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Review

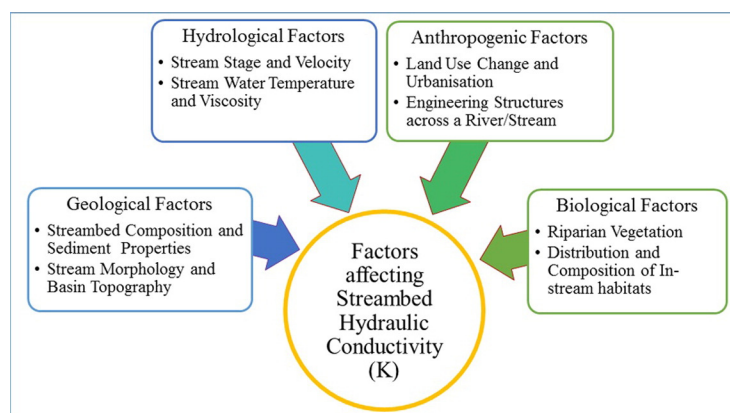
Significance of streambed hydraulic conductivity in stream-aquifer interaction - A systematic review of fundamentals and recent research

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HIGHLIGHTS

- The geological and ecological factors that influence streambed hydraulic conductivity are briefly discussed.
- Effects of engineering structures across river/stream on the variability of streambed hydraulic properties is discussed.
- Overview of the Statistical and Geo-statistical techniques employed for spatial interpolation of streambed K are presented.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainable planning and management of water resources is necessary to address the issue of fresh water scarcity all around the globe. Modeling the dynamics of stream–aquifer interaction is essential for formulating management strategies related to quantification of solute transport and exchange processes in the riparian zones within a watershed. Uncertainty in stream–aquifer interactions arises from the inherent complex-nested flow paths and spatio-temporal variability of streambed hydraulic properties. The streambed hydraulic conductivity (K) is a key factor controlling the water fluxes across the stream–aquifer interface which is dependent on the extent and interconnection of void spaces within the streambed that may occur as a consequence of factors such as intergranular porosity, fracture and bed planes. In the recent years, the spatio-temporal variability of streambed hydraulic conductivity is also accounted during the modeling of stream–aquifer interaction studies for achieving more accurate and reliable prediction models. This article discusses about various geological, hydrological, anthropogenic and biological factors that influence streambed hydraulic conductivity and evaluates several laboratory and in-situ methods of estimating streambed hydraulic conductivity. An overview of the statistical and Geo-statistical methods employed for spatial interpolation of streambed hydraulic conductivity are being presented. The article also addresses the effects of engineering structures across a river/stream on the variability of streambed hydraulic properties.

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1. Introduction

The river basin acts as a system, transforming the precipitation into surface and groundwater resources. Most gravel rivers have a permeable bed and a medium (interfacial zone) with high porosity composed by gravels beneath it, and an intensive interaction between free-surface flow and subsurface flow exists (Gordon et al., 2004). When dealing with the interaction between groundwater and surface water, it is evident that the spatial and temporal variability of soil water transport within the unsaturated zone exists and is directly related to soil hydraulic properties and hydrological processes (Kalbus et al., 2006; Fleckenstein et al., 2010; Valerio et al., 2010). Various aspects in the stream – aquifer interactions are presently not completely understood due to the spatial variability of the aquifer physical properties in the regional scale (hydraulic conductivity, porosity, transmissivity) and several other factors such as the degree of penetration of the stream into the aquifer and partitioning of flow between the interconnected domains of the macropore system, and the matrix (Dillon and Liggett, 1983; Cardenas, 2009; Tang et al., 2015). For determining the response of streams to rainfall and snowmelt and also the response in the form of groundwater level, the infiltration capacity of streambed soil needs to be evaluated. Soil water movement along different pathways and how long water particles reside in different soil zones are important and determine the quantity of recharge and quality of groundwater. The vertical downward flow is mainly controlled by gravity and the water movement in soils (homogeneous and heterogeneous) depends on hydraulic conductivity, suction potential and soil characteristics (Fox and Durnford, 2003; Menció et al., 2014). Soil hydraulic properties are highly nonlinear functions which are known to exhibit marked spatial variability in geologic media at various scales of observation.

Streams are hydraulically connected to groundwater, with stream water passing back and forth between the stream channel and the subsurface (Castro and Hornberger, 1991). Aquifer recharge via infiltration through ephemeral streambeds is considered to be a major source of groundwater recharge (Villeneuve et al., 2015). Depending on the amplitude of topographic variations, geometric and hydraulic properties of the streambed; the travel time, length and depth of the groundwater flow path varies significantly from the points of recharge to the points of discharge. Streambed hydraulic conductivity (K) is a key physical parameter, controlling the water fluxes across the stream-aquifer interface. It depends mostly on streambed sediment characteristics (e.g. effective porosity, grain size, packing), streambed processes (e.g. sedimentation, colmation and erosion) and the development of stream channel geometry and streambed morphology (e.g. dunes, anti-dunes, pool-riffle sequences, etc.) (Schneidewind et al., 2015). The streambed

soil sediments does not exhibit constant properties or conditions of stable equilibrium, as they are subjected to alternate wets and dries, swells and shrinks, dispersion and flocculation, cracking, compaction, aggregation, experience bio-chemical changes and structural rearrangements (Reid and Frostick, 1987; Rehg et al., 2005). The streambed hydraulic conductivity affects the groundwater residence time. Variations in groundwater residence, inflow and outflow rates can be associated with the hydraulic resistance of the clogging layer at the wetted perimeter of a streambed and river channel morphology (Katsuyama et al., 2010). The potential of groundwater recharge through streambed depends on the topography of the area, the velocity and depth of river stage and the hydro-geologic setting of the underlying aquifer. Water table fluctuation is a direct response of the groundwater draft or recharge within a watershed (Woessner, 2000; Wang et al., 2016a). The purpose of this brief review is to discuss various geological and ecological factors that influence streambed hydraulic conductivity and summarize the available laboratory and in-situ methods of estimating streambed hydraulic conductivity. The statistical and Geo-statistical methods employed for spatial interpolation of streambed K are qualitatively evaluated. The article also addresses the effects of engineering structures across a river/stream on the variability of streambed hydraulic conductivity.

2. Factors affecting streambed hydraulic conductivity

The factors that affect streambed and river network system to a larger extent include precipitation patterns, underlying geology, topography (or slope) and overall land use within a catchment. The factors responsible for spatio-temporal variability of streambed hydraulic conductivity can be broadly categorized into geological, hydrological, anthropogenic and biological features (Fig. 1). The geological factors that determine the rate of streambed hydraulic conductivity are streambed composition, sediment properties, stream morphology, and basin topography. Similarly the hydrological factors include stream stage and velocity; water temperature and viscosity. Riparian vegetation, climate, land use change and other anthropogenic activities are also responsible for the changes in streambed structure (Wang et al., 2004).

2.1. Influence of geological factors on streambed hydraulic conductivity

2.1.1. Effects of streambed composition and sediment properties

The physical properties and factors that primarily influence the rate of streambed hydraulic conductivity are sediment particle size and substratum heterogeneity; longitudinal variations in bed material depth and channel geometry; variations in hydraulic radius and roughness due to modifications in bed composition and bed form (Jackson,

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