Journal of Hydrology 376 (2009) 496–509

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Extremely rapid and localized recharge to a fractured rock aquifer

Tom Gleeson [a,*], Kent Novakowski [a], T. Kurt Kyser [b]

[a] Civil Engineering Department, Queen's University, Kingston, ON, Canada K7L 3N6
[b] Department of Geological Sciences and Geological Engineering, Queen's University, ON, Canada K7L 3N6

ARTICLE INFO

Article history:
Received 6 February 2009
Received in revised form 18 June 2009
Accepted 19 July 2009

This manuscript was handled by P. Baveye, Editor-in-Chief, with the assistance of Andrew Binley, Associate Editor

Keywords:
Recharge
Fractured rock
Numerical modeling
Stable isotopes
Water-table fluctuation
Snow melt

SUMMARY

The factors that govern recharge to fractured rock aquifers with overlying soil are poorly understood. The objective of this study is to determine if recharge to a fractured crystalline aquifer in a humid climate is governed by heterogeneous fracture networks and/or overlying soil characteristics. A 10 km^2 study area is instrumented with a network of 15 bedrock wells completed to observe conditions in the shallow bedrock aquifer. Hydrogeological characterization, detailed observation of the 2007 snowmelt freshet and numerical simulations are used. Snowmelt is a valuable natural tracer because it has a distinct thermal and isotopic signature and is applied simultaneously and evenly to the entire ground surface. Results indicate that soil thickness and bedrock transmissivity are both highly heterogeneous at the site scale but that much of the study area is underlain by silty sand with a thickness of >1 m. Cold, δ^2H depleted snowmelt locally recharged the bedrock aquifer to depths of at least 20 m within two days. Since recharge is typically quantified and discussed as an annual flux, the snowmelt event is extremely rapid. However, hydraulic, isotopic, and thermal data also indicate that most wells did not rapidly recharge. Numerical simulations indicate that soil thickness and hydraulic conductivity are critical parameters that controls whether the underlying bedrock aquifer rapidly recharges. The vertical fracture aperture, number of vertical fractures, the amount of snowmelt, water-table gradient, depth to water table and pressure–saturation relations are all less significant controls on the rate and amount of rapid recharge. Both field results and numerical simulations indicate that the rapid recharge process is localized to areas where the soil is very thin, such as the fringes of outcrops. Outcrops are exposed in <0.1% of the study area indicating that the process of rapid recharge is also extremely localized. This poorly documented hydrogeologic phenomenon has broad implications for groundwater management and protection, as well as our understanding of recharge processes in fractured rock aquifers.

Introduction

Recharge is a critical parameter for understanding, modeling and protecting groundwater systems from overexploitation and contamination (Lerner et al., 1990; Lerner, 1997; Scanlon et al., 2002). Recharge rates and patterns in fractured rock have been previously examined using groundwater ages, stable isotopes, numerical simulations and water-table responses (Cook et al., 1996, 2005; Lee et al., 1999; Abbott et al., 2000; Zanini et al., 2000; Cook and Robinson, 2002; Bockgard et al., 2004; Surrette, 2006; Praamsma et al., 2009a). Recharge studies in fractured rock are often complicated by preferential fracture flow paths, unknown vertical connections, matrix diffusion, uncertain specific yield and unpredictable hydraulic responses (Aeschbach-Hertig et al., 1998; Gburek and Folmar, 1999; Cook and Robinson, 2002; Scanlon et al., 2002). Local-scale recharge to fractured rock aquifers is affected by fracture aperture and connectivity, topographic features, overlying soil characteristics, soil–bedrock hydraulic conductivity contrasts, hydraulic gradients and the depth of the water table (Harte and Winter, 1996; Bockgard and Niemi, 2004) but the relative importance of these factors in different fractured rock settings is poorly understood.

Water tables rising rapidly and significantly during and after precipitation events have been observed at scattered fractured rock sites (Gburek and Folmar, 1999; Rodhe and Bockgard, 2006; Heppner et al., 2007; Milloy, 2007; Praamsma et al., 2009a). Multiple-meter water-table rises within hours of rain events have been documented in fractured sedimentary rocks overlain by 0.5–1.5 m of silty loam at a small research site in Pennsylvania (Gburek and Folmar, 1999; Risser et al., 2005; Heppner et al., 2007). Large water-table rises can reflect actual recharge (mass transfer across the water table) in an aquifer with low specific yield or be primarily a hydraulic response, possibly magnified by air entrapment during rapid recharge (Gburek and Folmar, 1999; Weeks, 2002). Without a precipitation tracer it is difficult to determine if a water-table rise is entirely attributable to actual recharge or is primarily a hydraulic response with little actual recharge. At a

* Corresponding author. Tel.: +1 (613) 533 2144.
E-mail address: tom@ce.queensu.ca (T. Gleeson).

0022-1694/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2009.07.056

crystalline rock site in Sweden overlain by thicker soils (10 m of till), the bedrock water table responds to precipitation but the rise is less then a meter (Rodhe and Bockgard, 2006). Rodhe and Bockgard (2006) interpret the water-table rise as primarily a hydraulic response to a weight increase in saturated soil during precipitation with a minor amount of actual recharge to the bedrock aquifer. Therefore previous studies suggest soil thickness may affect the recharge mechanism and rate in fractured rock aquifers. The heterogeneity of recharge patterns could not be evaluated at either of these sites due to the homogeneity of soil thickness, the limited study area and the small number of wells (Gburek and Folmar, 1999; Rodhe and Bockgard, 2006).

The objective of this study is to determine if recharge to a fractured crystalline aquifer at a local scale is controlled by heterogeneous fracture networks and/or overlying soil characteristics. Specifically, the role of soil thickness in controlling recharge processes is examined at a well characterized site with variable soil thickness. Additionally, natural tracers are observed to test whether rapid and significant water-table rises are due to actual recharge. Hydrogeologic and geophysical field work was used to characterize the bedrock aquifer and overlying soils. Detailed water table, groundwater temperature, groundwater δ^2H and meteorological data were collected during the 2007 snowmelt freshet. This well constrained recharge event was then numerically simulated to determine the hydrogeologic factors that govern the recharge processes in this setting.

Site description

This study focuses on the central part of the Tay River watershed in rural Eastern Ontario, Canada (Fig. 1). Elevations range from 150 to 190 m above sea level. The humid climate is characterized by an average annual precipitation of 0.95 m which is distributed relatively uniformly through out the year (30 years of data from Environment Canada Station 6104027 in Kemptville, ON augmented with 3 years of an onsite weather station). Typically 20% of the annual precipitation falls as snow. The 2007 snowmelt is described in see "Field methods".

In this topographically subdued catchment, a veneer of soil overlies two fractured rock aquifers: the Precambrian crystalline rock and the Paleozoic Nepean sandstone (Easton, 1992; Kettles, 1992). The Precambrian crystalline rocks are part of the Grenville Province of the Canadian Shield, and are a fracture-controlled aquifer with low permeability, storativity and primary porosity. Near the surface the most significant fractures in crystalline rocks are typically sub-horizontal sheeting fractures (Holzhausen, 1989; Sukhija et al., 2006). The geometric mean transmissivity from a regional-scale compilation of water well data ($n = 7875$) is 4.8×10^{-5} m^2/s (Singer et al., 2003). The overlying Nepean Sandstone occurs as an isolated sedimentary outlier at higher elevations in the study area, and is more permeable with a geometric mean transmissivity ($n = 7418$) of 2.3×10^{-4} m^2/s (Singer et al., 2003). Groundwater is primarily derived from shallow residential wells drilled into bedrock (Golder Associates Ltd., 2003). This study examines data from both the crystalline and sandstone aquifers. The veneer or blanket of soil is a sandy or silty diamicton (Kettles, 1992). Bedrock transmissivity and soil composition, hydraulic conductivity and thickness are examined in more detailed during this study.

Previous hydrogeological studies focused on a hay field adjacent to the Tay River (Milloy, 2007; Novakowski et al., 2007a; Levison and Novakowski, 2009; Praamsma et al., 2009a). The soil is drained (artificial interflow) by title drains that were installed in the hay field before previous hydrogeologic studies. A network of 11 bedrock monitoring wells with multi-level completions were constructed (TW1-11 in Fig. 1). A rain-gauge and climate stations were also installed. These studies indicated that discharge to the Tay River may be insignificant, that recharge can be localized and that the annual recharge rate may be very low. Predicting the location and quantifying the fluxes of recharge features remained elusive. In this study, we expand the well network to encompass ~10 km^2 in the central part of the watershed (Fig. 1B).

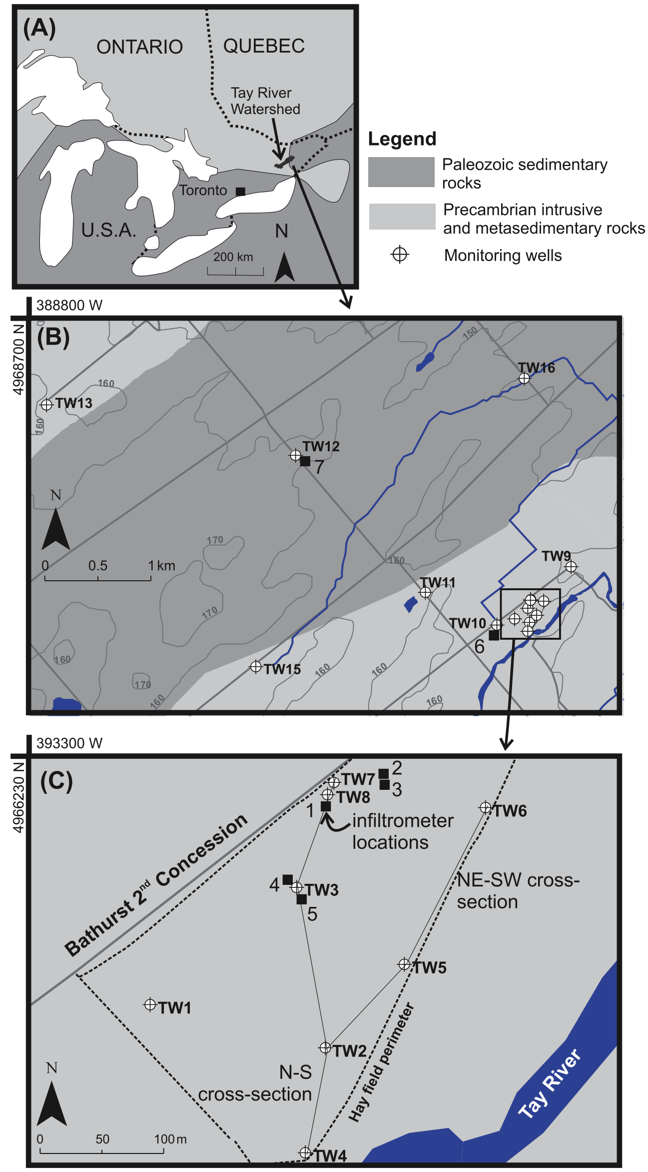

Fig. 1. (A) Location of Tay River watershed in Eastern Ontario at the contact between metamorphosed Precambrian rocks (light grey) and overlying Paleozoic sedimentary rocks (dark grey). (B) Study area showing topography in meters above sea level and the location of monitoring wells (white circles with crosses) and infiltrometer experiments (black squares). (C) Hay field well cluster (TW1-8) and infiltrometer experiments (1–5). The location of cross-sections in Fig. 2 also highlighted.

Field methods

In 2006, four additional 0.152 m diameter bedrock wells were drilled in the study area (TW12, 13, 15 and 16 on Fig. 1) resulting in an expanded network of 15 wells, completed for a total of 38 piezometers. Each bedrock well is completed with two 0.051 m diameter PVC piezometers separated by >3 m of bentonite and an