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Relative rates of solute and pressure propagation into heterogeneous alluvial aquifers following river flow events

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SUMMARY

Conventional theory for homogeneous aquifers states that pressure propagates more rapidly into aquifers than solutes following river stage rise. We demonstrate through numerical simulations of two-dimensional aquifer slices that the relative timing of pressure and solute responses in alluvial aquifers is a function of subsurface structures. Two generic conceptual models of heterogeneity are investigated, a vertical clogging layer and a horizontal sand string. Independent of the conceptual model, the hydraulic conductivity contrast is the primary controlling variable on the rates of pressure and solute transport from a river to an observation point. Conceptual models are compared using metrics for pressure and solute travel time that represent propagation of 50% change in each variable from river to observation point. While not possible in a homogeneous system, a solute travel time less than a pressure travel time can occur in the presence of both types of heterogeneity, and indicates that heterogeneity is controlling propagation from the river to the aquifer. Less than one order of magnitude contrast in hydraulic conductivities is sufficient to create a travel time ratio less than one. Contrasts of this magnitude are often exceeded in alluvial environments and thus simultaneous measurement of solute and pressure has the potential to constrain estimates of exchange flux in a way not possible with pressure measurements alone. In general, flux estimates derived from solute travel times provide more accurate estimates than those derived from pressure responses in heterogeneous environments. The magnitude of error in estimates derived from pressure responses is proportional to the hydraulic conductivity contrast. Travel times calculated from time series pressure and EC data collected in the Mitchell River in northern Australia are used to demonstrate application of this combined approach.

1. Introduction

Accurate assessment of river–aquifer exchange flux is vital for water resources management and as a basis for contaminant transport investigations. Interpretation of head data obtained during floods is often a key component in such assessments (Meyboom, 1961; Todd, 1956; Winter et al., 1998). However, the extent of river water movement into an aquifer cannot be determined solely from head data as head change measures energy propagation whereas water is a physical substance that advects, disperses and diffuses. The extent of water movement is more appropriately captured through measurement of solute concentrations or isotope ratios in aquifer and river. Analytical solutions that describe the differing influences of homogenous aquifer properties on rates of pressure and solute transport into a homogenous aquifer following a river flow event were recently presented (Welch et al., 2013). However, previous studies in heterogeneous systems have demonstrated limited correlation between techniques that estimate aquifer properties from metrics that represent solute and pressure transport (Trinchero et al., 2008). These studies also acknowledge a disconnect between the effective aquifer properties obtained for heterogeneous aquifers and the physical systems they purport to represent. Hence, there is a need to improve understanding of the physical processes that govern pressure and solute propagation in heterogeneous aquifer systems. Improved understanding of the influences of heterogeneity on observation data and methods of interpretation may help identify when heterogeneity needs to be incorporated into assessments of river–aquifer exchange flux.

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Nomenclature

A	fitting coefficient in capillary-head curve, m^{-1}
b	saturated aquifer thickness, m
b_2	thickness of sand string, m
D	aquifer diffusivity, m^2 d^{-1}
h_0	initial height of river, m
H	magnitude of river stage rise, m
K	aquifer hydraulic conductivity, m d^{-1}
K_1	low hydraulic conductivity part of aquifer, m d^{-1}
K_2	high hydraulic conductivity part of aquifer, m d^{-1}
K^N	equivalent homogenous hydraulic conductivity where flow is normal (perpendicular) to layers of different hydraulic conductivity, m d^{-1}
K^P	equivalent homogenous hydraulic conductivity where flow is parallel to layers of different hydraulic conductivity, m d^{-1}
L_1	width of clogging layer with hydraulic conductivity K_1, m
L_2	width of aquifer between clogging layer and observation point, m
n	fitting exponent in capillary-head curve, –
S	storativity, –
S_r	residual saturation, –
S_s	specific storage, m^{-1}
S_y	specific yield, –
t_s	solute travel time, time it takes for 50% of the difference between river and aquifer concentration change to occur at an observation point, d
t_p	pressure travel time, time it takes for 50% of the river stage rise to occur at an observation point, d
x	distance from river boundary to observation point, m

Conceptualisations of a river in an alluvial aquifer commonly include either a clogging layer at the interface between river and aquifer created by deposition of fine particles, or horizontal layers of differing hydraulic conductivity deposited over time by changing river conditions, commonly interbedded silts, sands, and clays (Woessner, 2000). Adequate characterisation of hydraulic conductivity zones in near-river environments is necessary for adequate estimates of exchange flux. However, at larger scales of interest to water managers, compromises in data collection and model complexity become necessary (Fleckenstein et al., 2006). Thus, while alluvial aquifers often contain heterogeneity within clogging layers, sand strings, and surrounding aquifers, generic models that capture two dominant zones have the potential to inform process understanding and hence interpretation of head and solute measurements. Systematic assessment of the influence of generic subsurface structures on rates of water and solute flux across the river–aquifer interface has not previously been attempted.

In order to obtain estimates of exchange flux from river flow events, head data has traditionally been interpreted alone, either through analytical solutions or complex numerical simulations (e.g., Engdahl et al., 2010). Analytical solutions for head propagation in homogenous aquifers and in the presence of a clogging layer have long been available (Hall and Moench, 1972; Hantush, 1965; Zlotnik and Huang, 1999), but in practice tend to incorporate the effects of other near-river processes rather than providing specific characterisation of the clogging layer (Barlow et al., 2000; Ha et al., 2007). Analytical solutions are not available for sand strings, or, until recently, for solutes. Measuring and analysing solute data during flow events presents one method by which confidence in flux estimates can be increased. Sparse solute data is most commonly used as an adjunct to head data in the calibration of numerical models (Hill and Tiedeman, 2007). However, the use of complex numerical models is not always warranted or possible. Methods such as principal component analysis (PCA) provide alternatives for using groundwater head and electrical conductivity (EC) data to infer river water infiltration, and to identify zones of differing hydraulic conductivity along a river (Page et al., 2012), but cannot identify the mechanisms governing pressure and solute transport. However it demonstrates that methods that combine observations of head change and solute change in aquifers during flow events have the potential to delineate changes in exchange flux resulting from subsurface heterogeneity without the need for complex numerical models or analysis.

In this paper we systematically examine the effects of clogging layers and sand strings on pressure and solute propagation into aquifers following river stage rise using numerical simulations and analytical solutions. Contrary to behaviour observed in homogenous systems, we establish that both types of alluvial structure can result in the rate of solute propagation exceeding the rate of pressure propagation. Thus, significant change in solute concentration may be observed before significant change in pressure propagation at locations within the aquifer. In general, estimates of exchange flux derived from solute travel times contain less error than those derived from pressure data. Subsequently we demonstrate how co-measurement of pressure and EC can be used to identify the dominating presence of subsurface structures and constrain estimates of aquifer properties and exchange flux using field data from an alluvial system in tropical North Queensland, Australia.

2. Methodology

Two conceptual models of subsurface alluvial architecture were investigated:

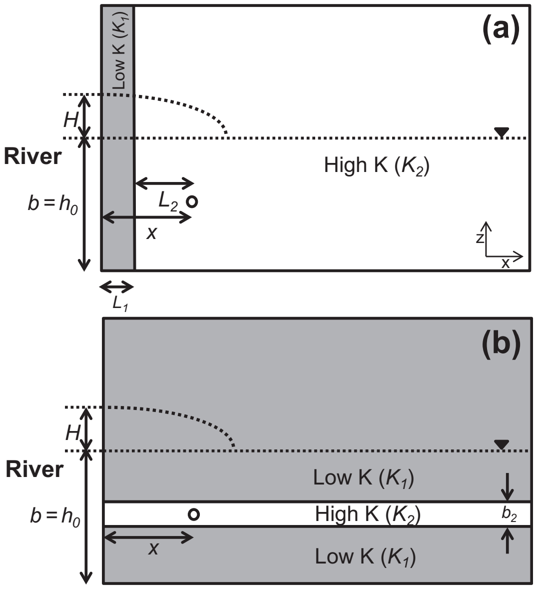

Fig. 1. Conceptual models of heterogeneity in alluvial aquifers, (a) vertical clogging layer and (b) horizontal sand string. The shaded area corresponds to low hydraulic conductivity (K_1) and white areas correspond to high hydraulic conductivities (K_2).