in Relation to Hydraulic Properties

Because of the intrinsic link between the hydraulic properties of sediments and their composition, sedimentological processes that modify the composition of a streambed also modify the hydraulic properties at the sediment-water interface [*Genereux et al*., 2008]. These sedimentological processes give rise to complex spatial patterns of streambed hydraulic conductivity [*Chen*, 2011; *Chen et al*., 2009; *Cheng et al*., 2011; *Cheng et al*., 2013; *Dong et al*., 2012]. Sedimentological processes are transient, and the hydraulic properties of streambeds are therefore variable in time. On the most basic level, sediments are deposited during low flow periods and mobilized during high flow events. A wide range of literature on the physics of sediment transport is available, and various textbooks dedicated to this subject exist [e.g., *Garcia*, 2008]. In the simplest terms, the empirical Hjulstrom curves [*Hjulstrom*, 1935] are used to determine whether a particle is transported, eroded, or deposited, depending on its size and the stream velocity. *Brunke* [1999] distinguishes between different types of erosion and sedimentation dynamics. During periods of low flow velocities, suspended sediments can settle on the top of the streambed, leading to clogging and reduction of the streambed hydraulic conductivity (a process known as external colmation). External erosion and deposition take place at the streambed surface and also affect streambed topography [*Blaschke et al*., 2003]. *Brunke* [1999] further highlights that fine sediments that pass through the top layer (termed the armor layer) can accumulate beneath it, leading to internal colmation, or pass deeper into the bed (termed depth filtration) [*Evans and Wilcox*, 2014]. While internal colmation and depth filtration do not modify the topography of the streambed, they cause changes to the streambed sedimentary composition.

A branch of sedimentology has focused on the effect of upwelling and downwelling water on the erosion and deposition of sediments (see Figure 1) [e.g., *Baldock and Nielsen*, 2010; *Francalanci et al*., 2008]. *Lu et al*. [2008] review laboratory studies on the effects of suction (downwelling water) and injection (upwelling) with respect to sediment transport and bed shear stress and report mixed results in the literature. The majority of researchers found that upwelling increases sediment transport and bed erosion and that downwelling inhibits sediment transport [e.g., *Cheng and Chiew*, 1999; *Lu et al*., 2012]. *Rosenberry and Pitlick* [2009b] have shown through laboratory experiments that the direction of flow in sediments can have a significant influence on the hydraulic properties of the streambed. They measured hydraulic properties in upwelling and downwelling zones and found that the seepage direction has a clear influence on the hydraulic properties of the streambed. In the field, areas of downwelling in streams have been shown to have lower hydraulic conductivities than that in upwelling areas of streams [*Chen et al*., 2013]. Because upwelling and downwelling can occur over small spatial scales (10^{-2} m), these mechanisms have the potential to play a significant role in the deposition of fine sediments. Hyporheic exchange at the meander scale (~10 m) can also drive sedimentological changes in the subsurface, as was documented by *Nowinski et al*. [2011].

Upwelling and downwelling effects have also been observed and studied in fields other than sedimentology. Stream ecologists have repeatedly shown that stream water infiltrates the subsurface (downwelling), mixes with groundwater, and re-enters the stream (upwelling) [*Boulton and Hancock*, 2006]. *Brunke and Gonser* [1997] and *Schälchli* [1992] documented that in the zones of upwelling groundwater, no sedimentation, or clogging takes place (Figures 1b and 1d). The clogging of streambeds has also been examined in the context of bank filtration [*Goldschneider et al*., 2007; *Schubert*, 2002].

Apart from hyporheic exchange and its critical role in redistributing fine sediments in the streambed, floods can also alter the sedimentary composition and therefore the hydraulic properties of the streambed. Numerous field studies observed changes of up to 2 orders of magnitude of hydraulic conductivity between flood events [*Genereux et al*., 2008; *Hatch et al*., 2010; *Rosenberry and Pitlick*, 2009a; *Schubert*, 2002; *Springer et al*., 1999]. These studies identified transience in hydraulic conductivity by directly measuring a time series of hydraulic conductivity in the streambed using falling head permeameter tests, thermal methods, or pumping tests. In another study, *Wu et al*. [2015] measured the hydraulic conductivity of a streambed at more than 400 locations and identified statistically significant differences before and after the flood season. After the flood season, the mean and

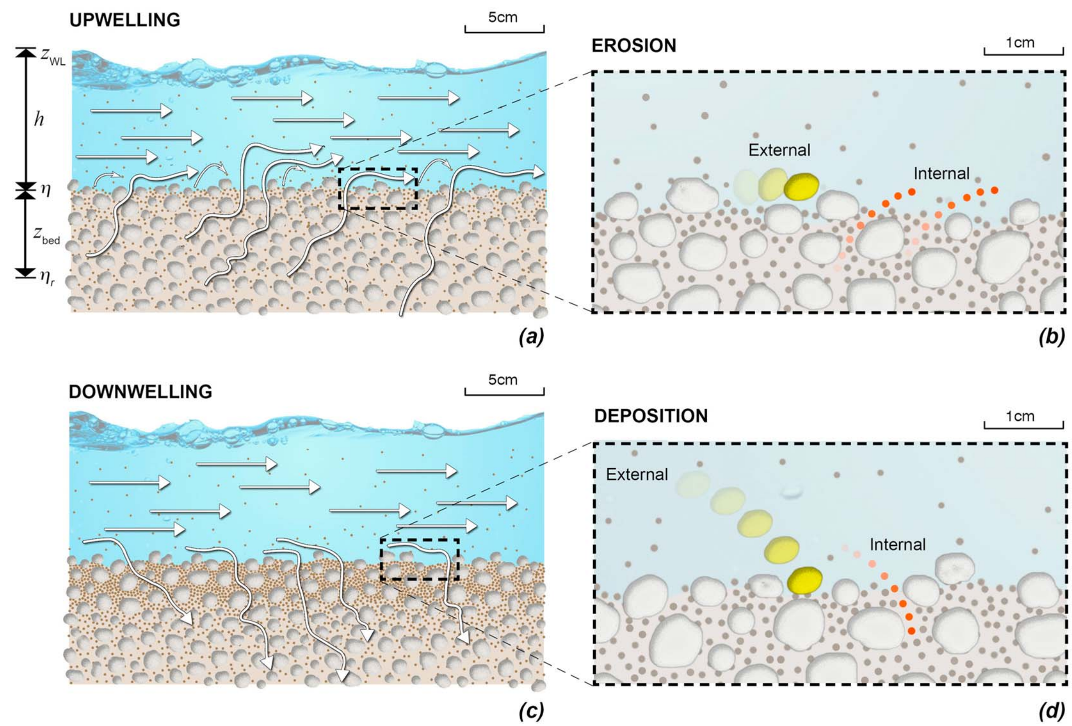

Figure 1. (a and c) Simplified representation of upwelling and downwelling groundwater and (b and d) the difference between internal and external sediment erosion and deposition processes. The lengths shown in Figure 1a are the elevation of the water in the stream (z_{WL}), the depth of water in the stream (h), the thickness of the streambed (z_{bed}), the elevation of the streambed (η), and the elevation of the bottom of the active streambed (η_r).

median hydraulic conductivity of the streambed decreased, and its variance increased indicating greater heterogeneity in the grain size distribution of the sediments forming the streambed. *Gianni et al.* [2016] presented a new approach that allows the detection of transience in hydraulic conductivity of the streambed based on time series measurements of stream stages and the hydraulic response in the aquifer. At their study site, an increase of one order of magnitude of hydraulic conductivity was observed after floods, as well as during periods where the stream drained the aquifer (as opposed to infiltrating it). They hypothesized that groundwater discharging to the stream remobilized the fine sediments from the streambed.

Hydrological processes such as hyporheic exchange, SW-GW interactions, and flood events therefore affect streambed sedimentary composition and therefore also affect streambed topography and hydraulic conductivity. These two physical characteristics of the streambed affect hyporheic exchange and SW-GW interactions (Tutorial 1). The deposition and erosion of sediments influence the streambed topography, which in turn influences the stream flow [*Simpson and Castelltort*, 2006]. An average change to hydraulic conductivity of one order of magnitude modifies the exchange rates between the surface and the subsurface by one order or magnitude, triggering complex feedback mechanisms between hydrological, hydrogeological, and sedimentary processes.

3. Mathematical Models of Surface Flow, Subsurface Flow, and Their Coupling in Catchment Hydrology

Freeze and Harlan [1969] presented a blueprint for the simulation of coupled surface water flow and groundwater flow processes in a catchment. They proposed a physically based approach that described flow using Darcy's law and the equation of mass continuity for the saturated and unsaturated zones. This approach accounts for changes in hydraulic conductivity in the unsaturated zone in response to a changing degree of saturation. The Saint-Venant equations are used to describe surface flow [*Barré de Saint-Venant*, 1871]. Figure 2 presents the processes included in the *Freeze and Harlan* [1969] approach, which includes the typical catchment processes described in Figure T2.1. The primary input to the model, precipitation, is redistributed

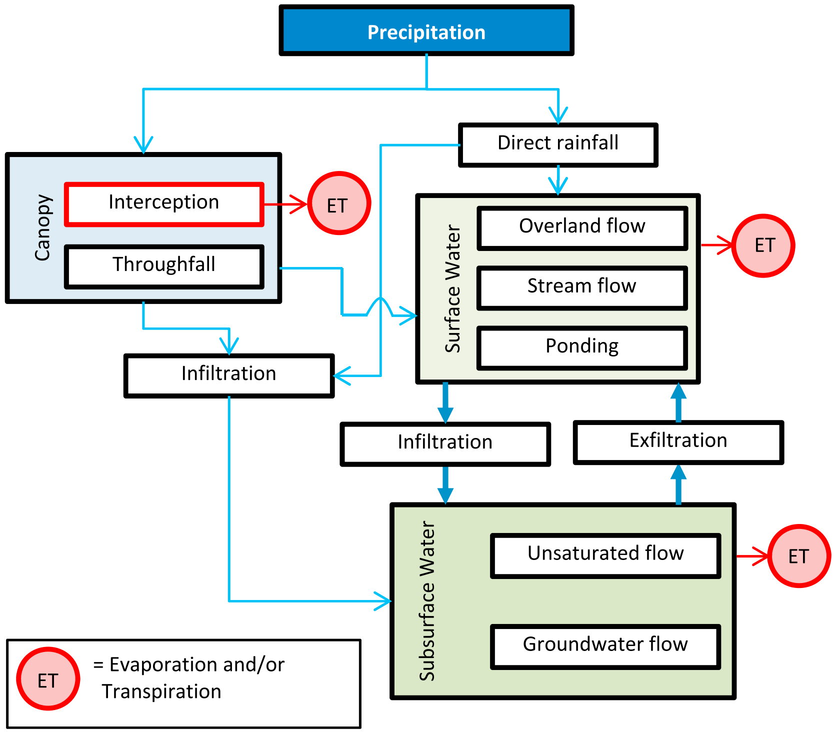

Figure 2. Hydrological processes captured in the *Freeze and Harlan* [1969] blueprint that apply across a range of spatial scales from the hillslope (~10^3 m^2) through to the whole catchment (>10^6 m^2). The interactions between the surface and subsurface are governed by the permeability at their interface which is treated as static.

in the various compartments of the catchment depending on the surface water and groundwater flow domain properties as well as evapotranspiration. The approach, therefore, allows the simulation of streamflow generation and depletion processes described in Tutorial 2.

Tutorial 2: Streamflow Generation Processes, Groundwater, and Sediment Transport

Streamflow generation processes describe the translation of precipitation to streamflow. These processes develop in response to precipitation as well as in relation to various catchment characteristics such as geology, topography, antecedent conditions, vegetation, or the drainage structure of the catchment. Figure T2.1 shows the different types of streamflow generation processes and streamflow depletion processes.

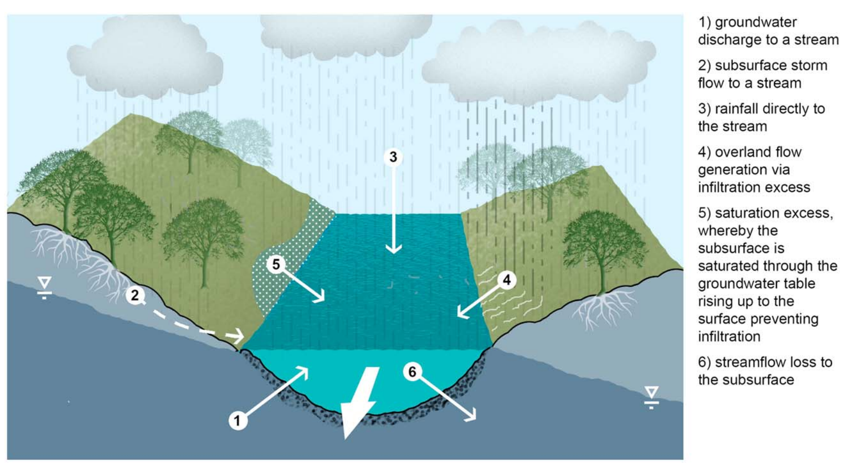

Figure T2.1. Overview of the most important streamflow generation and depletion processes.

Freeze [1974] and references therein provide a detailed description of these processes and their corresponding classical mathematical models; also, see *Beven* [2006] for an excellent selection of key papers focused on the experimental quantification of these processes. Quantifying the various streamflow generation mechanisms as well as their dynamics is the basis for predicting the hydraulic response of a catchment to rainfall [*Partington et al*., 2011; *Partington et al*., 2013].

Groundwater plays a major role in generating and maintaining stream flow [*Winter*, 2007]. Whether a stream is draining or infiltrating an aquifer depends on the stream's stage and the hydraulic head in the groundwater. As streamflow generation processes alter both the hydraulic heads in streams and groundwater, they ultimately control the spatial and temporal dynamics and patterns of surface water-groundwater interactions across a catchment, as well as the streamflow hydrograph.

Streamflow generation processes (in particular overland flow) influence the sediment supply to a stream [*Zi et al*., 2016] and the catchments overall sedimentary budget [*Huang and Niemann*, 2008]. Groundwater has long been recognized as a geomorphic agent [*Atkinson*, 1985], and streamflow generation processes, therefore, influence the dynamics of the streambed, triggering feedback mechanisms between hydrogeology and sedimentology. A quantitative understanding of how these processes interact and how the different spatial scales involved influence these feedback mechanisms is lacking.

The *Freeze and Harlan* [1969] blueprint remains the basis for the development of a large number of integrated surface and subsurface hydrological flow models. Examples of such models include the Integrated Hydrology Model [*VanderKwaak and Loague*, 2001], CATchment HYdrology model (CATHY) [*Camporese et al*., 2010], MODFLOW based Hydrologic Modeling System (MODHMS) [*Panday and Huyakorn*, 2004], GEOtop [*Rigon et al*., 2006], HydroGeoSphere [*Therrien et al*., 2010], ParFlow [*Kollet and Maxwell*, 2006], finite volume-based integrated hydrologic modeling [*Kumar et al*., 2009], Criteria-3-D [*Bittelli et al*., 2010], OpenGeoSys [*Delfs et al*., 2012], and the model presented by *Weill et al*. [2009]. These models simulate 3-D variably saturated subsurface flow with Richards' equation [*Richards*, 1931], coupled with either 1-D or 2-D surface water flow using the Saint-Venant equations or simplifications of these. The exchange between the surface and subsurface is described either by a Darcy type relationship, with fluid flux depending on the hydraulic conductivity of the interface material between the surface and subsurface as well as the hydraulic gradient across the interface [*Therrien et al*., 2010], or by a switching boundary condition [*Camporese et al*., 2014]. These models are often referred to as distributed models because they rely on numerical techniques such as finite differences or finite elements that allow a spatially variable representation of the physical properties of the surface and subsurface. The reader is referred to *Paniconi and Putti* [2015] for a detailed review of the historical development and current capabilities of integrated surface and subsurface hydrological models.

Current challenges regarding flow simulations using integrated surface and subsurface hydrological models are discussed in *Paniconi and Putti* [2015] and *Fatichi et al*. [2016]. These challenges are also relevant for the model blueprint presented here. One challenge relates to the nonlinearities of the surface-subsurface flow processes simulated. These nonlinearities require that robust numerical methods, such as the Newton-Raphson method, be used to linearize the governing flow equations. The performance of these linearization methods often depends on the level of discretization, which must be fine enough to correctly capture the flow processes [*Kaeser et al*., 2014]. The temporal scales for surface and subsurface flow are also different, with more rapid surface flow, and they also create challenges in the choice of temporal discretization. *Paniconi and Putti* [2015] mention challenges associated with the representation of surface and subsurface heterogeneities in integrated models, including the upscaling of subgrid heterogeneities. The representation of the flow coupling between the surface and subsurface domains is also an area of interest and current research.

Because they represent the main flow processes in a catchment or watershed, integrated surface and subsurface hydrological models are often applied at a large scale ($>10^6$ m^2) [*Paniconi and Putti*, 2015]. Although they can account for a heterogeneous distribution of subsurface properties, the spatial discretization for large-scale simulations is often too coarse to represent small-scale streambed heterogeneity, which is at the scale of centimeters to meters. For large-scale simulations, streambeds are therefore typically assumed to be homogeneous [e.g., *Goderniaux et al*., 2009]. Although *Kollet et al*. [2010] did not focus on water exchange in streambeds, they proposed a methodology based on parallel computing that would allow representation of small-scale streambed heterogeneity for large-scale simulations, thus opening possibilities for more detailed large-scale simulations.

The finer spatial discretization used for smaller-scale studies, for example, at the reach scale ($<10^3$ m^2), allows for a more detailed representation of streambed heterogeneities. In one example, *Boano et al*. [2010] linearized the surface and subsurface flow equations to develop an analytical solution to simulate water exchange between the surface and subsurface in a meandering stream. An assumption of homogeneous subsurface sediments was required to obtain the analytical solution. They acknowledge that it is the most critical assumption for their model and state that "increasing our understanding of the factors that control streambed heterogeneity will be a crucial issue in future hyporheic zone research". Other numerical studies of the impact of streambed heterogeneity on fluid exchange at the interface between surface and subsurface include *Cardenas et al*. [2004], *Frei et al*. [2009], *Irvine et al*. [2012], *Kurtz et al*. [2013], and *Tang et al*. [2015]. Most of these studies suggest that in quantifying SW-GW exchange, an appropriate equivalent homogeneous streambed can replace a heterogeneous one. However, *Irvine et al*. [2012] show that this representation holds only as long as the hydraulic connection (i.e., losing connected or losing disconnected [*Brunner et al*., 2011]) between a stream and an aquifer does not change. An equivalent homogeneous streambed determined for connected conditions correctly represents the heterogeneous streambed if connected conditions prevail, but not if the stream and aquifer become hydraulically disconnected and vice versa.

In the studies mentioned above, the streambed was assumed to be spatially heterogeneous; however, it was also a static entity without any temporal changes. While streambed dynamics have not traditionally been a focus for hydrological/hydrogeological modelers, these dynamics are central to stream morphodynamic models.

4. Mathematical Models of Fluvial Geomorphology/Sedimentology

There has been the development of a very wide range of numerical models simulating erosion and deposition processes in and around streambeds. While models differ significantly in terms of processes considered and their conceptualization, the key components of all morphological models of the streambed are a fluid flow model and the sediment continuity equation (e.g., Exner equation [*Paola and Voller*, 2005]), and submodels describing erosion, deposition, and transport of sediments. Figure 3 shows a possible structure of a sedimentological model and lists the erosion and deposition processes that are typically simulated. Surface flow is the primary driver for such models, with surface-subsurface exchanges typically ignored. An excellent overview of the one-, two-, and three-dimensional models available, as well as an in-depth discussion on their applicability to different fluvial and sedimentological conditions, was provided by *Papanicolaou et al*. [2008].

Sedimentary models differ in the way they describe the sedimentary composition. Recently, the journal *Advances in Water Resources* dedicated a special issue on "Numerical modelling of river morphodynamics: Latest developments and remaining challenges" [*Siviglia and Crosato*, 2016]. In the editorial summarizing the special issue, a key limitation is highlighted: "The majority of sedimentological models simulating reach scale morphodynamic processes use homogeneous sediments." As has been discussed in Tutorial 1, the hydraulic conductivity of the streambed is related to its grain size distribution. Simulating the transience of hydraulic conductivity, therefore, requires sedimentological models capable of simulating sediment mixtures and classes and their distribution in the streambed.

Stecca et al. [2016] summarizes the basis of models simulating sediment mixtures as follows: "The mathematical description of mixed-sediment morphodynamics is based on proper sediment continuity models, relating bed load transport to the size of sediment available at the bed surface, and keeping track of the development of size stratification within the bed." According to these authors, the first models capable of simulating different sediment classes were developed by *Hirano* [1971] and *Hirano* [1972] with the resulting system of partial differential equations referred to as the Saint-Venant-Hirano model [*Stecca et al*., 2016]. Numerous models and numerical approaches have been developed based on these equations, including *Stecca et al*. [2016], *Viparelli et al*. [2010], and *de Almeida and Rodríguez* [2011] who developed an unsteady 1-D flow morphology and bed-sorting model to simulate pool-riffle morphodynamics.

These recent studies demonstrate considerable advances regarding the simulation of streambed dynamics under consideration of different sediment classes. To the best of our knowledge, however, the current sedimentological models do not consider patterns of upwelling groundwater and infiltrating stream water that

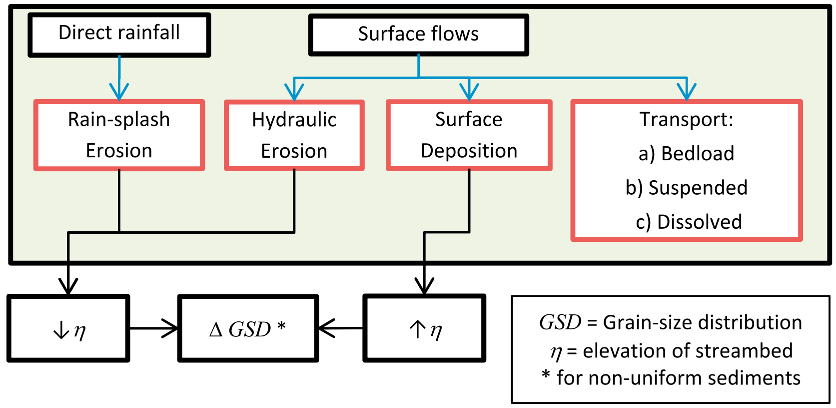

Figure 3. Example of a simplified conceptualization of a sediment transport model, showing links between flow and sedimentation processes.

results from the large- and small-scale hydrogeological conditions (see Tutorial 2). The next section discusses implications for a holistic simulation of streambed dynamics.

5. Are Current Models of Coupled Sedimentology, Hydrology, and Hydrogeology Adequate Given Their Intrinsic Link in Streambeds?

A simplified conceptual representation of interactions between flow and sediment transport processes is shown in Figure 4. To the best of our knowledge, there are currently no conceptualized, formal, and quantitative approaches that describe how SW-GW interactions (including both large-scale exchange as well as smaller-scale hyporheic exchange) affect the deposition of sediments in streambeds nor how they might be included in mathematical models of stream morphology and SW-GW interaction.

There is significant precedence for contemporaneous consideration of surface and subsurface flows in scientific analyses. The joint consideration of surface and subsurface flows has proven crucial for the understanding of ecological processes [*Banks et al*., 2011; *Boulton and Hancock*, 2006; *Boulton et al*., 2010], hyporheic exchange across the stream-aquifer interface [*Boano et al*., 2014] or the biogeochemical significance of stream corridors [*Harvey and Gooseff*, 2015], to mention just a few demonstrative examples.

Sediment transport models only consider surface water flow without explicit consideration of SW-GW exchanges [*Papanicolaou et al*., 2008]. Furthermore, at larger scales, net stream-aquifer exchange fluxes can have a large effect on total stream flow as well as water quality [*Winter et al*., 1998]. Because total flow rate (stream discharge) is a key control of sediment transport processes, the inclusion of stream-aquifer interactions on stream flow would allow for a more comprehensive and realistic simulation of sediment transport processes. This, in turn, would allow for more reliable estimates of SW-GW interactions in a flow model. In current sedimentological modeling approaches, however, discharge is commonly conceptualized as an inflow boundary condition, and this is overly simplistic at larger scales where SW-GW interactions strongly modify the total flow. Furthermore, SW-GW exchanges across all scales play an important role in the deposition of fine sediments. As fine sediments have a significant effect on the hydraulic properties of the streambed, complex feedback mechanisms between surface water, groundwater, and the sedimentary budget develop. Moreover, water quality and nutrient load are influenced by SW-GW exchanges which can trigger further feedback mechanisms with biofilms [*Treese et al*., 2009]. The entire system behavior is therefore both coupled and nonlinear with dynamic feedbacks in response to changes in either the sediment and/or hydrologic regime.

Despite the absence of SW-GW exchange fluxes in most conceptual models for sediment transport, there is a body of evidence that this is a critical omission under certain conditions. For example, recent experiments on turbulent surface flows at the bed form scale (10^{-2} m) [*Blois et al*., 2014] demonstrate that stream-aquifer exchanges play an important role in influencing the surface flow field and resulting shear stress at the streambed which will in turn influence the erosion and deposition of sediments. At both the bed form and reach scales, stream-aquifer exchange processes can be of critical importance. Neglecting them in stream morphological models may, therefore, be inappropriate for some hydrological environments.

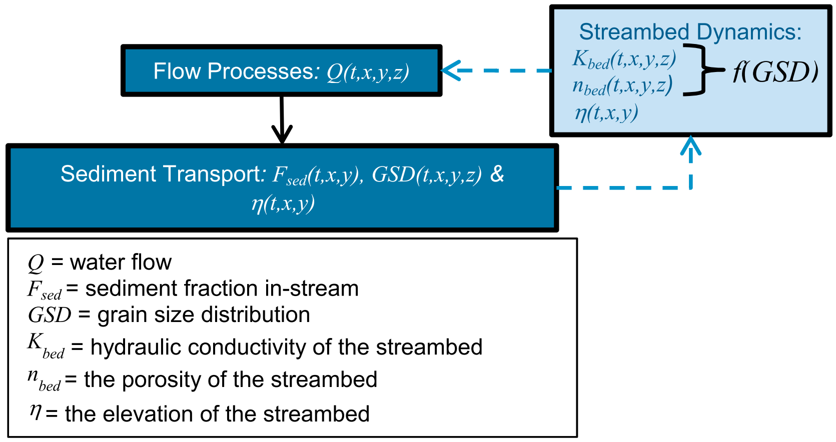

Figure 4. Capturing feedbacks between flow (including surface and subsurface flow) and sediment processes. The flow solution informs the transport of sediments within the stream but is also dependent on the physical properties of the streambed. Additionally, the nature of the exchange $Q(t, x, y, \eta)$ will influence the deposition and erosion rates.

Heppner et al. [2006], *Warsta et al.* [2013], *Kim et al.* [2013], and *Zi et al.* [2016] present examples of integration of sediment transport into hydrological models. In these models, coupled SW and GW models simulate fluid flow, on top of which an advection-dispersion model simulates sediment transport. A 1-D stream sediment model capable of simulating feedback mechanisms between hydraulic conductivity and sediment transport was constructed by *Simpson and Meixner* [2012]. This work showed that the inclusion of sedimentological processes could lead to an order of magnitude change in the exchange flux between the stream and aquifer system during a flood event and a doubling of the exchange flux after the event. However, as sedimentary and erosion processes were driven by surface water flow only, feedbacks between surface and subsurface processes were not included. Nonetheless, this study demonstrated the criticality of including these coupled processes in models and provided early insights that a more routine coupling of flow and sediment processes is required to understand the dynamics of hydrological systems (as outlined in Figure 4).

Although some current physically based streamflow generation models can account for erosion and sedimentation processes, they do not simulate the associated changes in hydraulic properties. Transient effects and feedbacks cannot yet be understood nor quantified in the context of streamflow generation or hyporheic exchanges. Further, because of the coupled and nonlinear nature of the physics involved in these processes, it becomes difficult, if not impossible, to quantify such processes without the use of mathematical modeling approaches.

On the basis of this literature review, one can reasonably conclude that current sedimentological, hydrological, and hydrogeological models and currently existing coupled variations are necessary for solving a range of important sedimentology, hydrology, and hydrogeology questions. However, the current state of these coupled models is still critically deficient and therefore insufficient for advancing these disciplines, and providing quantitative answers to fundamental scientific questions.

6. A Blueprint to Couple Surface-Subsurface Flow and Sedimentological Processes and Models

By linking the conceptual models for hydrological and sedimentological processes outlined in Figure 2 (the *Freeze and Harlan* [1969] blueprint) and Figure 3, respectively, a more comprehensive updated “blueprint” is developed in Figure 5. In the following sections, we present quantitative approaches (where available) that can be used to represent these processes mathematically.

The feedbacks between hydrological and sedimentological processes need to be captured through coupling of the two models, similarly to the coupling of surface and subsurface flows. The flow solution accounts for the changing elevation and permeability of the sediment interface, while the sediment transport solution

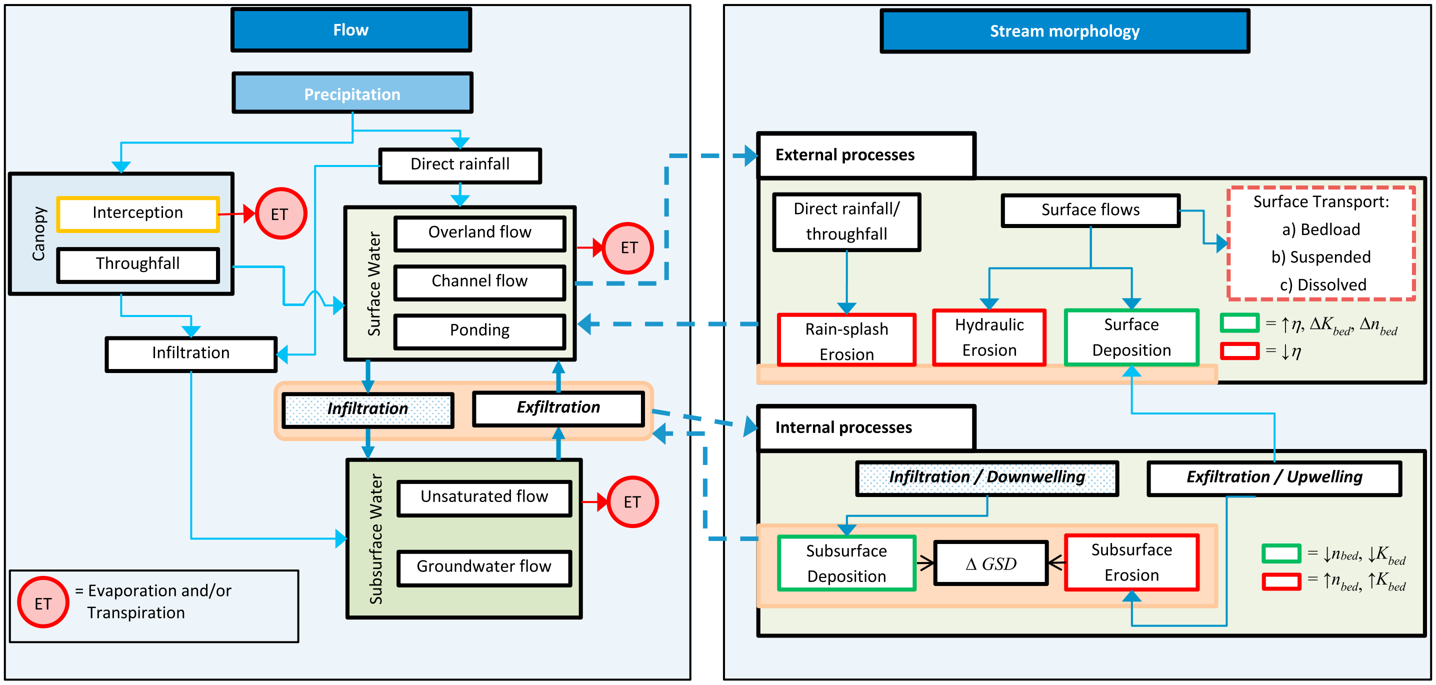

Figure 5. A simplified conceptualization of flow and sediment models and their interdependence. Flow processes on the surface and in the subsurface are shown with a key control on exchange between the two being the land surface (its elevation (η) and hydraulic conductivity and porosity (K_{bed}, n_{bed})). The sediment transport model is driven by both surface and subsurface flows and this conceptualization focuses on the aspects of sediment transport at the interface which modify elevation, hydraulic conductivity, and porosity. The influence to the streambed of particular processes in the external and internal process boxes are shown by their color, i.e., red = erosion and green = deposition, with the effect on the streambed indicated by the legend to the right of each of the boxes.

considers how SW-GW interactions control the flow field. Multiple options for this coupling could be used, including sequential, iterative, and full coupling. The latter is preferable to avoid errors by implicitly capturing these feedbacks, but it is computationally more demanding. A first approach could be a sequential iterative solution strategy, where for a given time step, the iteration loop involves solving first the surface and subsurface flow equations and then the sediment transport equation. The streambed elevation and permeability are then updated, and the iteration continues until convergence.

It becomes readily apparent in the development of the conceptual and mathematical framework that the mathematical formulation presented here provides a demonstrative example only. A key driver for the formulation presented here relates to the regional scale SW-GW interaction problems that motivated this analysis. Thus, the physics and mathematical formulation presented here are driven by this problem and driven by this scale. We have aimed for a relatively general formulation. However, depending on both problem scale and requisite physics, different physical and mathematical formulations will be required for solving different problems. This exemplar framework and mathematical formulation presented here, therefore, provides a guide for future model development but should not constrain it.

6.1. Flow Model

The incompressible Navier-Stokes equations are the most common fundamental description of water flow. Solving these equations alone is challenging, but making several assumptions about the nature of surface flows and subsurface flows [e.g., *Neuman*, 1977], allows description of a surface-subsurface flow model. The level of assumptions varies, but for this extension to the *Freeze and Harlan* [1969] blueprint, we suggest that it accounts for variably saturated flow in the subsurface and gradually varied unsteady flows on the surface. It should necessarily handle boundary conditions of inflows and outflows to the system via natural (rainfall, evapotranspiration, etc.) and anthropogenic (irrigation, GW pumping, etc.) mechanisms. The mathematical formulation and assumptions for components of a surface-subsurface flow model (excluding implementation of boundary conditions) are described below.

6.1.1. Surface Flow

Surface flow in streams and over hillslopes can be represented with varying degrees of complexity ranging from the more complex Reynolds-averaged Navier-Stokes (RANS), large eddy simulation (LES), and detached eddy simulation (DES) flow equations, through to the simple kinematic wave equation. As noted earlier, our primary motivation is SW-GW interaction at the regional scale. Thus, for the conceptual model presented here, a suitable flow equation for a stream should account for unsteady flows at the reach or catchment scale, which is achievable with the dynamic wave equations (also known as the Saint-Venant equations); points and times of supercritical flow will exhibit higher velocities and turbulence making them more erosive than subcritical flows and will also affect SW-GW exchange fluxes. Note that flow equations with fewer assumptions (e.g., the Navier-Stokes equations) could be implemented as well, which theoretically would allow simulation of pore-scale processes in the streambed. For flow adjacent to the stream on hillslopes and across plains a much simpler equation may be warranted, such as the diffusion wave or kinematic wave approximation. At the bed form scale, pressure distributions resulting from hydrodynamic pressures induced by undulating bed forms [e.g., *Janssen et al.*, 2012; *Packman et al.*, 2004] are important for understanding hyporheic flows; hence, the hydrodynamic component of flow cannot be ignored. In such cases, the more complex RANS, LES, or DES needs to be solved to identify the upwelling and downwelling zones [*Trauth et al.*, 2013].

At large scales (e.g., over whole catchments), the dynamic wave equations are capable of simulating meander-scale hyporheic flows [e.g., *Revelli et al.*, 2008]. Note that these equations do not include the vertical component of flow and are not be suitable for bed form scale hyporheic flow [*Gomez-Velez et al.*, 2014]. The dynamic wave equations can be used to capture the depth-averaged flow accounting for local and convective inertial force, pressure gradient, and friction and weight, without oversimplifying the processes of interest (both for flow and sediment transport):

$$\frac{\partial h}{\partial t} + \nabla \cdot h\mathbf{q}_{\mathrm{surf}} = h\Gamma_{ex} + \sum Q_{s/s,\mathrm{surf}} \ (\text{continuity}) \tag{1}$$

$$\frac{\mathrm{D}h\mathbf{q}_{\mathrm{surf}}}{\mathrm{D}t} + gh(\nabla \cdot z_{\mathrm{WL}} - (\mathbf{S} - \mathbf{S}_f)) = 0 \ (\text{momentum}) \tag{2}$$

where h is the height of water above the surface (L), t is time (T), $\mathbf{q}_{\mathrm{surf}}$ is the surface flow flux (LT^{-1}), Γ_{ex} is the exchange between the surface and subsurface (T^{-1}), $Q_{s/s,\mathrm{surf}}$ (LT^{-1}) are source/sink terms (which can be positive or negative), z_{WL} is the location of the water surface relative to a fixed datum (L), g is the gravitational constant (LT^{-2}), $\mathbf{S}$ is the slope vector (S_x,S_y), where S_x and S_y are the slopes of the surface in the x and y directions respectively (LL^{-1}), and $\mathbf{S}_f$ is the friction slope vector (S_{fx}, S_{fy}), where S_{fx} and S_{fy} are the frictional slopes in the x and y directions respectively (LL^{-1}).

Using the equations above, the individual channels, or streams, can be represented in a large-scale watershed model using one of two methods. The first method consists of refining the spatial discretization of the surface in the neighborhood of streams. This method is used, for example, in the HydroGeoSphere model, which solves the 2-D surface flow equation over the whole simulation domain, and it does not require an exact definition of streams and channels a priori, but it requires small-scale resolution of the surface topography. Given a sufficiently fine spatial discretization, the model will correctly represent the drainage network, as streams will form in topographic depressions. Another method consists of solving the 2-D surface flow equation over the whole simulation domain and to couple it to a 1-D surface flow representation of individual channels or streams. That approach requires a priori definition and location of the drainage network to build the 1-D elements, such as the approach used for example in the CATHY model. One advantage of this approach is that it does not require as fine a spatial discretization near streams as the first method and can, therefore, reduce the computational burden.

6.1.2. Subsurface Flow

Three-dimensional saturated and unsaturated flow through anisotropic heterogeneous porous media can be described using the Richards equation [*Richards*, 1931] as follows:

$$-\nabla \cdot \mathbf{q}_{\mathrm{sub}} + \Gamma_{ex} + \sum Q_{s/s} = \frac{\partial}{\partial t}(\theta_s S_w) \tag{3}$$

where $\mathbf{q}_{\mathrm{sub}}$ is the subsurface fluid flux (LT^{-1}), Γ_{ex} is the exchange between the surface and subsurface, $Q_{s/s}$ are source/sink terms (which can be positive or negative) ($\mathrm{L}^3\mathrm{L}^{-3}\mathrm{T}^{-1}$), θ_s is the saturated water content ($\mathrm{L}^3\mathrm{L}^{-3}$), and S_w is the water saturation of the porous media related to the water content θ ($S_w = \theta/\theta_s$).The fluid flux $\mathbf{q}_{\text{sub}}$ is defined as

$$\mathbf{q}_{\text{sub}} = -\mathbf{K}\cdot k_r \nabla(\psi + z) \tag{4}$$

where $\mathbf{K}$ is the hydraulic conductivity tensor (LT^{-1}), k_r is the relative permeability ($-$), ψ is the pressure head (L), and z is the elevation above the datum (L).

The hydraulic conductivity tensor is defined as

$$\mathbf{K} = \frac{\rho g}{\mu}\mathbf{k} \tag{5}$$

where ρ is fluid density (ML^{-3}), g is the gravitational constant (LT^{-2}), μ is the dynamic viscosity ($ML^{-1}T^{-1}$), and $\mathbf{k}$ is the permeability tensor (L^2).

Constitutive relationships are defined that relate pressure head to the saturation (S_w) and relative permeability (k_r) of the porous media. Common functions are the *Brooks and Corey* [1964] and *van Genuchten* [1980] relationships.

Subsurface flow can also take place in other features such as fractures [*Therrien and Sudicky*, 1996] and macropores as well as through anthropogenic features such as tile drains. While of importance in many catchments, these flow paths are beyond the focus of this particular review.

6.1.3. Surface-Subsurface Exchange and Boundary Conditions

Flow across the surface-subsurface interface can be simulated using sequential, iterative, and coupled approaches [*Furman*, 2008]. Depending on the surface and subsurface flow equations solved, flow across the interface can be represented by assuming continuity of pressure [*Therrien et al.*, 2010], first-order exchange [*Ebel et al.*, 2009], and boundary condition switching [*Camporese et al.*, 2014].

Hydrological systems are driven by the complex forcing of rainfall and evapotranspiration [*Katul et al.*, 2012; *Sprenger et al.*, 2016]. Rainfall and evapotranspiration (ET) can be handled spatiotemporally using a Neumann-type boundary condition. Interception of rainfall is handled empirically with a finite storage capacity after which point throughfall occurs. Actual ET is typically calculated from potential ET. Numerous approaches [e.g., *Kristensen and Jensen*, 1975] are available to estimate actual ET based on climatic forcing and the state of the system [e.g., *Katul et al.*, 2012; *Sprenger et al.*, 2016]. Lateral subsurface boundaries representing groundwater flows at the extremities of the model domain can be represented using Dirichlet- and Neumann-type boundaries for specified heads and/or fluxes. Direct anthropogenic forcing via irrigation, detention basins, stream extractions, and groundwater pumping/injection can also be represented using Dirichlet-, Neumann-, and Cauchy-type boundary conditions.

6.1.4. Boundary Shear Stress

It is necessary to estimate boundary shear stress from surface flows at the surface-subsurface boundary to determine whether erosion occurs or not, as a shear stress above the critical shear stress for particular sediments is required to entrain sediments. Resistance to flow occurs across a range of scales, which can be categorized by grain resistance, bed load resistance, bed form resistance, bar resistance, and bank and planform resistance [*Dietrich and Whiting*, 1989]. For the case of grain resistance, and assuming steady uniform flow conditions, the following relation can be used for approximating streambed boundary shear stress [*Dietrich and Whiting*, 1989]:

$$\tau = \gamma h S \tag{6}$$

where τ is the shear stress at the surface-subsurface interface ($ML^{-1}T^{-2}$), γ is the specific weight of the fluid ($ML^{-2}T^{-2}$), and S is the slope (LL^{-1}).

6.2. Sediment Transport and Sedimentological Model

The key components of a geomorphological model of the streambed are the driving fluid flow model and the sediment continuity equation (such as the Exner equation) and submodels describing erosion, deposition, and transport of sediments [*Paola and Voller*, 2005]. The treatment of erosion, deposition, and transport of sediments usually depends on the dominant sediment sizes and can include all or only some of dissolved, suspended and/or bed loads. The sediment load can be classified using the Rouse number [*Rouse*, 1937], which relates the settling velocity to the shear stresses on the sediment from the flow. Vegetation also plays an important role in the geomorphological processes [*Camporeale et al*., 2013; *Ruiz-Villanueva et al*., 2016] by stabilizing floodplains and banks; however, accounting for a vegetation model that incorporates the complex processes associated with both live and dead vegetation is beyond the scope of this blueprint.

Sediment transport within the stream must account for both the mostly immobile (streambed) and mobile sediments (in-stream). The sediment mass balance for the stream and subsurface sediments can be described using a form of the Exner mass balance equation, described in equations 14 and 15 of *Paola and Voller* [2005], (also refer to Figure 1a):

$$\text{Stream}: \frac{\partial}{\partial t}\int_{\eta}^{z_{\mathrm{WL}}} \alpha_f \mathrm{d}z + \vec{\nabla}_H \vec{\phi}_f + \Omega_{\mathrm{out}}(\eta) - \Omega_{\mathrm{in}}(\eta + z_{\mathrm{WL}}) - \int_{\eta}^{z_{\mathrm{WL}}} \Gamma_f \mathrm{d}z = 0 \tag{7}$$

$$\text{Subsurface}: \int_{\eta_r}^{\eta} \frac{\partial \alpha_s}{\partial t} \mathrm{d}z + \alpha_s(\eta)\frac{\partial \eta}{\partial t} - \alpha_s(\eta_r)\frac{\partial \eta_r}{\partial t} + \vec{\nabla}_H \vec{\phi}_s + \Omega_{\mathrm{out}}(\eta_r) - \Omega_{\mathrm{in}}(\eta) - \int_{\eta_r}^{\eta} \Gamma_s \mathrm{d}z = 0 \tag{8}$$

where z_{WL} is the elevation of the stream surface relative to the datum (L), η is the streambed elevation relative to the datum (L), η_r is the elevation of bottom of the streambed sediments (L), α_f and α_s are the sediment densities in the stream and subsurface respectively (ML^{-3}), $\vec{\nabla}_H$ is the horizontal divergence operator $\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, 0\right)$, ϕ_f and ϕ_s are the horizontal vector mass sediment fluxes per unit width in the stream (i.e., bed load, suspended load and wash load) and subsurface respectively (ML^{-1}T^{-1}), $\Omega_{\mathrm{out}}(\eta)$ is the sediment exchange flux per unit area over the interface between the stream and subsurface (ML^{-2}T^{-1}), $\Omega_{\mathrm{in}}(z_{\mathrm{WL}})$ is the sediment exchange flux per unit area of the water surface boundary (ML^{-2}T^{-1}), $\Omega_{\mathrm{out}}(\eta_r)$ is the sediment exchange flux per unit area of the bedrock interface (ML^{-2}T^{-1}), and Γ_f and Γ_s are the rate of sediment production or destruction in the stream and subsurface, respectively (ML^{-3}T^{-1}). The elevation of the bottom of the streambed sediments η_r is assumed to correspond to the lowermost elevation where sedimentological processes occur. For example, it could be the interface between the more permeable streambed sediments and a less permeable geological unit, such as bedrock.

Equations (7) and (8) can be simplified by making the following assumptions and modifications:

1. There is no production or destruction of sediments in the stream or subsurface; therefore, the last terms in equations (7) and (8) can be removed.
2. The elevation of the bottom of the streambed η_r is assumed to be constant because, for the timescales considered, sedimentological processes are assumed to be very slow and negligible below that elevation; therefore, the third and fifth terms in equation (8) can be removed.
3. Because of the relatively slow sedimentological processes, horizontal sediment flux in the subsurface relative to the stream horizontal sediment flux can be ignored; thus, the fourth term from equation (8) can be removed.
4. Using the average sediment density in the stream and an average sediment density in the subsurface, the first terms of equations (7) and (8) are simplified.
5. Because of averaging the sediment density, only a small thickness (i.e., the streambed) is considered.
6. The third term in equation (7) and the sixth term in equation (8) describing sediment exchange between the stream and subsurface are equivalent and are herein referred to as Ω_{exch}.

These assumptions and modifications allow equations (7) and (8) to be simplified to

$$\text{Stream}: \frac{\partial h\overline{\alpha}_f}{\partial t} = -\vec{\nabla}_H \vec{\phi}_f + \Omega_{\mathrm{in}}(z_{\mathrm{WL}}) - \Omega_{\mathrm{exch}} \tag{9}$$

$$\text{Streambed}: \frac{\partial z_{\mathrm{bed}}\overline{\alpha}_s}{\partial t} = -\overline{\alpha}_s\frac{\partial \eta}{\partial t} + \Omega_{\mathrm{exch}} \tag{10}$$

where $\overline{\alpha}_f$ and $\overline{\alpha}_s$ are the averaged sediment density in the stream (of thickness h) and streambed (of thickness z_{bed}), respectively.

The streambed mass balance equation can be rewritten in terms of volumetric balance. The grain size distribution of sediments is split into i discrete classes and divided by the average density of the sediments in class i, yielding i equations of the form:

$$\text{Streambed}: \quad \frac{\partial F_{\mathrm{bed},i}}{\partial t} = -\frac{F_{\mathrm{bed},i}}{z_{\mathrm{bed}}}\frac{\partial \eta}{\partial t} + \frac{\Omega_{\mathrm{exch},i}}{z_{\mathrm{bed}}\overline{\rho}_{\mathrm{bed},i}} \tag{11}$$

where $F_{\mathrm{bed},i}$ is the fraction of sediment class i in the streambed (L^3L^{-3}) and $\overline{\rho}_{\mathrm{bed},i}$ is the average density of sediment class i (ML^{-3}).

The sediment mass flux $\Omega_{\mathrm{exch},i}$ for sediments in class i across the surface-subsurface interface is dependent on the stream flow, whether there is upwelling or downwelling, the sizes of the sediments, and whether erosion or deposition is dominant. This exchange will comprise an external and internal component:

$$\Omega_{\mathrm{exch}} = \sum_{i=1}^{I}\left(\Omega_{\mathrm{external},i} + \Omega_{\mathrm{internal},i}\right) \tag{12}$$

where $\Omega_{\mathrm{external},i}$ is driven by surface flow ($\mathbf{q}_{\mathrm{surf}}$), $\Omega_{\mathrm{internal},i}$ is driven by the stream-streambed exchange, which in turn is driven by surface-subsurface exchange flow (Γ_{exch}), and I is the number of classes. The internal exchange flux $\Omega_{\mathrm{internal},i}$ modifies the streambed sediment concentration of sediment class i.

The internal processes account for mass changes in the subsurface which will influence sediment density and hence porosity (n_{bed}) and hydraulic conductivity (K_{bed}). Assuming that the internal processes are restricted to only the uppermost part of the subsurface (z_{bed}), this can be done by considering a fixed volume V_{bed} ($\partial x \partial y z_{\mathrm{bed}}$) of the subsurface adjoining the surface-subsurface interface.

6.2.1. Sediment Erosion and Deposition

A key component of the proposed model is in the partitioning of sediment erosion/depositional processes occurring on the bed surface and from within the bed, and there are still challenges ahead therein. This is a very complex process that is dependent on (1) the nature of the SW-GW exchange (upwelling or downwelling) and (2) the composition and structure of the streambed, in particular, the grains size distribution, pore geometry (cross-sectional area along the direction of flow), and pore volume. In the case of downwelling, the pore geometry and volume will control the capacity of the streambed to internally capture sediments, with only stream sediments smaller than the pore openings able to enter the streambed. In the case of upwelling, the flow rate and internal critical shear stress for each of the sediment classes will determine the transport of sediments out of the streambed. As upwelling flow rates are normally very small compared to stream flow, it follows that the shear stress on the sediments generated in the pore spaces is also very low. Hence, transport of sediments out of the streambed due to seepage would only occur for very fine sediments [*Martin*, 1970]. This upwelling will also be of importance for the deposition of very fine sediments, as upwelling will prevent deposition of the fines when the velocity of upwelling pore water exceeds the fall velocity of the sediment.

The sediment exchange drives changes to streambed topography as well as its physical properties. Entrainment of the bed sediment into the stream is dependent on the transport capacity of the stream. It is also dependent on the critical shear stress for the different sediments on the bed surface, and an approach similar to *Stecca et al.* [2016] that utilizes an active layer could be applied. The external removal and delivery of sediment (Ω_{exch}) to the streambed along with the movement of sediment in-stream and the external delivery of sediment to the stream from overland areas is covered in the following section. Internal sediment processes associated with surface-subsurface flow exchanges is covered in section 6.2.3.

6.2.2. Stream and Overland Flow Driven Sediment Transport

Streamflow driven sediment transport is considered for a range of explicit sediment sizes by splitting up the sediments into discrete size classes. The equation for in-stream sediment transport can be obtained by rewriting equation (9) in terms of volumetric fraction of sediments and assuming vertically uniform distribution of sediments. The equation for transport of each sediment class i can be written as

$$\frac{\partial F_{\mathrm{str},i}}{\partial t} = -\nabla \cdot a_i F_{\mathrm{str},i}\mathrm{q}_{\mathrm{surf}} + \left(\frac{1}{V_w}\sum_{j=1}^{BC} q_j^b F^*_{\mathrm{str}_j,i}\right) - \frac{\Omega_{\mathrm{exch},i}}{h\overline{\rho}_{\mathrm{str},i}} \tag{13}$$

where $F_{\mathrm{str},i}$ represents the in-stream sediment fraction for sediment class i (L^3L^{-3}), a_i is a retardation coefficient for each sediment class i to account for sediments advecting slower than the stream flow speed (−) (i.e., for rolling, sliding, and saltating sediments), V_w is the water volume of interest $\partial x \partial y h$ (L^3), $\Omega_{\mathrm{exch},i}$ represents the sediment exchange for sediment class i in the streambed, BC represents the number of inflow boundary conditions applied, $q_j^{\,b}$ is the flow from boundary condition j (L^3T^{-1}), and $F^*_{\mathrm{str}_j,i}$ is the sediment fraction in the inflowing water from boundary condition j for sediment class i (L^3T^{-1}), and $\overline{\rho}_{\mathrm{str},i}$ is the average density of sediment class i in the stream (ML^{-3}).

A number of models exist for the treatment of overland flow sediment transport, and the same model as used for in-stream sediment transport could be applied, but also accounting for rain splash-driven erosion [e.g., *Ran et al.*, 2007] in the external sediment exchange term ($\Omega_{\mathrm{external}}$). Other models exist like the Hairsine-Rose model [*Hairsine and Rose*, 1992a, 1992b] that analytically captures erosion due to sheet or rill flow, which could also be included.

6.2.3. Modification of Streambed Properties Through Internal Streambed Processes

Internal deposition or filtration during downwelling is a process that typically only occurs for finer-grained sediments ($\Omega_{\mathrm{internal}}$) but is a function of both the influent sediment diameter and the pore space opening area, so it is also theoretically possible for larger sediments. The result will be no or negligible changes to bed elevation η, but it will result in a decrease both in porosity n_{bed} and conductivity K_{bed}. This process is a function of the hydraulic gradient, stream sediments, and grain size distribution (GSD) of the streambed [*Schälchli*, 1992].

Internal erosion due to upwelling is another complex process in which there are no changes to streambed elevation, but an increase in n_{bed} and K_{bed}. No quantification of such processes appears to exist in the literature for natural systems, although there is significant literature in water treatment engineering, where backwashing of porous media filters is carried out. However, backwashing requires fluidization of the near homogeneous filter material which is typically not found in natural settings. A conceptual approach that relates the pore velocity in the upwelling zone to a shear stress which shifts the streambed sediments needs to be applied.

As previously stressed, the intrinsic link between the hydraulic properties of streambeds and their sedimentary composition has been studied for decades [*Alyamani and Şen*, 1993; *Krumbein and Sloss*, 1951; *Vukovic and Soro*, 1992]. More recently, improved characterization of sediments structures and pore-scale numerical modeling [*Narsilio et al.*, 2009] have been used to develop relationships between grain size and permeability of soils. To define a relationship between the GSD, hydraulic conductivity (i.e., K(GSD)), and porosity (i.e., n (GSD)), it can be assumed that the distribution of sediments is homogeneous while averaging over the thickness of the streambed z_{bed} and neglecting the packing arrangement of sediments. The value of K can be calculated using a range of pedotransfer functions (see methods in *Rosas et al.* [2015]); however, due to its use of the full GSD, a more appropriate approach may be that applied by *Simpson and Meixner* [2012], which made use of the pedotransfer function of *Arya et al.* [1999a]:

$$K(\theta_i) = \frac{c\phi_e}{\pi}\sum_j^N R_j^{(x-2)} w_j \left[0.667en_j^{\left(1-\alpha_j\right)}\right]^{\frac{x-2}{2}} \tag{14}$$

where θ_i is the water content (L^3L^{-3}), c is a fitting parameter, ϕ_e is the effective porosity, R_j is the mean particle radius of the jth fraction (L), w_j is mass fraction, solid particles, jth fraction (M^{-1}), e is the void ratio (L^3L^{-3}), n_j is the number of particles in the jth fraction (−), α_j is a scaling parameter for the jth fraction (−), and x is the exponent on pore radius (−).

An idealized approximation to the porosity in the streambed can be calculated using sediments fractions $F_{\mathrm{bed},i}$ according to the method detailed in *Ouchiyama and Tanaka* [1986].

7. Discussion

This new blueprint identifies a critical need for the inclusion of streambed transience as a next frontier in improving the understanding of catchment functioning, SW-GW interaction, and streambed dynamics. It recognizes that there are still processes that can be included and that this is one possible mathematical formulation for a coupled streambed sedimentological-hydrological-hydrogeological modeling framework. This blueprint raises a number of challenges with respect to the level of understanding of sedimentological processes and the scale at which they occur, numerical and computational aspects, limitations of model application, and finally, what the model can be used for. These challenges are discussed below.

7.1. Sedimentological Considerations

Due to the large variability in both stream types [*Rosgen*, 1994] and dominance in sediment transport processes, it is not possible to have a single, universal equation for the erosion and deposition submodels that is suitable for all streams, as noted by *Davy and Lague* [2009]. It is, therefore, unavoidable that suitable submodels to describe erosion and deposition are chosen on a case by case basis to inform the sediment exchange term in equation (13). The effects of changes in fluid density and viscosity on the nature of flow and bed shear stress as a consequence of entrained sediments are not considered in this blueprint, although these are important processes [*Wainwright et al*., 2015] that will warrant further consideration in future mathematical implementations of the blueprint. The definition of the active streambed thickness poses some challenges and will likely be a key area of uncertainty within the model. However, sensitivity to this thickness can be tested without much difficulty and will act to guide further attention to the streambed definition more generally.

Additional research is still required to assemble all of the suitable empirical relations with respect to hydraulic properties of the sediments and sediment erosion and deposition processes. A major challenge also exists in dealing with predicting the anisotropy of streambeds, which could have significant implications for hyporheic cycling [*Cheng et al*., 2013; *Zlotnik et al*., 2011]. The current approaches that relate grain size distributions to hydraulic properties do not allow estimation of anisotropy ratios of hydraulic conductivity. Furthermore, while the internal streambed sediment processes involved in upwelling and downwelling conditions have received attention in engineering applications, they must be observed and quantified in natural settings. To develop a better understanding of these processes in natural systems, our current observational field-based approaches of flow and sedimentary processes in streambeds need significant improvement. Finally, biogenic processes, such as bioturbation or the development of biofilms, can also have a significant influence on the hydraulic properties of the streambed, adding an additional level of complexity [*Albertson et al*., 2014; *Boano et al*., 2014; *Sanford*, 2008; *Song et al*., 2010; *Treese et al*., 2009]. This review, however, did not cover these processes, and their integration with numerical models will pose additional, exciting challenges and opportunities and will further call for increased collaboration between all disciplines concerned with fluvial systems, and in particular ecologists, microbiologists, and chemists.

7.2. Numerical and Computational Challenges

The numerical challenges in running such a model, once developed, will be considerable, given the very different types of equations describing surface flow, sedimentary processes, and the coupling with the subsurface. These challenges are already routinely encountered in coupling models of, for example, the vadose zone with groundwater or coupling surface water and groundwater. They arise due to the inherent differences in physics in different compartments of the hydrologic cycle. This, in turn, creates difference and incompatibilities between the spatial and temporal dimensions and resolutions required for accurately simulating these various hydrological compartments. Thus, "stitching" across these various compartments remains a general computational and numerical challenge for hydrologic sciences and is not limited to the coupling with sedimentology described here.

7.3. Scales of Processes Within the Mathematical Implementation

As with existing models of surface-subsurface flow or stream morphology, applications of such models will vary in scale, and particular features of systems will require the necessary spatial and temporal resolution to be simulated. The mathematical implementation provided in this review is not universal for all scales as important physics are simplified at the catchment (regional) scale that motivated this analysis. Thus, explicitly capturing bed form scale features such as upwelling and downwelling around streambed undulations will not be possible with the Saint-Venant flow equations and will require the more complex Navier-Stokes equations; however, at larger scales, a mechanistic implementation in a simplified transient model of streambed properties will be possible and will allow a simplified simulation of important feedbacks to streamflow generation processes (see also section 7.5). The proposed blueprint can strategically inform the development of such a mechanistic approach in a simpler model.

At the regional scale, the catchment water balance or sediment yields are typically of interest to the hydrogeologist or hydrologist. The near-stream partitioning of rainfall is strongly influenced by the streambed and hence is expected to affect catchment functioning. The proposed model allows one to explore if and to what extent the near-stream and large-scale catchment water balances are affected. The streambed will influence both water quality through the various pathways in which water progresses through the catchment and the timing of stream water and near-stream groundwater as it passes through. Because it is a primary control on near-stream SW-GW exchange, ignoring the transience in streambed properties could potentially lead to a very significant difference in understanding and predicting catchment functioning and system responses.

7.4. Purpose and Applications of the Proposed Blueprint

A possible mathematical implementation of the proposed blueprint has been given within the review; however, it is worth stressing that this is not the only possible implementation. The proposed mathematical formulation will be suitable for application of the coupled model at resolution scales from tens to hundreds of meters and larger. Application to smaller spatial scales, e.g., centimeters to meters, will require implementation of the more complex Navier-Stokes equations for the surface flow solution, which raises additional challenges. The blueprint's purpose is to encourage unification of these currently unlinked model types that is reflective of the quantitative evidence reported in the literature.

It is anticipated that applications will vary from the purely theoretical (on idealized systems) to applied studies designed to elucidate our understanding of real systems.

7.5. Parameterization for Simulation of Existing Flow Systems

As with the hydrologic sciences more generally, there will obviously be challenges in parameterizing the blueprint model in real catchments. Parameterization of the physical properties for the equations of flow and sediment transport, which take on a single value per cell/element in the model, are not simply effective or averaged properties. This single value loses some physical meaning and tends to behave as a surrogate for multiple properties or processes. As an example, once the resolution of a model reaches hundreds of meters per cell/element, streamflow generation processes are oversimplified and don't capture the expansion of saturated areas adjacent to streams or indeed even the near-surface soil moisture content near the stream. As with any model, understanding the nature of appropriate parameterization, its implications for model prediction, and associated model surrogacy is paramount.

This is where appropriate calibration of the model's physical properties at the regional scale is necessary. Through the calibration process, correlated parameters can be identified and subsequently explored through uncertainty analysis [*Brunner et al*., 2012]. Such an analysis can help identify the critical observations that should be included in the calibration process [*Schilling et al*., 2014]. This allows identification of the field observations required to inform the processes relevant across the different spatial and temporal scales. There will be several applications where simplification is appropriate (for example, the large-scale hydrological balance discussed above) but will be accompanied with additional uncertainty. A complex model can provide the means for estimating the price of simplification in terms of uncertainty and therefore how to manage and reduce it [*Doherty and Christensen*, 2011]. For example, the detailed coupled model can provide information for time scales of colmation/decolmation and SW-GW exchange fluxes. This information can be integrated into faster, albeit simpler, models through dynamic boundary conditions. This approach allows for consideration, to a certain extent, of the transience of the system in more efficient modeling frameworks. Such "sequential coupling" approaches have already been successfully used in the context of hyporheic flow [*Trauth et al*., 2013] and are likely to prove useful with the proposed blueprint.

7.6. Implications of the Blueprint

The increased understanding of the transport of fine particles and their redistribution in the streambed will allow for new insights in the transport of contaminants and on the mechanism of physical streambed clogging. The latter process is of great concern for stream ecosystems because it reduces the streambed hydraulic conductivity and has strong negative impacts on ecological habitats [*Descloux et al*., 2013; *Jones et al*., 2015; *Kemp et al*., 2011; *Mathers et al*., 2014]. Simulating how discharge develops along a stream, rather than defining it as a boundary condition as is widely done in sedimentological models, will further allow the elimination of a source of major uncertainty in large-scale models. Apart from the fundamental scientific aspects, such an increased understanding is required for a number of engineering and water resources management approaches, including a better design of stream restoration projects or the understanding of the fate of micropollutants and nutrient dynamics in relation to the transport of fine particles, to mention just a few examples.

It is recognized that the current blueprint focuses on physical matters, namely, hydraulics and flow dynamics only. There are a number of important outstanding issues. These include solute transport, water quality, geochemical reactions, and microbiologically mediated processes. Microbiological clogging of the streambed is one pertinent example [*Nogaro et al*., 2010; *Rubol et al*., 2014]. Chemical and biological processes are likely to be important in controlling the nature and properties of the streambed. We therefore anticipate that future evolution of the blueprint and associated model development will include these and other important controlling chemical and biological factors.

8. Conclusions

Field evidence shows that event, seasonal and annual changes in the hydraulic conductivity in streambeds, can reach several orders of magnitude, with major implications for the dynamics of SW-GW interactions. Although modeling of streamflow generation has evolved significantly since the publication of *Freeze and Harlan* [1969] blueprint, integrated surface-subsurface hydrologic models still largely assume that the streambed structure and topography is static and that its hydraulic conductivity remains constant in time. The static treatment of the streambed in hydrological models prevents a more rigorous representation of streamflow generation process dynamics and near-stream SW-GW interactions in particular. Stream morphodynamic models have proven highly useful for many applications. However, exclusion of groundwater flow processes and stream-aquifer exchanges within such models neglects critical morphodynamic processes and overlooks the effect groundwater discharge exerts on streamflow, especially at large scales. A holistic and quantitative understanding of both SW-GW interactions and streambed morphodynamics requires integration of hydrology, hydrogeology, and sedimentology in a unifying conceptual and quantitative framework. This paper proposes a new blueprint for advancing this important matter and is likely to have wide-ranging applications across SW-GW interaction and streambed problems.

The motivation for the proposed blueprint came from stream-aquifer interaction studies at scales of hundreds of meters or larger. This review presents one possible mathematical formulation for coupling motivated by this larger spatial scale. Other formulations will be necessary depending on the nature of the problem and its associated spatial and temporal scales. For example, we can anticipate that other sedimentology models for erosion and deposition may be required under certain conditions and that the Navier-Stokes equations for surface flow may need to be substituted for the Saint-Venant equations at much smaller spatial scales (less than meters).

This review has deliberately set out to discuss the philosophy and conceptual approach for such a coupled streambed sedimentological-hydrological-hydrogeological modeling framework. It is an intentionally strategic treatment of the topic. The authors have deliberately refrained from the implementation of the model in order to maintain a higher level philosophical, strategic and conceptual discussion on this matter. A more detailed treatment of the development, implementation, and application of the model will necessarily be the subject of future work. This would involve a detailed treatment of matters (model development, code testing, comparative analysis of mathematical formulation, numerical solvers, etc.) that may have otherwise distracted from the core purpose of this review and the conceptual blueprint development presented here. The authors can also anticipate that future work will include critical water quality, solute transport, geochemical, and microbiological matters. These matters are likely to play an important role in modifying the properties of the streambed and exert considerable influence in the coupling of streambed sedimentology, hydrology, and hydrogeology. We, therefore, recognize the enormous potential and need for future work. Nonetheless, we hope that this paper serves as a useful and catalytic basis for scientific discussion amongst sedimentologists, hydrologists, and hydrogeologists and that it inspires future work on the development and application of the blueprint models envisioned here. We believe that the suggested blueprint and its implementation and application will constitute an urgently required and significant breakthrough for the hydrological, geological, and groundwater sciences.

Acknowledgments
The authors would like to thank the Editor Grek Okin, Editor-in-chief Mark Moldwin, and three anonymous reviewers for their insightful comments and suggestions that have contributed to improving this paper. We sincerely thank Grace Lin for designing the figures in this paper. This project is partly supported through funding from the Murray Darling Basin Authority and its partner governments. No data were used in producing this manuscript.

References

Agency, T. E. (2009), The Hyporheic Handbook: A handbook on the groundwater-surface water interface and hyporheic zone for environment managers.

Albertson, L. K., L. S. Sklar, P. Pontau, M. Dow, and B. J. Cardinale (2014), A mechanistic model linking insect (Hydropsychidae) silk nets to incipient sediment motion in gravel-bedded streams, *J. Geophys. Res. Earth Surf.*, *121*, 1833–1852, doi:10.1002/2013JF003024.

Alyamani, M. S., and Z. Şen (1993), Determination of hydraulic conductivity from complete grain-size distribution curves, *Ground Water*, *31*(4), 551–555.
Arya, L. M., F. J. Leij, P. J. Shouse, and M. T. van Genuchten (1999a), Relationship between the hydraulic conductivity function and the particle-size distribution, *Soil Sci. Soc. Am. J.*, *63*(5), 1063–1070.
Arya, L. M., F. J. Leij, M. T. van Genuchten, and P. J. Shouse (1999b), Scaling parameter to predict the soil water characteristic from particle-size distribution data, *Soil Sci. Soc. Am. J.*, *63*(3), 510–519.
Atkinson, T. C. (1985), Groundwater as a geomorphic agent, Binghampton Symposia in Geomorphology, International Series No. 13, R. G. LaFleur (ed.), Allen and Unwin, Boston and London. No. of pages: 390, *Earth Surf. Processes Landforms*, *10*(1), 88–89.
Baldock, T. E., and P. Nielsen (2010), Discussion of "Effect of Seepage-Induced Nonhydrostatic Pressure Distribution on Bed-Load Transport and Bed Morphodynamics" by Simona Francalanci, Gary Parker, and Luca Solari, *J. Hydraul. Eng.*, *136*(1), 77–79.
Banks, E. W., P. Brunner, and C. T. Simmons (2011), Vegetation controls on variably saturated processes between surface water and groundwater and their impact on the state of connection, *Water Resour. Res.*, *47*, W11517, doi:10.1029/2011WR010544.
Barré de Saint-Venant, A. J. C. (1871), Théorie du Mouvement Non Permanent des Eaux, avec Application aux Crues de Rivières et à l'Introduction des Marées dans leur Lit, *C. R. Séances Acad. Sci., Paris, Fr.*, *73*(4), 237–240.
Bartzke, G., and K. Huhn (2015), A conceptual model of pore-space blockage in mixed sediments using a new numerical approach, with implications for sediment bed stabilization, *Geo Mar. Lett.*, *35*(3), 189–202.
Beven, K. J. (2006), *Streamflow Generation Processes*, pp. 432, IAHS.
Bittelli, M., F. Tomei, A. Pistocchi, M. Flury, J. Boll, E. S. Brooks, and G. Antolini (2010), Development and testing of a physically based, three-dimensional model of surface and subsurface hydrology, *Adv. Water Resour.*, *33*(1), 106–122.
Blaschke, A. P., K.-H. Steiner, R. Schmalfuss, D. Gutknecht, and D. Sengschmitt (2003), Clogging processes in hyporheic interstices of an impounded river, the Danube at Vienna, Austria, *Int. Rev. Hydrobiol.*, *88*(3–4), 397–413.
Blois, G., J. L. Best, G. H. Sambrook Smith, and R. J. Hardy (2014), Effect of bed permeability and hyporheic flow on turbulent flow over bedforms, *Geophys. Res. Lett.*, *41*, 6435–6442, doi:10.1002/2014GL060906.
Boano, F., C. Camporeale, and R. Revelli (2010), A linear model for the coupled surface-subsurface flow in a meandering stream, *Water Resour. Res.*, *46*, W07535, doi:10.1029/2009WR008317.
Boano, F., J. W. Harvey, A. Marion, A. I. Packman, R. Revelli, L. Ridolfi, and A. Wörman (2014), Hyporheic flow and transport processes: Mechanisms, models, and biogeochemical implications, *Rev. Geophys.*, *52*, 603–679, doi:10.1002/2012RG000417.
Boulton, A. J. (2007), Hyporheic rehabilitation in rivers: Restoring vertical connectivity, *Freshwater Biol.*, *52*(4), 632–650.
Boulton, A. J., and P. J. Hancock (2006), Rivers as groundwater-dependent ecosystems: A review of degrees of dependency, riverine processes and management implications, *Aust. J. Bot.*, *54*(2), 133–144.
Boulton, A. J., S. Findlay, P. Marmonier, E. H. Stanley, and H. M. Valett (1998), The functional significance of the hyporheic zone in streams and rivers, *Annu. Rev. Ecol. Syst.*, *29*(1), 59–81.
Boulton, A. J., T. Datry, T. Kasahara, M. Mutz, and J. Stanford (2010), *Ecology and Management of the Hyporheic Zone: Stream-Groundwater Interactions of Running Waters and their Floodplains* edited, pp. 40, North American Benthological Society, Canada.
Brooks, R. H., and A. T. Corey (1964), *Hydraulic Properties of Porous Media: Hydrology Papers*, pp. 24, Colorado State Univ., Fort Collins, Colo.
Brunke, M. (1999), Colmation and depth filtration within streambeds: Retention of particles in hyporheic interstices, *Int. Rev. Hydrobiol.*, *84*(2), 99–117.
Brunke, M., and T. O. M. Gonser (1997), The ecological significance of exchange processes between rivers and groundwater, *Freshwater Biol.*, *37*(1), 1–33.
Brunner, P., and C. T. Simmons (2012), HydroGeoSphere: A fully integrated, physically based hydrological model, *Ground Water*, *50*, 170–176, doi:10.1111/j.1745-6584.2011.00882.x.
Brunner, P., P. G. Cook, and C. T. Simmons (2011), Disconnected surface water and groundwater: From theory to practice, *Ground Water*, *49*(4), 460–467.
Brunner, P., J. Doherty, and C. T. Simmons (2012), Uncertainty assessment and implications for data acquisition in support of integrated hydrologic models, *Water Resour. Res.*, *48*, W07513, doi:10.1029/2011WR011342.
Camporeale, C., E. Perucca, L. Ridolfi, and A. M. Gurnell (2013), Modeling the interactions between river morphodynamics and riparian vegetation, *Rev. Geophys.*, *51*, 379–414, doi:10.1002/rog.20014.
Camporese, M., C. Paniconi, M. Putti, and S. Orlandini (2010), Surface-subsurface flow modeling with path-based runoff routing, boundary condition-based coupling, and assimilation of multisource observation data, *Water Resour. Res.*, *46*, W02512, doi:10.1029/2008WR007536.
Camporese, M., E. Daly, P. E. Dresel, and J. A. Webb (2014), Simplified modeling of catchment-scale evapotranspiration via boundary condition switching, *Adv. Water Resour.*, *69*, 95–105.
Cardenas, M. B., J. L. Wilson, and V. A. Zlotnik (2004), Impact of heterogeneity, bed forms, and stream curvature on subchannel hyporheic exchange, *Water Resour. Res.*, *40*, W08307, doi:10.1029/2004WR003008.
Chen, X. (2011), Depth-dependent hydraulic conductivity distribution patterns of a streambed, *Hydrol. Processes*, *25*(2), 278–287.
Chen, X. H., W. H. Dong, G. X. Ou, Z. W. Wang, and C. Liu (2013), Opposite distribution pattern of streambed hydraulic conductivity in losing and gaining stream reaches, *Hydrol. Earth Syst. Sci. Discuss.*, *10*(2), 1693–1723.
Chen, X., J. Song, C. Cheng, D. Wang, and S. O. Lackey (2009), A new method for mapping variability in vertical seepage flux in streambeds, *Hydrogeol. J.*, *17*(3), 519–525.
Cheng, C., J. Song, X. Chen, and D. Wang (2011), Statistical distribution of streambed vertical hydraulic conductivity along the Platte River, Nebraska, *Water Resour. Manage.*, *25*(1), 265–285.
Cheng, D.-H., X.-H. Chen, A.-D. Huo, M. Gao, and W.-K. Wang (2013), Influence of bedding orientation on the anisotropy of hydraulic conductivity in a well-sorted fluvial sediment, *Int. J. Sediment Res.*, *28*(1), 118–125.
Cheng, N.-S., and Y.-M. Chiew (1999), Incipient sediment motion with upward seepage, *J. Hydraul. Res.*, *37*(5), 665–681.
Constantz, J. (2016), Streambeds merit recognition as a scientific discipline, *Wiley Interdiscip. Rev.: Water*, *3*(1), 13–18.
Davy, P., and D. Lague (2009), Fluvial erosion/transport equation of landscape evolution models revisited, *J. Geophys. Res.*, *114*, F03007, doi:10.1029/2008JF001146.
de Almeida, G. A. M., and J. F. Rodríguez (2011), Understanding pool-riffle dynamics through continuous morphological simulations, *Water Resour. Res.*, *47*, W01502, doi:10.1029/2010WR009170.
Delfs, J.-O., F. Blumensaat, W. Wang, P. Krebs, and O. Kolditz (2012), Coupling hydrogeological with surface runoff model in a Poltva case study in Western Ukraine, *Environ. Earth Sci.*, *65*(5), 1439–1457.
Descloux, S., T. Datry, and P. Marmonier (2013), Benthic and hyporheic invertebrate assemblages along a gradient of increasing streambed colmation by fine sediment, *Aquat. Sci.*, *75*(4), 493–507.

Dietrich, W. E., and P. J. Whiting (1989), Boundary shear stress and sediment transport in river meanders of sand and gravel, in *River Meandering*, *Water Resour. Monogr*., edited by S. Ikeda and G. Parker, pp. 1–50, AGU, Washington, D. C.

Doherty, J., and S. Christensen (2011), Use of paired simple and complex models to reduce predictive bias and quantify uncertainty, *Water Resour. Res.*, *47*, W12534, doi:10.1029/2011WR010763.

Dong, W., X. Chen, Z. Wang, G. Ou, and C. Liu (2012), Comparison of vertical hydraulic conductivity in a streambed-point bar system of a gaining stream, *J. Hydrol.*, *450–451*, 9–16.

Ebel, B. A., B. B. Mirus, C. S. Heppner, J. E. VanderKwaak, and K. Loague (2009), First-order exchange coefficient coupling for simulating surface water–groundwater interactions: Parameter sensitivity and consistency with a physics-based approach, *Hydrol. Processes*, *23*(13), 1949–1959.

Elliott, A. H., and N. H. Brooks (1997), Transfer of nonsorbing solutes to a streambed with bed forms: Theory, *Water Resour. Res.*, *33*(1), 123–136, doi:10.1029/96WR02784.

Evans, E., and A. C. Wilcox (2014), Fine sediment infiltration dynamics in a gravel-bed river following a sediment pulse, *River Res. Appl.*, *30*(3), 372–384.

Fatichi, S., et al. (2016), An overview of current applications, challenges, and future trends in distributed process-based models in hydrology, *J. Hydrol.*, *537*, 45–60.

Francalanci, S., G. Parker, and L. Solari (2008), Effect of seepage-induced nonhydrostatic pressure distribution on bed-load transport and Bed morphodynamics, *J. Hydraul. Eng.*, *134*(4), 378–389.

Freeze, R. A. (1974), Streamflow generation, *Rev. Geophys. Space Phys.*, *12*(4), 627–647.

Freeze, R. A., and J. A. Cherry (1979), *Groundwater*, pp. 604, Prentice-Hall, Englewood Cliffs, N. J.

Freeze, R. A., and R. L. Harlan (1969), Blueprint for a physically-based, digitally-simulated hydrologic response model, *J. Hydrol.*, *9*(3), 237–258.

Frei, S., J. H. Fleckenstein, S. J. Kollet, and R. M. Maxwell (2009), Patterns and dynamics of river–aquifer exchange with variably-saturated flow using a fully-coupled model, *J. Hydrol.*, *375*(3–4), 383–393.

Furman, A. (2008), Modeling Coupled Surface–Subsurface Flow Processes: A Review, *Vadose Zone J.*, *7*(2), 741–756.

Garcia, M. H. (2008), *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice*, pp. 1132, American Society of Civil Engineers, Reston, Va.

Genereux, D. P., S. Leahy, H. Mitasova, C. D. Kennedy, and D. R. Corbett (2008), Spatial and temporal variability of streambed hydraulic conductivity in West Bear Creek, North Carolina, USA, *J. Hydrol.*, *358*(3–4), 332–353.

Gianni, G., J. Richon, P. Perrochet, A. Vogel, and P. Brunner (2016), Rapid identification of transience in streambed conductance by inversion of floodwave responses, *Water Resour. Res.*, *52*(4), 2647–2658, doi:10.1002/2015WR017154.

Goderniaux, P., S. Brouyère, H. J. Fowler, S. Blenkinsop, R. Therrien, P. Orban, and A. Dassargues (2009), Large scale surface–subsurface hydrological model to assess climate change impacts on groundwater reserves, *J. Hydrol.*, *373*(1–2), 122–138.

Goldschneider, A. A., K. A. Haralampides, and K. T. B. MacQuarrie (2007), River sediment and flow characteristics near a bank filtration water supply: Implications for riverbed clogging, *J. Hydrol.*, *344*(1–2), 55–69.

Gomez-Velez, J. D., S. Krause, and J. L. Wilson (2014), Effect of low-permeability layers on spatial patterns of hyporheic exchange and groundwater upwelling, *Water Resour. Res.*, *50*, 5196–5215, doi:10.1002/2013WR015054.

Gran, K., and C. Paola (2001), Riparian vegetation controls on braided stream dynamics, *Water Resour. Res.*, *37*(12), 3275–3283, doi:10.1029/2000WR000203.

Hairsine, P. B., and C. W. Rose (1992a), Modeling water erosion due to overland flow using physical principles: 1. Sheet flow, *Water Resour. Res.*, *28*(1), 237–243, doi:10.1029/91WR02380.

Hairsine, P. B., and C. W. Rose (1992b), Modeling water erosion due to overland flow using physical principles: 2. Rill flow, *Water Resour. Res.*, *28*(1), 245–250, doi:10.1029/91WR02381.

Hartwig, M., and D. Borchardt (2015), Alteration of key hyporheic functions through biological and physical clogging along a nutrient and fine-sediment gradient, *Ecohydrology*, *8*(5), 961–975.

Harvey, J., and M. Gooseff (2015), River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins, *Water Resour. Res.*, *51*, 6893–6922, doi:10.1002/2015WR017617.

Harvey, J. W., and K. E. Bencala (1993), The Effect of streambed topography on surface-subsurface water exchange in mountain catchments, *Water Resour. Res.*, *29*(1), 89–98, doi:10.1029/92WR01960.

Hatch, C. E., A. T. Fisher, C. R. Ruehl, and G. Stemler (2010), Spatial and temporal variations in streambed hydraulic conductivity quantified with time-series thermal methods, *J. Hydrol.*, *389*(3–4), 276–288.

Heppner, C. S., Q. Ran, J. E. VanderKwaak, and K. Loague (2006), Adding sediment transport to the integrated hydrology model (InHM): Development and testing, *Adv. Water Resour.*, *29*(6), 930–943.

Hirano, M. (1971), River-bed degradation with armoring, *Proc. Jpn. Soc. Civ. Eng.*, *195*, 55–65.

Hirano, M. (1972), Studies on variations and equilibrium state of a river bed composed of nonuniform material, *Trans. JSCE*, *4*.

Hjulstrom, F. (1935), Studies of the morphological activity of rivers as illustrated by the River Fyris, *Bull. Geol. Inst. Univ. Uppsala*, *25*, 221–527.

Huang, X., and J. D. Niemann (2008), How do streamflow generation mechanisms affect watershed hypsometry?, *Earth Surf. Processes Landforms*, *33*(5), 751–772.

Irvine, D. J., P. Brunner, H.-J. H. Franssen, and C. T. Simmons (2012), Heterogeneous or homogeneous? Implications of simplifying heterogeneous streambeds in models of losing streams, *J. Hydrol.*, *424–425*, 16–23.

Janssen, F., M. B. Cardenas, A. H. Sawyer, T. Dammrich, J. Krietsch, and D. de Beer (2012), 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.

Jones, I., I. Growns, A. Arnold, S. McCall, and M. Bowes (2015), The effects of increased flow and fine sediment on hyporheic invertebrates and nutrients in stream mesocosms, *Freshwater Biol.*, *60*(4), 813–826.

Kaeser, D., T. Graf, F. Cochand, R. McLaren, R. Therrien, and P. Brunner (2014), Channel representation in physically based models coupling groundwater and surface water: Pitfalls and how to avoid them, *Groundwater*, *52*, 827–836, doi:10.1111/gwat.12143.

Kasahara, T., and S. M. Wondzell (2003), Geomorphic controls on hyporheic exchange flow in mountain streams, *Water Resour. Res.*, *39*(1), 1005, doi:10.1029/2002WR001386.

Katul, G. G., R. Oren, S. Manzoni, C. Higgins, and M. B. Parlange (2012), Evapotranspiration: A process driving mass transport and energy exchange in the soil-plant-atmosphere-climate system, *Rev. Geophys.*, *50*, RG3002, doi:10.1029/2011RG000366.

Kemp, P., D. Sear, A. Collins, P. Naden, and I. Jones (2011), The impacts of fine sediment on riverine fish, *Hydrol. Processes*, *25*(11), 1800–1821.

Kim, J., V. Y. Ivanov, and N. D. Katopodes (2013), Modeling erosion and sedimentation coupled with hydrological and overland flow processes at the watershed scale, *Water Resour. Res.*, *49*, 5134–5154, doi:10.1002/wrcr.20373.

Kollet, S. J., and R. M. Maxwell (2006), Integrated surface–groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model, *Adv. Water Resour.*, *29*, 945–958.

Kollet, S. J., R. M. Maxwell, C. S. Woodward, S. Smith, J. Vanderborght, H. Vereecken, and C. Simmer (2010), Proof of concept of regional scale hydrologic simulations at hydrologic resolution utilizing massively parallel computer resources, *Water Resour. Res.*, *46*, W04201, doi:10.1029/2009WR008730.

Kristensen, K. J., and S. E. Jensen (1975), A model for estimating actual evapotranspiration from potential evapotranspiration, *Nordic Hydrol.*, *6*(3), 170–188.

Krumbein, W. C., and L. L. Sloss (1951), *Stratigraphy and Sedimentation*, pp. 497, W. H. Freeman, San Francisco, Calif.

Kumar, M., C. J. Duffy, and K. M. Salvage (2009), A second-order accurate, finite volume–based, integrated hydrologic modeling (FIHM) framework for simulation of surface and subsurface flow, *Vadose Zone J.*, *8*(4), 873–890.

Kurtz, W., H. J. Hendricks Franssen, P. Brunner, and H. Vereecken (2013), Is high-resolution inverse characterization of heterogeneous river bed hydraulic conductivities needed and possible?, *Hydrol. Earth Syst. Sci.*, *17*(10), 3795–3813.

Lu, Y., Y.-M. Chiew, and N.-S. Cheng (2008), Review of seepage effects on turbulent open-channel flow and sediment entrainment, *J. Hydraul. Res.*, *46*(4), 476–488.

Lu, Y., Y.-j. Lu, and Y.-m. Chiew (2012), Incipient motion of cohesionless sediments on riverbanks with ground water injection, *Int. J. Sediment Res.*, *27*(1), 111–119.

Luo, Y., W. Guo, H. Ngo, L. Nghiem, F. Hai, J. Zhang, S. Liang, and X. Wang (2014), A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment, *Sci. Total Environ.*, *473–474*, 619–641, doi:10.1016/j.scitotenv.2013.12.065.

Martin, C. S. (1970), Effect of a porous sand bed on incipient sediment motion, *Water Resour. Res.*, *6*(4), 1162–1174, doi:10.1029/WR006i004p01162.

Mathers, K. L., J. Millett, A. L. Robertson, R. Stubbington, and P. J. Wood (2014), Faunal response to benthic and hyporheic sedimentation varies with direction of vertical hydrological exchange, *Freshwater Biol.*, *59*(11), 2278–2289.

Narsilio, G. A., O. Buzzi, S. Fityus, T. S. Yun, and D. W. Smith (2009), Upscaling of Navier–Stokes equations in porous media: Theoretical, numerical and experimental approach, *Comput. Geotech.*, *36*(7), 1200–1206.

Neuman, S. P. (1977), Theoretical derivation of Darcy's law, *Acta Mech.*, *25*(3–4), 153–170.

Nogaro, G., T. Datry, F. Mermilled-Blondin, S. Descloux, and B. Montuelle (2010), Influence of streambed sediment clogging on microbial processes in the hyporheic zone, *Freshwater Biol.*, *55*(6), 1288–1302, doi:10.1111/j.1365-2427.2009.02352.x.

Nowinski, J. D., M. B. Cardenas, and A. F. Lightbody (2011), Evolution of hydraulic conductivity in the floodplain of a meandering river due to hyporheic transport of fine materials, *Geophys. Res. Lett.*, *38*, L01401, doi:10.1029/2010GL045819.

Ouchiyama, N., and T. Tanaka (1986), Porosity estimation from particle size distribution, *Ind. Eng. Chem. Fundam.*, *25*(1), 125–129.

Owens, P. N., et al. (2005), Fine-grained sediment in river systems: Environmental significance and management issues, *River Res. Appl.*, *21*, 693–717, doi:10.1002/rra.878.

Packman, A., M. Salehin, and M. Zaramella (2004), Hyporheic exchange with gravel beds: Basic hydrodynamic interactions and bedform-induced advective flows, *J. Hydraul. Eng.*, *130*(7), 647–656.

Panday, S., and P. S. Huyakorn (2004), A fully coupled physically-based spatially-distributed model for evaluating surface/subsurface flow, *Adv. Water Resour.*, *27*(4), 361–382, doi:10.1016/j.advwatres.2004.02.016

Paniconi, C., and M. Putti (2015), Physically based modeling in catchment hydrology at 50: Survey and outlook, *Water Resour. Res.*, *51*, 7090–7129, doi:10.1002/2015WR017780.

Paola, C., and V. R. Voller (2005), A generalized Exner equation for sediment mass balance, *J. Geophys. Res.*, *110*, F04014, doi:10.1029/2004JF000274.

Papanicolaou, A., M. Elhakeem, G. Krallis, S. Prakash, and J. Edinger (2008), Sediment transport modeling review—Current and future developments, *J. Hydraul. Eng.*, *134*(1), 1–14.

Partington, D., P. Brunner, C. T. Simmons, R. Therrien, A. D. Werner, G. C. Dandy, and H. R. Maier (2011), A hydraulic mixing-cell method to quantify the groundwater component of streamflow within spatially distributed fully integrated surface water–groundwater flow models, *Environ. Modell. Software*, *26*(7), 886–898.

Partington, D., P. Brunner, S. Frei, C. T. Simmons, A. D. Werner, R. Therrien, H. R. Maier, G. C. Dandy, and J. H. Fleckenstein (2013), Interpreting streamflow generation mechanisms from integrated surface-subsurface flow models of a riparian wetland and catchment, *Water Resour. Res.*, *49*, 5501–5519, doi:10.1002/wrcr.20405.

Ran, Q., C. S. Heppner, J. E. VanderKwaak, and K. Loague (2007), Further testing of the integrated hydrology model (InHM): Multiple-species sediment transport, *Hydrol. Processes*, *21*(11), 1522–1531.

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

Richards, L. A. (1931), Capillary conduction of liquids through porous mediums, *J. Appl. Phys.*, *1*(5), 318–333.

Rigon, R., G. Bertoldi, and T. M. Over (2006), GEOtop: A distributed hydrological model with coupled water and energy budgets, *J. Hydrometeorol.*, *7*(3), 371–388.

Rosas, J., K. Z. Jadoon, and T. M. Missimer (2015), New empirical relationship between grain size distribution and hydraulic conductivity for ephemeral streambed sediments, *Environ. Earth Sci.*, *73*(3), 1303–1315.

Rosenberry, D. O., and J. Pitlick (2009a), Local-scale variability of seepage and hydraulic conductivity in a shallow gravel-bed river, *Hydrol. Processes*, *23*(23), 3306–3318.

Rosenberry, D. O., and J. Pitlick (2009b), Effects of sediment transport and seepage direction on hydraulic properties at the sediment–water interface of hyporheic settings, *J. Hydrol.*, *373*(3–4), 377–391.

Rosgen, D. L. (1994), A classification of natural rivers, *Catena*, *22*(3), 169–199.

Rouse, H. (1937), Modern conceptions of the mechanics of turbulence, *Trans. Am. Soc. Civ. Eng.*, *90*, 463–543.

Rubol, S., A. Freixa, A. Carles-Brangarí, D. Fernàndez-Garcia, A. M. Romaní, and X. Sanchez-Vila (2014), Connecting bacterial colonization to physical and biochemical changes in a sand box infiltration experiment, *J. Hydrol.*, *517*, 317–327.

Ruiz-Villanueva, V., H. Piégay, A. A. Gurnell, R. A. Marston, and M. Stoffel (2016), Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges, *Rev. Geophys.*, *54*, 611–652, doi:10.1002/2015RG000514.

Salehin, M., A. I. Packman, and M. Paradis (2004), Hyporheic exchange with heterogeneous streambeds: Laboratory experiments and modeling, *Water Resour. Res.*, *40*, W11504, doi:10.1029/2003WR002567.

Sanford, L. P. (2008), Modeling a dynamically varying mixed sediment bed with erosion, deposition, bioturbation, consolidation, and armoring, *Comput. Geosci.*, *34*(10), 1263–1283.

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

Schälchli, U. (1992), The clogging of coarse gravel river beds by fine sediment, *Hydrobiologia*, *235–236*(1), 189–197.

Schilling, O. S., J. Doherty, W. Kinzelbach, H. Wang, P. N. Yang, and P. Brunner (2014), Using tree ring data as a proxy for transpiration to reduce predictive uncertainty of a model simulating groundwater–surface water–vegetation interactions, *J. Hydrol.*, *519*, 2258–2271.

Schmadel, N. M., A. S. Ward, C. S. Lowry, and J. M. Malzone (2016), Hyporheic exchange controlled by dynamic hydrologic boundary conditions, *Geophys. Res. Lett.*, *43*, 4408–4417, doi:10.1002/2016GL068286.

Schubert, J. (2002), Hydraulic aspects of riverbank filtration-field studies, *J. Hydrol.*, *266*(3–4), 145–161.

Simpson, G., and S. Castelltort (2006), Coupled model of surface water flow, sediment transport and morphological evolution, *Comput. Geosci.*, *32*(10), 1600–1614.

Simpson, S. C., and T. Meixner (2012), Modeling effects of floods on streambed hydraulic conductivity and groundwater-surface water interactions, *Water Resour. Res.*, *48*, W02515, doi:10.1029/2011WR011022.

Siviglia, A., and A. Crosato (2016), Numerical modelling of river morphodynamics: Latest developments and remaining challenges, *Adv. Water Resour.*, *93*, 1–3.

Song, J., X. Chen, and C. Cheng (2010), Observation of bioturbation and hyporheic flux in streambeds, *Front. Environ. Sci. Eng. China*, *4*(3), 340–348.

Sophocleous, M. (2002), Interactions between groundwater and surface water: The state of the science, *Hydrogeol. J.*, *10*(1), 52–67.

Sprenger, M., H. Leistert, K. Gimbel, and M. Weiler (2016), Illuminating hydrological processes at the soil-vegetation-atmosphere interface with water stable isotopes, *Rev. Geophys.*, *54*, 674–704, doi:10.1002/2015RG000515.

Springer, A. E., W. D. Petroutson, and B. A. Semmens (1999), Spatial and temporal variability of hydraulic conductivity in active reattachment bars of the Colorado River, Grand Canyon, *Ground Water*, *37*(3), 338–344.

Stecca, G., A. Siviglia, and A. Blom (2016), An accurate numerical solution to the Saint-Venant-Hirano model for mixed-sediment morphodynamics in rivers, *Adv. Water Resour.*, *93*, 39–61.

Tang, Q., W. Kurtz, P. Brunner, H. Vereecken, and H. J. Hendricks Franssen (2015), Characterisation of river–aquifer exchange fluxes: The role of spatial patterns of riverbed hydraulic conductivities, *J. Hydrol.*, *531*, 111–123.

Therrien, R., and E. A. Sudicky (1996), Three-dimensional analysis of variably-saturated flow and solute transport in discretely-fractured porous media, *J. Contam. Hydrol.*, *23*(1–2), 1–44.

Therrien, R., R. G. McLaren, E. A. Sudicky, and S. M. Panday (2010), HydroGeoSphere: A three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport, *Rep.*, Groundwater Simulations Group, Waterloo, Ont., Canada.

Trauth, N., C. Schmidt, U. Maier, M. Vieweg, and J. H. Fleckenstein (2013), Coupled 3D stream flow and hyporheic flow model under varying stream and ambient groundwater flow conditions in a pool-riffle system, *Water Resour. Res.*, *49*, 5834–5850, doi:10.1002/wrcr.20442.

Treese, S., T. Meixner, and J. F. Hogan (2009), Clogging of an effluent dominated semiarid river: A conceptual model of stream-aquifer interactions 1, *J. Am. Water Resour. Assoc.*, *45*, 1047–1062, doi:10.1111/j.1752-1688.2009.00346.x.

VanderKwaak, J. E., and K. Loague (2001), Hydrologic-response simulations for the R-5 catchment with a comprehensive physics-based model, *Water Resour. Res.*, *37*(4), 999–1013, doi:10.1029/2000WR900272.

van Genuchten, M. T. (1980), A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J.*, *44*(5), 892–898.

Viparelli, E., O. E. Sequeiros, A. Cantelli, P. R. Wilcock, and G. Parker (2010), River morphodynamics with creation/consumption of grain size stratigraphy, 2: numerical model, *J. Hydraul. Res.*, *48*(6), 727–741.

Vukovic, M., and A. Soro (1992), *Determination of Hydraulic Conductivity of Porous Media from Grain Size Composition*, Water Resour. Publ., Littleton, Colo.

Wainwright, J., L. Turnbull, T. G. Ibrahim, I. Lexartza-Artza, S. F. Thornton, and R. E. Brazier (2011), Linking environmental régimes, space and time: Interpretations of structural and functional connectivity, *Geomorphology*, *126*(3–4), 387–404.

Wainwright, J., A. J. Parsons, J. R. Cooper, P. Gao, J. A. Gillies, L. Mao, J. D. Orford, and P. G. Knight (2015), The concept of transport capacity in geomorphology, *Rev. Geophys.*, *53*, 1155–1202, doi:10.1002/2014RG000474.

Warsta, L., A. Taskinen, H. Koivusalo, M. Paasonen-Kivekäs, and T. Karvonen (2013), Modelling soil erosion in a clayey, subsurface-drained agricultural field with a three-dimensional FLUSH model, *J. Hydrol.*, *498*, 132–143.

Weill, S., E. Mouche, and J. Patin (2009), A generalized Richards equation for surface/subsurface flow modelling, *J. Hydrol.*, *366*(1–4), 9–20.

Winter, T. C. (2007), The role of ground water in generating streamflow in headwater areas and in maintaining base flow, *J. Am. Water Resour. Assoc.*, *43*(1), 15–25.

Winter, T. C., J. W. Harvey, O. L. Franke, and W. M. Alley (1998), Ground water and surface water: A single resource edited by U. circular.

Wu, G., L. Shu, C. Lu, X. Chen, X. Zhang, E. K. Appiah-Adjei, and J. Zhu (2015), Variations of streambed vertical hydraulic conductivity before and after a flood season, *Hydrogeol. J.*, *23*(7), 1603–1615.

Zi, T., M. Kumar, G. Kiely, C. Lewis, and J. Albertson (2016), Simulating the spatio-temporal dynamics of soil erosion, deposition, and yield using a coupled sediment dynamics and 3D distributed hydrologic model, *Environ. Modell. Software*, *83*, 310–325.

Zlotnik, V. A., M. B. Cardenas, and D. Toundykov (2011), Effects of multiscale anisotropy on basin and hyporheic groundwater flow, *Ground Water*, *49*(4), 576–583.