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The hydraulic conductivity structure of gravel-dominated vadose zones within alluvial floodplains

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SUMMARY

The floodplains of many gravel-bed streams have a general stratigraphy that consists of a layer of topsoil covering gravel-dominated subsoil. Previous research has demonstrated that this stratigraphy can facilitate preferential groundwater flow through focused linear features, such as paleochannels, or gravelly regions within the vadose zone. These areas within the floodplain vadose zone may provide a route for interactions between the floodplain surface and alluvial groundwater, effectively extending the hyporheic zone across the floodplain during high stream stage. The objective of this research was to assess the structure and scale of texture heterogeneity within the vadose zone within the gravel subsoils of alluvial floodplains using resistivity data combined with hydraulic testing and sediment sampling of the vadose zone. Point-scale and broad-scale methodologies in combination can help us understand spatial heterogeneity in hydraulic conductivity without the need for a large number of invasive hydraulic tests. The evaluated sites in the Ozark region of the United States were selected due to previous investigations indicating that significant high conductivity flow zones existed in a matrix which include almost no clay content. Data indicated that resistivity corresponded with the fine content in the vadose zone and subsequently corresponds to the saturated hydraulic conductivity. Statistical analysis of resistivity data, and supported by data from the soil sampling and permeameter hydraulic testing, identified isolated high flow regions and zones that can be characterized as broad-scale high hydraulic conductivity features with potentially significant consequences for the migration of water and solutes and therefore are of biogeochemical and ecological significance.

1. Introduction

Heterogeneity in the subsurface has important ramifications for many aspects of hydrology, most commonly aquifer storage (Fetter, 2001) but also in understanding hyporheic flow in floodplains (Poole et al., 2006; Jones et al., 2008). Efforts to understand the heterogeneity of aquifers have utilized down-well flowmeters (Rehfeldt et al., 1992), tracer tests (Sudicky, 1986), pumping tests (Cardiff et al., 2009; Berg and Illman, 2011), and the joint analysis of those methods (Li et al., 2008; Bohling et al., 2012). However, investigators have acknowledged that, in highly heterogeneous settings, the ability to model heterogeneity is dependent on the density and spatial distribution of the data points (Rehfeldt et al., 1992; Slater, 2007; Alexander et al., 2011). Investigations designed to investigate heterogeneity based on conventional methods thus need to balance data density on the one hand and the time and expense of data collection on the other (Iqbal et al., 2005). Additionally, the performance of numeric models of heterogeneous systems can suffer from cell fabrics that are too fine, and research has been focused on methods to generalize heterogeneous systems to reduce model run time without compromising the realistic portrayal of the physical system (Fleckenstein and Fogg, 2008).

Like the saturated zone, the vadose zone contains heterogeneity that is of research interest. For instance, Fuchs et al. (2009) and Heeren et al. (2010) investigated a horizontal preferential flow path (PFP) originating in a gravel subsoil layer within the vadose zone of an alluvial floodplain. The rate of flow and horizontal transport within the PFP limited the sorption of dissolved phosphorus

Abbreviations: BFC, Barren Fork Creek; ER, electrical resistivity; ERI, electrical resistivity imaging; FC, Flint Creek; HC, Honey Creek; K_{sat}, saturated hydraulic conductivity; PFP, preferential flow pathway.

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(P), and consequently P was transported several meters through the subsurface gravel. However, investigations examining the heterogeneity of the vadose zone are limited relative to the saturated zone by the fact that pumping and tracer tests, which depend on groundwater movement, are impossible. Those studies must utilize other methods, including particle size analysis (Nimmo et al., 2004; Dann et al., 2009), air permeability (Dixon and Nichols, 2005; Chief et al., 2008) and permeameter testing (Xiang et al., 1997; Reynolds, 2010; Miller et al., 2011). When the vadose zone is dominated by coarse gravel such efforts are made more difficult by the problems associated with sampling in gravel: large particles resist penetration by and clog samplers, excavated pits are prone to collapse, and high hydraulic conductivity rates require large volumes of water for in situ permeameter testing.

Most applications of borehole permeameter methods involve fine grained soils that allow hand-augering of test holes and which only require a small water reservoir to maintain a constant head. However, in non-cohesive gravels, test holes are difficult to excavate by hand, unsupported holes are prone to collapse, and large volumes of water are necessary to maintain a constant head for the duration of a hydraulic test. To overcome the difficulties presented by coarse alluvial gravels, Miller et al. (2011) designed a steel permeameter that used a direct-push drilling machine to place a slotted-pipe at a specific sampling depth and a 3790 L (1000 gal) trailer-mounted water tank to maintain constant head conditions. A standard 48 by 3.25 in (1.22 by 0.082 m) section of Geoprobe Systems (Kejr Inc., Salina, KS) direct push pipe, with a 0.3 in (7.9 mm) wall thickness, was modified to create a screen by cutting 27 vertical slots 0.002 m (0.07 in.) wide by 0.203 m (8 in.) long arranged in three groups around the pipe perimeter and separated by solid (unslotted) areas. With this method, measurements can be made at successive depths at the same test location (Miller et al., 2011; Fox et al., 2012).

However, borehole permeameters quantify the soil hydraulics via hydraulic conductivity at a point scale with significant effort in gravel soils. A broad-scale non-invasive survey technique to investigate the subsurface would potentially allow rapid and broad spatial scale estimation at potentially fine spatial resolutions of vadose zone heterogeneity, compared to other point scale techniques which provide only local estimates of hydraulic properties (Bohling et al., 2007). The point-scale techniques can be used to ground-truth the broad-scale survey. Hydraulic tomography is commonly used for hydrogeologic characterization but requires the use of multiple pump tests to produce a series of pressure excitation/response data valid for saturated subsoils (Cardiff et al., 2009; Alexander et al., 2011; Berg and Illman, 2011).

Electrical resistivity imaging (ERI) is a rapid, non-invasive geophysical method that investigates the shallow subsurface by measuring how the materials affect a current of known amperage passing from one electrode to another through the ground (Telford et al., 1990; Herman, 2001; Milsom, 2003; Burger et al., 2006; Slater, 2007). A collinear array of multiple electrodes produces a dataset consisting of apparent resistivities at depths determined by the geometry of the electrode configuration (Herman, 2001). Mathematical inversion of the "apparent resistivity" creates a two dimensional (distance and depth) model of the resistivity of the earth material (Loke and Dahlin, 2002; Halihan et al., 2005; Slater, 2007). The resistivity of earth materials is non-unique, with many different materials having similar and overlapping resistivities (Zohdy et al., 1974; Burger et al., 2006), and interpreting the geology of subsurface resistivity patterns requires independent evidence, such as site stratigraphy, *in situ* or laboratory testing, or core samples.

ERI has been used to map floodplain fluvial sediments (Baines et al., 2002; Bersezio et al., 2007; Crook et al., 2008; Tye et al., 2011; and Ward et al., 2012), to detect gravel for commercial gravel prospecting (Auton, 1992; Beresnev et al., 2002), for geologic investigation of glacial deposits (Smith and Sjogren, 2006), for mapping buried paleochannels (Gourry et al., 2003; Green et al., 2005), and for imaging hyporheic zone solute transport (Ward et al., 2010; Menichino et al., 2012). Anterrieu et al. (2010) found that two-dimensional ER profiles of a mining waste-rock pile correlated well with a model created from independently acquired data including cores, particle size distributions, and other geophysical surveys. ER techniques have also been applied to estimating the rock particle content of coarse, heterogeneous soils where the rock fragments are dispersed within a fine soil matrix (Huntley, 1986; Rey et al., 2006; Rey and Jongmans, 2007; Tetegan et al., 2012). These studies have shown that ERI can be used to detect gravel in contrast to other fine-grained sediment; thus the method has potential to reveal heterogeneity within the gravel of the floodplain vadose zone of the study sites.

Gravel soils tend to have high hydraulic conductivities and high resistivities, as well as the tendency to drain and achieve field capacity quickly (Lesmes and Friedman, 2005). Recent work has advanced understanding of gravel soils by modeling them as binary systems consisting of mixtures of coarse and fine elements where the particle size of the fine fraction is smaller than the pore size of the coarse fraction, and the coarse particles have no secondary porosity (Koltermann and Gorelick, 1995; Zhang et al., 2011). In those models, a "coarse porosity" maximum (ϕ_c) exists when the fine fraction is zero and the entire soil consists of self-supporting coarse sediment with large, open pores resulting in high electrical resistivity and high hydraulic conductivity, and a fine porosity maximum (ϕ_f) exists when the soil mixture contains only the fine fraction leading to a low electrical resistivity and low hydraulic conductivity (Kamann et al., 2007) (Fig. 1). A porosity minimum (ϕ_{min}) exists within the binary model when the coarse fraction is self-supporting (particles resting on one another), but the pore spaces produced by the coarse particles are entirely occupied by the fine fraction. In this condition, the only open pores exist within the fine fraction, and the coarse fraction behaves as pore-free inclusions within a fine matrix effectively reducing the overall porosity. Constant-head flow tests on coarse/fine mixtures suggest that K_{sat} increases rapidly when the fine content decreases past the porosity minimum, and thus the fines content of gravel-dominated soils have a controlling effect on its hydraulic behavior (Koltermann and Gorelick, 1995; Kamann et al., 2007; Zhang et al., 2011). Alyamani and Sen (1993) have similarly acknowledged the role of fine particles in controlling hydraulic conductivity equation of sand aquifers by including the d_{10} and I_0 in their particle size distribution-based empirical hydraulic conductivity equation. Thus, for the special case of coarse vadose zone sediments, a saturated hydraulic conductivity/resistivity relationship may exist that does not rely on formation factor F and soil-water sampling.

The empirical relationship presented by Archie (1942), often referred to as "Archie's Law", represented a breakthrough in understanding the resistivity of fluid-saturated systems. A resistivity survey produces apparent resistivity values that "average" the resistivity of the entire path traveled by the current. This is problematic in the porous subsurface regions where the travel path may be complex and include one or more fluids and the current may travel preferentially through only one of the phases. Archie's Law considers the solid particles to be insulators and the current to be carried exclusively by the saturating fluid, and that the resistivity of the solid particles is proportional to the ratio of the bulk resistivity and the resistivity of the fluid. Clay mineral particles are surrounded by an electrical double layer composed of cations that is capable of conducting electrical current, and thus Archie's assumption of insulating particles is valid when clay minerals are absent.

While testing the electrical properties of pore fluid can be relatively straightforward in saturated systems, it is less so in the