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Evaluating local-scale anisotropy and heterogeneity along a fractured sedimentary bedrock river using EM azimuthal resistivity and ground-penetrating radar

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ABSTRACT

Fractured sedimentary bedrock rivers exhibit complicated flow patterns controlled by the geometry, extent and connectivity of fractures and dissolution-enhanced conduits. In a bedrock river environment these features variably connect surface water to groundwater. Given the nature of discrete fracture and conduit networks, these flow systems can be anisotropic and heterogeneous over a wide range of scales. Portable and non-invasive geophysical methods are ideal for the initial characterization of shallow hydrogeologic systems in ecologically sensitive environments. Here, we evaluate the utility of the electromagnetic (EM) azimuthal resistivity method for characterizing shallow vertical and subvertical fracture set orientations in the presence of localized dissolution-enhanced features near a sedimentary bedrock river located in Southern Ontario, Canada. Multiple EM coil spacings ranging from 1 to 10 m in vertical and horizontal dipole modes were applied at two locations within a 10 × 25 m study plot; azimuthal rotations were conducted using symmetric and asymmetric geometries. The observed anisotropic response was evaluated using 100 MHz ground-penetrating radar (GPR) measurements collected across the study plot area. A joint analysis of EM and GPR data revealed that fracture-based anisotropy can be identified in the presence of local heterogeneities (i.e., dissolution-enhanced features) at scales considerably smaller than those of previous studies. These non-invasive geophysical data sets can be used to optimize the design of multi-borehole groundwater monitoring stations along bedrock river channels, such that angled boreholes could be emplaced and orientated to intercept major fracture networks and local dissolution features. These data could also improve 3-D fracture network conceptualizations utilizing discrete information from angled and vertical boreholes.

1. Introduction

Portable and non-invasive geophysical methods can provide valuable insight into hydrologic processes in ecologically-sensitive environments. Given the dynamic, complex and interdependent nature of these ecohydrological systems, critical interfaces where groundwater interacts with surface water, such as the hyporheic zone, are more likely to be impacted by groundwater pumping, surface water withdrawal, and contamination (Winter et al., 1998). While the importance of hyporheic processes has been extensively examined (e.g., Vannote et al., 1980; Meyer, 1997; Woessner, 2000), recent advances in geophysical sensors, portable drills, and depth-discrete multilevel monitoring systems have enabled the collection of higher-resolution information with reduced impact to surrounding ecosystems (e.g., Conant et al., 2004; Hatch et al., 2006; Schmidt et al., 2007; Gabrielli and McDonnell, 2011; Ward et al., 2012). These developments have improved our capacity to study dynamic processes.

A river's inherent sensitivity to anthropogenic impacts makes minimally-invasive geophysical methods well-suited for conceptualization of complex hydrogeologic systems. While the application of geophysical methods for enhanced hydrologic process characterization in alluvial rivers has received reasonable attention (e.g., Birkhead et al., 1996; Crook et al., 2008; Ward et al., 2010; Musgrave and Binley, 2011; Wojnar et al., 2013), there has been very limited studies of rivers that flow directly along a fractured sedimentary bedrock surface (e.g., Oxtobee and Novakowski, 2002). By definition, a bedrock river flows directly on an exposed bedrock streambed, without the attenuative effects of sand or sediment overburden. Because bedrock rivers are more challenging to instrument (Tinker and Wohl, 1998b), our hydrogeologic understanding of fractured rock riverbeds has become biased toward alluvial river conceptual models (Woessner, 1998; Winter et al., 1998).

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The majority of bedrock river studies focus on fluvial geomorphological processes in the bedrock channel (e.g., Tinker and Wohl, 1998a; Hodge et al., 2011) and comparisons between alluvial and bedrock constrained multi-channel river networks (Meshkova and Carling, 2013). Oxtobee and Novakowski (2002) conducted a comprehensive field investigation of a bedrock creek using geographical, hydrological and geochemical data to evaluate groundwater–surface water interaction between Twenty Mile Creek and the local aquifer near Smithville, ON, Canada. They concluded that the interaction between the river and aquifer was limited with >95% of the groundwater underflowing the creek during baseflow condition. Within their study area, the absence of strong vertical fracturing limited groundwater exchange in the vicinity of the creek.

Given the importance of bedrock rivers to groundwater supply and the potential threats to surrounding ecological environments, there is an intrinsic need to develop integrated investigative field applications capable of providing high-resolution spatial information about the fracture and dissolution-enhanced conduit networks beneath these riverbeds (Hancock, 2002). Non-invasive geophysical data could inform localized hydrogeologic observations, and collectively advance our static and dynamic conceptual understanding of flow and transport along discrete fracture networks which variably connect groundwater to surface water.

The Eramosa River, in Ontario, Canada, exhibits a bedrock river environment where the utility of portable geophysical methodologies can be tested, along with the capacity to detect shallow fracture networks. This river flows along a variably exposed, highly-fractured and fragmented Silurian dolostone floodplain with abundant karst features visible at the surface (Kunert et al., 1998). Groundwater and surface water interaction is hypothesized to occur through discrete vertical fractures and dissolution-enhanced conduits (e.g., Steelman et al., 2015); the distribution and extent of these flow paths is expected to vary with depth and along the reach of the river. Effective conceptualization of dynamic hyporheic zone processes requires direct measurement of groundwater and surface water conditions; however, optimized emplacement of groundwater monitoring stations in a fractured sedimentary bedrock river requires prior knowledge of shallow fracture networks and suspected karst features at depth. Non-invasive geophysical information could be used to locate and design a distribution of groundwater monitoring stations.

The objective of this study is to assess the capacity of the azimuthal electromagnetic (EM) resistivity method for the detection of local-scale vertical and subvertical fractures and features possibly affecting groundwater–surface water exchange along a sedimentary bedrock river. To achieve this, a series of azimuthal resistivity surveys were conducted at two stations located within a 10 × 25 m intensive study plot. The azimuthal measurements were assessed using full-resolution ground-penetrating radar (GPR) measurements using 100 MHz antennas to support interpretation of fracture sets and possible dissolution features or heterogeneities impacting the anisotropic response.

2. Background

2.1. Fracture networks and dissolution features along sedimentary bedrock rivers

Surface and subsurface connectivity along rivers that flow directly on sedimentary bedrock surfaces with exposed vertical fracture networks will exhibit very complicated flow patterns relative to their alluvial counterparts largely due to the nature of their effective porosities (i.e., interconnected pores vs. discrete fracture networks) (Tinker and Wohl, 1998b). Consequently, bedrock rivers can be anisotropic and heterogeneous over a wide range of spatial scales (Fig. 1). Primary fracture orientation, spacing, aperture, length and connectivity can vary over tens (local) to thousands (regional) of meters. This extreme variation in contributing factors often results in anisotropic and heterogeneous flow patterns, which may be influenced by dissolution processes. Integrated geophysical applications yielding high-resolution spatial information about the fracture geometry, distribution, frequency and intensity can improve conceptualizations of hydrogeologic flow systems across larger spatial scales, thereby advancing our understanding of shallow hydrologic processes along bedrock riverbeds.

The primary interaction of groundwater and surface water along a sedimentary rock riverbed will be controlled by fractures and conduits connecting the rockbed interface to subsurface hydrostratigraphic units. Geophysical research on shallow bedrock flow systems has focused on the characterization of major dissolution features and structures, such as epikarst, caverns, and sinkholes (e.g., Batayneh et al., 2002; Al-fares et al., 2002; Kruse et al., 2006), and local-to-regional scale fracture characteristics (e.g., Taylor and Fleming, 1988; Lane et al., 1995; Busby, 2000). More recently, Skinner and Heinson (2004) developed a set of borehole-to-surface direct current and electromagnetic induction methods to delineate laterally extensive preferential hydraulic pathways in a shallow fractured bedrock environment. Using the azimuthal resistivity method, which detects directional changes in apparent horizontal electrical conductivity, they were able to identify the azimuth of maximum hydraulic connectivity along vertical and sub-vertical conduits. Although the authors noted the presence of inhomogeneities in the rock, and expressed the potential impact on the interpretation of homogeneous fracture anisotropy, they did not examine the nature of the inhomogeneities and their relationship to the local-scale fracture network.

Although regional-scale fracture properties may be useful for large-scale conceptual models (Taylor and Fleming, 1988; Busby, 2000), these data sets are of limited value in the evaluation of local-scale processes, such as water interactions at the hyporheic interface. The high-resolution detail of field-based spatial representations of vertical fracture networks, bedding plane geometries and localized dissolution-enhanced conduits is fundamental to the conceptualization of fracture-flow in close proximity to the bedrock riverbed interface. The identification of heterogeneous anisotropy, caused by the presence of isolated flow features in a fractured system, can provide valuable insights about potential preferential pathways.

Given the success of previous electrical investigations on the detection of anisotropy in heterogeneous environments (e.g., Slater et al., 1998; Watson and Barker, 1999; Skinner and Heinson, 2004; Watson and Barker, 2005; Watson and Barker, 2010; Yeboah-Forson and Whitman, 2014) we have applied the EM azimuthal resistivity method to the conceptualization of vertical fracture networks in a shallow bedrock river environment. However, unlike previous studies we have applied multiple coil spacings, magnetic dipole orientations, and survey configurations over an intensive 250 m^2 study area to characterize horizontal fracture anisotropy, while also evaluating the influence of local-scale inhomogeneities (e.g., cavities, dissolution-enhanced features) on the anisotropic signal.

2.2. Utility of azimuthal resistivity method

The electrical resistivity of fractured bedrock composed of vertical or subvertical joint sets with a preferred orientation will vary depending on the direction of the applied electrical current (Habberjam, 1975; Taylor and Fleming, 1988). Measured apparent electrical resistivity will be highest when the current flows parallel to the dominant fracture sets and lowest when the current flows orthogonal to the fracture sets. This so-called paradox of anisotropy can be explained by an increase in the density of the injected or induced electric current that is forced to flow along the strike of the anisotropy (Wasscher, 1961; Al-Garni and Everett, 2003).

For decades researchers have been advancing the application of the azimuthal resistivity method to jointed bedrock systems to better understand hydraulic transmissivity (e.g., Ritzi and Andolsek, 1992), hydraulic connectivity (e.g., Skinner and Heinson, 2004; Abdullahi and