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Groundwater flows in weathered crystalline rocks: Impact of piezometric variations and depth-dependent fracture connectivity

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SUMMARY

Groundwater in shallow weathered and fractured crystalline rock aquifers is often the only perennial water resource, especially in semi-arid region such as Southern India. Understanding groundwater flows in such a context is of prime importance for sustainable aquifer management. Here, we describe a detailed study of fracture properties and relate the hydraulic connectivity of fractures to groundwater flows at local and watershed scales. Investigations were carried out at a dedicated Experimental Hydrogeological Park in Andhra Pradesh (Southern India) where a large network of observation boreholes has been set up. Twenty-height boreholes have been drilled in a small area of about 18,000 m^2 in which borehole loggings and hydraulic tests were carried out to locate the main flowing fractured zones and investigate fractures connectivity. Several hydraulic tests (nineteen slug tests and three pumping tests) performed under two water level conditions revealed contrasting behavior. Under high water level conditions, the interface including the bottom of the saprolite and the first flowing fractured zone in the upper part of the granite controls groundwater flows at the watershed-scale. Under low water level conditions, the aquifer is characterized by lateral compartmentalization due to a decrease in the number of flowing fractures with depth. Depending on the water level conditions, the aquifer shifts from a watershed flow system to independent local flow systems. A conceptual groundwater flow model, which includes depth-dependent fracture connectivity, is proposed to illustrate this contrasting hydrological behavior. Implications for watershed hydrology, groundwater chemistry and aquifer vulnerability are also discussed.

1. Introduction

Groundwater in weathered and fractured crystalline aquifers constitutes the only available water resource in many areas, especially in arid and semi-arid regions (Gustafson and Krásný, 1994). In Southern India, since the Green Revolution of the 70s, the overexploitation of groundwater resources for agriculture, particularly to irrigate rice crops, has led to water table depletion (Shah et al., 2003; Maréchal et al., 2006; Reddy et al., 2009; Dewandel et al., 2010; Maréchal, 2010; Perrin et al., 2011a), and the deterioration of groundwater quality, especially fluoride contamination (Ayoob and Gupta, 2006; Perrin et al., 2011b; Pettenati et al., 2013). Understanding groundwater flows and transport processes in such a context is therefore of prime importance to reach a sustainable management of groundwater resources.

Fractured crystalline aquifers composed mainly of metamorphic and igneous rocks are subject to weathering processes, especially chemical weathering that leads to a typical profile with variable hydraulic conductivity and porosity (Larsson, 1984; Foster, 1984; Jones, 1985; Acworth, 1987; Houston and Lewis, 1988; Wright, 1992; Anand and Paine, 2002; Dewandel et al., 2006). Several studies have focused on the hydraulic properties of such systems and hydrogeological conceptual models have been proposed

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that include from top to bottom: weathered rock including the saprolite, fractured rock and fresh or un-fractured rock (Larsson, 1984; Chilton and Foster, 1995; Taylor and Howard, 2000; Maréchal et al., 2004; Wyns et al., 2004; Dewandel et al., 2006; Banks et al., 2009). Groundwater flow in such media is localized in a small part of the rock volume and is mainly controlled by fracture connectivity (National Research Council, 1996; Paillet, 1998; Day-Lewis et al., 2000; Le Borgne et al., 2006). Connectivity is dependent on the geometrical properties of the fracture network, i.e. the distribution of fracture lengths, fracture orientations as well as fracture density (Bour and Davy, 1998; de Dreuzy et al., 2001). Unfortunately, these geometrical properties are often difficult to estimate in the field, especially on a large-scale, since large amounts of data are required (National Research Council, 1996). An alternative approach consists of using a continuum approach (Courtois et al., 2010; Dewandel et al., 2012) to simplify these complex systems and upscale the hydraulic parameters. However, such continuum approaches usually assume that the system is relatively well-connected, at least on a large enough scale, to allow the point to point measurements of hydraulic properties to be regionalized.

In a relatively stable tectonic context like Southern India, fractures are mainly dilating fractures or joints (mode 1 opening-mode) (National Research Council, 1996) which in general provide permeability for groundwater flow. Near horizontal dilating fractures at shallow depths are commonly known as sheeting joints or exfoliation joints in intrusive igneous rocks such as granite (Dale, 1923; Twidale, 1973; Bahat et al., 1999). One particularity of these fractures is their development parallel to the surface of the plutonic body. From a structural point of view, it is generally acknowledged that fracture frequency decreases with depth in the first hundred meters below ground surface (Dale, 1923; Twidale, 1973). Several authors (Howard et al., 1992; Briz-Kishore, 1993; Dewandel et al., 2006) reported that the main flowing fractured zone is located in the upper part of the bedrock, just below the saprolite. Since fracture density is expected to decrease with depth (Maréchal et al., 2004; Dewandel et al., 2006), fracture connectivity should play an important role in groundwater flow, and may control fluxes at the watershed scale, at least at a given depth. However, the relationship between the geometrical specificities of fractures and groundwater flows at local and watershed scales, especially at depth, is not clearly understood.

Here, we describe a detailed study of geometrical and hydraulic properties of fractures that was carried out at different depths and on different scales to improve the conceptual model of groundwater flow in weathered crystalline aquifers at the site scale. This study took advantage of the Experimental Hydrogeological Park in Southern India where a set of observation boreholes have been drilled for scientific purposes. Several hydrogeological experiments at borehole and aquifer scales and under different hydrological conditions were done to estimate the hydraulic properties and main flow paths on the site. Finally, the implications of these results are discussed at watershed scale to investigate the consequences of fracture connectivity on watershed hydrogeology.

2. Hydrogeological context

2.1. Geological setting

The Experimental Hydrogeological Park (EHP) is situated near Choutuppal village in the Nalgonda district (Andhra Pradesh State, Southern India) 60 km to the south-east of Hyderabad (Latitude: 17°17′47″N; Longitude: 78°55′12″E) (Fig. 1). The EHP was developed by the French Geological Survey (BRGM) and the National Geophysical Research Institute (NGRI) on the campus of NGRI in Choutuppal. The site is included in the SOERE H + International hydrogeological sites network. The EHP is covered by sparse vegetation and characterized by a gentle slope towards the northeast of around 2%. The ground surface elevation measured at the center of EHP is about 365.5 meters above mean sea level. Numerous farmlands, including rice fields, with pumping boreholes belonging to farmers, are present around the EHP.

About 66% of the Andhra Pradesh State is composed of an Archean granitic and gneissic complex (Fig. 2). Locally, these formations may be intruded by dolerite dykes or quartz reefs (G.S.I., 1999, 2005; Perrin et al., 2011a; Dewandel et al., 2011). From a geomorphological viewpoint, the Nalgonda district is a gently undulating region with hummocky hills, boulders, ridges and inselbergs. The fracturing of granite is mainly characterized by dilating fractures. This kind of fracture displays specific characteristics and detailed descriptions of other sites in the world are given in Dale (1923), Jahns (1943), Twidale (1973), Bahat et al. (1999), Vidal Romaní and Twidale (1999), Hencher et al. (2011). It is generally accepted that dilating fracture can be slightly curved but are mostly horizontal, developing sub-parallel to the rock surface. Their spacing increases with depth from a few centimeters near the surface to a few meters, typically one to ten meters (Dale, 1923; Jahns, 1943). They can develop at up to one hundred meters depth (Jahns, 1943), and can display a lateral extension of more than one hundred meters (Hencher et al., 2011). These fractures may end in the fresh rock or by crossing other pre-existing fractures (Hencher et al., 2011). A few sub-vertical dilatant fractures can also be observed on several outcrops around EHP. Such outcrops which are relatively numerous and scattered over the watershed, can constitute isolated boulders extending into the saprolite or the granite surface. No evidence of faulting or tectonic activity has been observed in the area. The fracture orientations can be grouped into three families (Pira, 2009): N55-75, N130-155 and N165-175. Nevertheless, it remains difficult to relate or extrapolate such fracture orientations to bedrock fractures at depth.

The EHP consists of twenty-height boreholes of different depths (Table 1). The thickness of the saprolite, according to the information obtained from drilling, varies between thirteen to twenty-four meters. Note that some relatively fresh and very poorly fractured granite may be observed in few places within EHP. However, no boreholes have been drilled in these places. Six boreholes have been drilled into the saprolite (CH3-L, CH10-L, CH21, CH22, CH23 and CH24) at specific depths, not exceeding seventeen meters. Two boreholes cross cut the saprolite and the first eight meters of granite at about twenty-three meters depth (CH3-S and CH10-S). The other boreholes stop at fifty or seventy meters from the ground surface. All boreholes have been equipped with a plain casing extending into the saprolite. All of them were screened or open in front of the contact zone between the saprolite and fractured granite. Below the contact zone, all boreholes were uncased (i.e., open hole). Four boreholes into the saprolite (CH21 to CH24) were also uncased from the last two meters to allow specific experiments within the vadose zone. The boreholes configuration was chosen to allow characterizations focused on the lateral hydraulic connectivity of fractures.

The typical geological profile obtained in the EHP by drilling cuttings analysis, follows the lithological description by Dewandel et al. (2006) which from top to bottom consists of:

- Red soil from the first decimeters to the first meter: rich in iron and/or aluminum oxides.
- Sandy regolith from about 1–3 m deep: yellowish color, sandy-clay composition, sandy texture with a lot of quartz grains.
- Saprolite from about 3 to 13–24 m deep, derived from in situ weathering of granite: yellowish to brownish color, coarse sand-size clasts texture and laminated structure. This horizon exhibits preserved fractures.