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# Large water-table response to rainfall in a shallow bedrock aquifer having minimal overburden cover

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ABSTRACT

Rapid recharge events manifested as significant increases in hydraulic head have been observed in many fractured bedrock aquifers around the world. Often the response in hydraulic head exceeds what would be observed in an equivalent porous media by more than an order of magnitude. As the mechanisms that cause these events are poorly understood particularly under highly-transient conditions, a detailed investigation was conducted at a well-characterized field site in eastern Canada. During the spring and summer of 2012, frequent measurements of hydraulic head were obtained in gneissic terrain covered by a thin veneer of drift materials using 21 multi-level monitoring wells installed in the bedrock. Each of the wells was hydraulically tested from the water table to total depth using a straddle-packer system and fractures intersecting the wells were identified using a borehole camera prior to the construction of the multi-level piezometers. Rainfall and weather data were also collected over the same time period. A piezometer located on a bedrock outcrop which responded rapidly to rainfall was identified and used as a focus for numerical simulations. To determine the properties of the drift materials in the vicinity of the outcrop, a ground penetrating radar (GPR) survey was conducted over a 40 × 40 m area to map depth to bedrock and five in-situ permeameter tests were performed to estimate the hydraulic conductivity. Three-dimensional numerical simulations were conducted to reproduce the response in the piezometer for both short (24 h) and long (one month) timescales. The numerical simulations were used to determine what parameters have the greatest impact on controlling rapid recharge. Based on this study it was concluded that the large magnitude head rises recorded in this piezometer are a result of recharge to steeply inclined fractures exposed on or immediately adjacent to the outcrop. The hydraulic head responds rapidly because of the low specific yield of the rock to which the transmissive features are connected. The modelling also showed that as little as 0.4 m of drift material can completely eliminate the response in the well especially during times when evapotranspiration is high.


## 1. Introduction

Groundwater recharge is typically a smaller percentage of annual rainfall for fractured bedrock aquifers compared to porous media settings. Recharge in fractured rock has been found to be range between 0.4% and 10% of average annual rainfall (Harte and Winter, 1995; Rodhe and Bockgård, 2006; Milloy, 2007; Gleeson et al., 2009; Croteau et al., 2010; Chesnaux, 2013) depending on the rock type and climate. These are compared to recharge rates of the order of 20%–40% of annual rainfall for porous media in similar climates (Fetter, 2001; Gerber and Howard, 2002).

Recharge in fractured rock is dependent on many factors such as overburden thickness and cover, the topography of the bedrock surface, fracture connectivity and aperture, fracture spacing, and the nature of the interface between the soil overburden and the fractures. Within a watershed these factors can vary significantly resulting in groundwater recharge that is highly spatially variable (Lee and Lee, 2000; Risser et al., 2009; Gleeson et al., 2009). Temporally, in a temperate climate, recharge is also dependent on the changes in abstractions that occur during the growing season, with evapotranspiration (ET) typically having the largest seasonal variability (Lafleur et al., 2005). Abbott et al. (2000) attributed groundwater recharge zones to areas where ET was much lower due to climate and elevation in a bedrock watershed in Vermont. Similarly, Gburek and Folmar (1999) recorded large spatial and temporal variability during the growing season using lysimeter

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measurements at a site in Pennsylvania where depth to bedrock is shallow (average 1.5 m of overburden). Notably, response in hydraulic head to rainfall in two wells located 49 m apart in that study were significantly different from one another, and the larger magnitude responses were attributed to differences in fracture hydraulic properties connecting the piezometers to the aquifer (Risser et al., 2009).

Large-magnitude rises in hydraulic head in response to rainfall have been recorded at a variety of fractured rock sites around the world (Gburek and Folmar, 1999; Rodhe and Bockgård, 2006; Milloy, 2007; Gleeson et al., 2009; Praamsma et al., 2009). In the Gburek and Folmar (1999) study discussed above, several meters of water table rise was observed over a few hours. Rodhe and Bockgård (2006) noted response in wells in a granite aquifer in central Sweden, overlain by 10 m of till that was observed to occur rapidly, and at a magnitude much greater than would be typically observed in porous media. Rapid large-magnitude response to rainfall events have been observed at a field site in Ontario, where rises in hydraulic head on the order of 1.0–3.0 m were recorded at one well over a few hours, while nearby, similarly-constructed wells responded with much smaller head rise of less than one 1.0 m (Milloy, 2007; Gleeson et al., 2009). In each of these cases, the response could be indicative of actual recharge (water table rise), or a hydraulic effect due to mechanical loading, air entrapment, or a combination of these (e.g. Weeks, 2002; Rodhe and Bockgård, 2006). At present the actual mechanism responsible for this process is unconfirmed and in order to properly model and predict recharge at the larger scale, the mechanism should be resolved.

The influence of overburden thickness on local recharge in fractured rock aquifers is also poorly understood (Gleeson et al., 2009). Kosugi et al. (2006) used soil and bedrock tensiometers to investigate flow between soil and shallow bedrock, and they noted that the soil on the bedrock moderated intensity of infiltration into the fractured bedrock. In a study conducted by Stothoff (1997) overburden thickness on fractured bedrock was modelled using an equivalent porous media approach for each unit over decade-long cycles in an arid environment. A one-dimensional semi-infinite, finite-element model was used to estimate average annual infiltration from a decade of hourly rainfall data. The results of this study strongly linked average annual recharge as a percentage of precipitation to overburden thickness. Recharge was found to vary significantly with small changes in overburden thickness. For instance, 0.02 m of overburden thickness yielded an annual recharge of 30% of annual precipitation. Increasing overburden thickness in the model to 0.25 m decreased recharge to less than 1% of annual precipitation (Stothoff, 1997). The study however neglected the transient effects of individual storm events and did not include the influence of two- or three-dimensional flow. Gleeson et al. (2009) used two-dimensional numerical modelling and the results of field measurements using isotopic tracer to determine the factors producing rapid recharge responses at a site in Ontario. The modelling in that study focused on a two-dimensional domain with limited vertical fracturing and no spatial variation in depth to bedrock within the model.

The purpose of this research is to explore the mechanisms behind rapid responses in hydraulic head using a three-dimensional numerical modelling study in conjunction with field measurement of recharge events. We also undertake to determine the most important parameters that generate these rapid head rises, and thereby better understand the mechanics of recharge to shallow fractured rock at the scale of an outcrop (ie approximately 10 m by 10 m). To conduct the study we collected detailed rainfall data and hydraulic head from 21 multi-level wells completed in a bedrock aquifer over a four km by eight km area. Numerical modelling was used to recreate recorded events and determine the factors controlling rapid recharge in this setting.

## 2. Field site

During the spring and summer of 2013, detailed measurements of hydraulic head were obtained from the Tay River Field site near Perth, Ontario (Fig. 1). This site has been hydraulically characterized in previous studies (Milloy, 2007; Gleeson et al., 2009; Praamsma et al., 2009; Trimper, 2010; Levison and Novakowski, 2012) to a high degree and there are 21 multi-level and open-hole piezometers distributed over a small area (four km by eight km). These piezometers have exhibited variable response to rainfall in years previous. The field site is located in the Tay River Watershed, which is a tributary of the Rideau river system in the Great Lakes drainage basin on the Canadian Shield. The watershed is 95 km long and approximately 800 km$^2$ in area. Average temperatures vary from 20 °C in the summer to −12 °C in the winter (Environment Canada, 2013). Average annual precipitation is between 850 and 975 mm in the region (RVCA, 2002). Annual precipitation in the area is distributed relatively uniformly throughout the year, according to averages compiled by Environment Canada over a 30 year period (Station 6104027 in Kemptville, ON.).

The majority of piezometers at the site are located in a hay field adjacent to the Tay River, with satellite wells located on the periphery (Fig. 1). The hay field is approximately 5.5 ha in size and 11 multi-level and open-hole piezometers are completed in this area, only some of which are used in this study. The topography of the hay field is flat, with elevations ranging from 157 to 152 masl. The crop grown in the hay field is perennial grass. There are several rock outcrops in the field and overburden thickness ranges from 0 to 4 m. The outcrop focused on in this study is located in the center of the field and contains wells TW03S and TW20. The bedrock is syenite-migmatite gneiss (Wilson, 1961), and the overburden is a thin glacial till consisting of a clayey sand (Levison and Novakowski, 2012).

Boreholes were drilled previously using air rotary percussion methods (0.152 m in diameter) and lithology was identified using chip samples (Milloy, 2007; Gleeson et al., 2009). Hydraulic testing was conducted in each of the boreholes using a straddle-packer system and slug, constant-head or pumping tests. Test zones below the water table were isolated using a packer system having test intervals ranging from 1.5 m to 3.0 m in length (Milloy, 2007; Praamsma et al., 2009). The testing was conducted to obtain hydraulic estimates contiguously from the water table to total depth in each borehole. Transmissivity and fracture aperture (equivalent single fracture) were estimated for each of these intervals (Milloy, 2007; Praamsma et al., 2009). A borehole camera was used to log the fracture features most likely to be open to groundwater flow. Boreholes were completed as multi-level piezometers based on the occurrence of high transmissivity zones and likely-to-be-open fracture features using 1.5 in. PVC slotted screens and PVC risers to surface (Milloy, 2007; Praamsma et al., 2009). Sand packs were placed around the screens and bentonite seals were used to isolate intervals. The barometric efficiency of the wells in the hay field was studied by Milloy (2007) and barometric efficiencies indicate a shallow unconfined aquifer.

Specific yield ($S_y$) is an important parameter for estimating recharge (Healy and Cook, 2002) and the range for the bedrock at this site was estimated by Milloy (2007) to be from $5.4 \times 10^{-4}(-)$ to $9.6 \times 10^{-4}(-)$ in the hay field area estimated by using vertical and sub-vertical fracture apertures. Values of $S_y$ were also estimated from pumping tests conducted in several wells on the site including TW20and were found to cluster around the lower end of this range and below (i.e. $\sim 1.0 \times 10^{-4}$). These values