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Research papers

Borehole characterization of hydraulic properties and groundwater flow in a crystalline fractured aquifer of a headwater mountain watershed, Laramie Range, Wyoming

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ABSTRACT

Fractured crystalline aquifers of mountain watersheds may host a significant portion of the world's freshwater supply. To effectively utilize water resources in these environments, it is important to understand the hydraulic properties, groundwater storage, and flow processes in crystalline aquifers and field-derived insights are critically needed. Based on borehole hydraulic characterization and monitoring data, this study inferred hydraulic properties and groundwater flow of a crystalline fractured aquifer in Laramie Range, Wyoming. At three open holes completed in a fractured granite aquifer, both slug tests and FLUTe liner profiling were performed to obtain estimates of horizontal hydraulic conductivity (K_h). Televiewer (i.e., optical and acoustic) and flowmeter logs were then jointly interpreted to identify the number of flowing fractures and fracture zones. Based on these data, hydraulic apertures were obtained for each borehole. Average groundwater velocity was then computed using K_h, aperture, and water level monitoring data. Finally, based on all available data, including cores, borehole logs, LIDAR topography, and a seismic P-wave velocity model, a three dimensional geological model of the site was built. In this fractured aquifer, (1) borehole K_h varies over ~4 orders of magnitude (10^{-8}–10^{-5} m/s). K_h is consistently higher near the top of the bedrock that is interpreted as the weathering front. Using a cutoff K_h of 10^{-10} m/s, the hydraulically significant zone extends to ~40–53 m depth. (2) FLUTe-estimated hydraulic apertures of fractures vary over 1 order of magnitude, and at each borehole, the average hydraulic aperture by FLUTe is very close to that obtained from slug tests. Thus, slug test can be used to provide a reliable estimate of the average fracture hydraulic aperture. (3) Estimated average effective fracture porosity is 4.0×10^{-4}, therefore this fractured aquifer can host significant quantity of water. (4) Natural groundwater velocity is estimated to range from 0.4 to 81.0 m/day, implying rapid pathways of fracture flow. (5) The average ambient water table position follows the boundary between saprolite and fractured bedrock. Groundwater flow at the site appears topography driven.

1. Introduction

A significant portion of the world's population relies on rivers that are sourced from fractured aquifers in mountain regions. In the western USA, alpine watersheds supply both surface water and groundwater to meet the water demands of over 60 million people (Barnett et al., 2005; Bales et al., 2006). In many parts of the world, especially in semi-arid to arid regions such as in India and Africa, groundwater in crystalline aquifers is the only source of drinking water (Gustafson and Krásný, 1994; Guihéneuf et al., 2014). To appropriately manage such resources, particularly in view of the projected warming in mountain environments compared to low lying regions (Pepin et al., 2015), new hydrological knowledge about groundwater in mountain crystalline aquifers is required. However, groundwater storage and flow in most mountain environments are poorly known (Tague and Grant, 2009; Kurylyk and Hayashi, 2017). Mountain watersheds, which often consist of granitic or metamorphic rocks, are characterized with rough terrains that are difficult to access. Mountains are often sparsely populated, thus few groundwater monitoring wells exist from which long term water level or characterization data can be obtained. Surficial soil or vegetation covers in these environments are often thin or absent, giving rise to the perception that mountains are impervious to flow and thus have minimum storage for groundwater (Hood and Hayashi, 2015). However, groundwater flow and storage in alpine watersheds can constitute

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a significant portion of the annual water budget, as demonstrated by Hood and Hayashi (2015). As water demands increase in the future, mountain environments, similar to the downstream regions, may become increasingly vulnerable to contamination.

This research aims to characterize a fractured crystalline aquifer in a headwater mountain watershed in Wyoming to understand both groundwater storage and groundwater flow. Results of this study will provide parameters for developing hydrological models to capture the properties and processes in the future. To quantify both groundwater storage and flow in a crystalline fractured aquifer, hydraulic aperture of fractures is a critical parameter to determine. On the one hand, the aperture provides information on fracture porosity and groundwater storage. On the other hand, the aperture can be used to calculate an average linear velocity that indicates the speed of groundwater flow through fractures. In order to obtain an estimate of the aperture, two parameters of the aquifer are often characterized: transmissivity or hydraulic conductivity of the aquifer, and the number of hydraulically active fractures.

Many hydraulic testing methods exist that can be used to obtain transmissivity or hydraulic conductivity of a fractured aquifer. Pumping tests, which are the most common method used in the field to interrogate large scale aquifer properties, can give an average horizontal hydraulic conductivity (K_h) estimates over the entire producing zones of an aquifer (several tens of meters). Slug tests, by modeling water level response in a well due to rapid submergence and subsequently removal of a solid slug, can provide K_h estimate in the vicinity of the test well. Liquid slugs (i.e., addition/removal of fluid) can also be used to provide K_h estimates. Most commonly used analytical solutions for slug tests are (1) Hvorslev (1951) semi-log plot method for partial or fully penetrating wells in homogeneous confined or unconfined aquifers with negligible aquifer storativity, (2) Cooper et al. (1967) curve fitting method for fully penetrating wells in homogeneous confined aquifers, and (3) Bouwer and Rice (1976) method for completely or partially penetrating wells in homogeneous unconfined aquifers screened below the water table. All these methods are originally developed for homogeneous porous media. Shapiro and Hsieh (1998) compared the results of slug tests in fractured rock interpreted with a homogeneous (i.e., Cooper et al. (1967) solution) and a heterogeneous model. They found that the transmissivity estimated from both models are within one order of magnitude, thus equivalent transmissivity can be obtained from slug test results for strongly heterogeneous media. However, slug tests results can be skewed by non-ideal conditions in and adjacent to the wellbore. If a low permeability (positive) skin exists in a wellbore, both the Hvorslev (1951) and Bouwer and Rice (1976) methods are more likely to yield hydraulic conductivity estimates of the well-skin rather than that of the actual aquifer (Hyder et al., 1994; Hyder and Butler, 1995). As pointed out by Butler et al. (1996), the existence and nature of skin effects should be evaluated during the interpretation of slug tests.

Both the pumping and standard slug test (without packer system) methods, though commonly employed in the field, cannot resolve aquifer heterogeneity in the vertical direction. When vertical resolution of aquifer heterogeneity is required, high-resolution hydraulic testing methods are needed. For example, inflatable packers can be used to isolate one or more sections of a borehole for water injection or withdrawal during a well test (e.g., Cook, 2003; Quinn et al., 2012). Multilevel slug test is implemented by making use of a double-packer system to determine a series of K_h estimates for discrete depths in a well (e.g., Zlotnik and McGuire, 1998; Zlotnik and Zurbuchen, 2003; Zemansky and McElwee, 2005), while a dipole flow test is conducted by using a triple-packer system with a pump submerged in between two lower packers (e.g., Zlotnik et al., 2001). Other commonly used high-resolution borehole hydraulic methods include borehole flowmeter logging (e.g., Molz et al., 1989; Paillet, 1998; Paradis et al., 2011), direct push permeameter (e.g., Butler et al., 2007), and FLUTe liner profiling (e.g., Keller et al., 2014). All the hydraulic testing methods, with the exception of the flowmeter logging, calls for the introduction or removal of a volume of water from the aquifer, which can pose issues at contaminated sites where contaminant mobilization and waste water disposal need to be minimized.

To determine the number of hydraulically active (i.e., flowing) fractures in a crystalline aquifer, borehole image logs and core logs can be used. However, large errors can arise in the interpretation of such logs. For example, micro-cracks are difficult to identify from borehole images, and core logs can contain drilling induced fractures that can be misidentified as formation fractures (Quinn et al., 2011a,b). Moreover, not all fractures identified are necessarily hydraulically active. For a fractured dolostone aquifer, Quinn et al. (2011a,b) proposed a method for identifying flowing fractures that naturally exist in the formations. They used constant-head step tests with increasing injection rates to determine a set of critical flow rates and critical Reynolds (Re_c) numbers when non-Darcian flow started to develop. Their method employs an iterative procedure by changing the assumed number of flowing fractures in each test interval until a high correlation coefficient between Re_c and calculated aperture was reached. However, their method was effective only under high flow rates that induce non-Darcian flow, while for Darcian flow regimes, the method is not applicable.

For a crystalline fractured aquifer in a headwater mountain watershed in Wyoming, this study aims to estimate both K_h and the number of hydraulically active fractures in order to obtain fracture aperture data. We conducted a detailed aquifer characterization study using borehole televiewer logs, flowmeter logs, and borehole hydraulic tests (specifically, slug tests and FLUTe blank liner profiling) on three boreholes that tap into this aquifer. Our research took place at the Blair Wallis Fractured Rock Hydrology Research Well Field, which lies in the Laramie Range in southeastern Wyoming, where nine bedrock wells have been drilled and completed at various depths. The three boreholes investigated cover a range of depth and fracture intensity at the site, and were thus selected for a focused hydraulic characterization study. By jointly interpreting results from all borehole tests, both transmissibility (T) and horizontal hydraulic conductivity (K_h) were obtained at different vertical resolutions. The number of flowing fractures for the same tested intervals were determined by jointly interpreting borehole televiewer (i.e., optical and acoustic) and impeller flowmeter logging under ambient flow conditions. Finally, hydraulic apertures at various vertical scales were determined, based on which fracture porosity and groundwater velocity under ambient flow condition were also estimated. The implications of our results at the well field are discussed at the watershed scale to infer the importance of bedrock groundwater in the mountain environment.

2. Study site

Most crystalline aquifers consist of three zones: an upper weathered zone, a middle fractured zone, and a lower and often less fractured zone (Krásný and Sharp, 2003). The Blair Wallis Fractured Granite Hydrology Research Well Field lies within the Crow Creek Watershed of the Laramie Range which lies within US Forest Service land about 21 km southeast of Laramie, Wyoming (Fig. 1(a) and (b)). Local climate data from the Crow Creek SNOTEL station of the last 10 years show that the Blair Wallis well field has a mean annual temperature of 5.4 °C and receives 620 mm of annual precipitation, of which 90% falls as snow (National Resources Conservation Service, 2015). During the summer season (June to September), average temperature is around 15 °C, while in the winter months (December to March), average temperature is around -5°C. The geology of the well field consists of fractured granite bedrock overlain by 10–18 m of weathered granite (saprolite). Based on jointly interpretation of both borehole televiewer logs and flowmeter logs at the site, bedrock flowing fracture intensity diminishes with depth. Based on water level monitoring data collected from the well field, the fractured bedrock is saturated with groundwater while the saprolite is either unsaturated or partially saturated. By examining