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Groundwater recharge, flow and stable isotope attenuation in sedimentary and crystalline fractured rocks: Spatiotemporal monitoring from multi-level wells

Stephanie N. Wright^a and Kent S. Novakowski^a

^aDepartment of Civil Engineering, Queen's University, Kingston ON, Canada K7L 3N9

Corresponding author email: stephanie.wright@queensu.ca

Co-author email: kent.novakowski@queensu.ca

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Abstract

The complexities of fractured rock systems necessitate the use of multi-level monitoring wells for the measurement of isotopic tracers with depth. These methods, however, are rarely employed in groundwater flow studies, particularly involving temporal isotope measurements in multiple rock types. To understand the use of isotopic snowmelt tracers for exploring surface connections and recharge, an investigation was undertaken at three geologically-distinct field sites in south-eastern Ontario, Canada. Results of constant head injection tests at 2-m intervals were used to identify and isolate high transmissivity zones (2–3 in each well) for the construction of eight multi-level wells (22 intervals) for groundwater sampling. Deuterium and oxygen-18 were measured in rain (n=64), snow (n=67), soil water (n=118) and groundwater (n=594) on a bi-weekly to monthly basis over two seasonal snowmelt cycles (> 1.5 years). In combination with stable isotopes, measurements of hydraulic head, groundwater temperature, specific conductance and two rounds of tritium sampling contributed to the development of a conceptual model for snowmelt recharge and flow in sandstone, limestone and crystalline rock. Seasonal variation of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ was observed in all rock types indicating recent recharge and strong surface connections. The dampening and residence time of the snowmelt tracer increased with depth in crystalline rock. Attenuation was highest in higher-porosity sedimentary rock and strong confining conditions were observed to inhibit recent recharge. Substantial isotopic attenuation measured in the overburden indicated that the strong snowmelt signal measured in groundwater stems from water infiltrating through areas with thin or no overburden. Identification of the periodic trends and distinct isotopic horizons in this study would not have been possible without the use of multi-level wells.

Keywords

Fractured rock; Stable Isotopes; Snowmelt recharge; Solute transport; Regional groundwater flow; Field characterization

1 Introduction

Bedrock aquifers with thin or no overburden are vulnerable to surface contamination due to the limited or lack of attenuating processes in the overlying soil (Levison and Novakowski, 2009; Lubianetzky et al., 2015; Singhal and Gupta, 2010). The hydraulic properties of the overburden material also control the vertical flux of recharge into the bedrock (Appels et al., 2015; Gleeson et al., 2009). Due to the limited storage and retention capacity of thin overburden and the low storativity and specific yield of fractured rock, the hydraulic head responses to rainfall events can be up to several meters in these settings (Cai and Ofterdinger, 2016; Gburek and Folmar, 1999; Miles and Novakowski, 2016). Storativity can also govern the resilience of an aquifer in response to extreme climatic events such as droughts and floods (Hugman et al., 2012). With many fractured rock systems having little storage, there is a risk for overexploitation, particularly during times of drought. To protect vulnerable bedrock aquifers from these factors, an understanding of recharge mechanisms and contaminant transport from the surface is critical.

Although there has been research on bedrock aquifers, the extreme physical heterogeneity has prompted continued investigation. The hydrologic system is further complicated by recharge in areas with variable overburden thickness, transient precipitation patterns, wide ranges in hydraulic gradients and transmissivities, fluctuating unsaturated zones and multiple land use characteristics (Clark and Fritz, 1997; Cook and Herczeg, 2000). Responses in hydraulic head to rainfall events have been used to explore some of these recharge characteristics in fracture rock (Cai and Ofterdinger, 2016; Miles and Novakowski, 2016; Nimmo et al., 2015; Rodhe and Bockgård, 2006). These studies have exclusively relied on the observed hydraulic responses without applying other lines of evidence to support this interpretation. The use of hydraulic responses alone, for example, may lead to the misinterpretation of hydraulic artifacts for recharge (Weeks, 2002). By coupling conservative tracers with water level measurements, however, a conceptual model can more accurately be constrained (Banks et al., 2011; Cook and Herczeg, 2000; Praamsma et al., 2009; Saha et al., 2013)

Oxygen-18 and deuterium in precipitation are examples of conservative and stable tracers that have been used extensively within the field of hydrology to investigate complex systems (Banks et al., 2011; Cartwright et al., 2012; Clark and Fritz, 1997; Craig, 1961; Dansgaard, 1964; Doveri and Mussi, 2014; Ettayfi et al., 2012; Huijgevoort et al., 2016; Tweed et al., 2004; Zanini et al., 2000). The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values and temperature of snowmelt in particular can be a valuable tracer for revealing recharge and transport processes in fractured rock (Gleeson et al., 2009). Not only does snowmelt have a distinct isotopic and temperature signature from typical groundwater values, but infiltration occurs early spring when plants are dormant and evapotranspiration is low. Spring snowmelt can also be more effective at recharging aquifers due to longer, low intensity infiltration compared to summer rainfall events which can occur with high enough intensity to cause overland flow (Cai and Ofterdinger, 2016; Earman et al., 2006; Winograd et al., 1998).

Contaminant transport concepts for fractured rock can be applied when using environmental tracers such as snowmelt. To delineate flow and transport of a contaminant or solute tracer in fractured rock, multi-level systems are widely applied (Lapcevic et al., 1999). This is due to the substantial heterogeneity which occurs across short vertical and horizontal scales in fractured rock wells (Shapiro, 2002) and the potential for vertical cross contamination within an open borehole (Reilly et al., 1989; Sterling et al., 2005). Although many studies in fractured rock have utilized $\delta^{18}\text{O}$ and $\delta^2\text{H}$ as a characterization tool for recharge, flow and transport, sampling from multi-level or nested wells in this research is relatively rare (Banks et al., 2011; Nunes et al., 2017; Oxtobee and Novakowski, 2002; Regan et al., 2017; Zanini et al., 2000). Despite the use of multi-level or nested wells in these studies, only one sampling event was utilized, which restricts interpretation to one point in time and cannot indicate arrival or residence times of recharge. Studies that do incorporate temporal sampling of stable isotopes in bedrock groundwater are typically from springs (Deiana et al., 2017; Jódar et al., 2016; Winograd et al., 1998), domestic wells

(Abbott et al., 2000; Velderman, 1994), open boreholes (Doveri and Mussi, 2014; Negrel et al., 2011) or open-hole discrete samplers (Padilla et al., 2015; Saxena, 1984). Sampling from open boreholes or springs blends the contributions from discrete fractures and inhibits the ability to identify the relative contribution of individual flow systems with depth. Praamsma et al. (2009) is perhaps one of the only existing studies that utilizes multi-level wells with temporal $\delta^{18}\text{O}$ and $\delta^2\text{H}$ sampling, yet this study only took place in one bedrock environment at a local scale.

The use of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ as environmental tracers can be limited depending on the degree to which the isotopic precipitation signal attenuates prior to reaching the water table. Dampening of the isotopic signal has been well defined in granular porous media and has been attributed to advective and diffusive mixing in the unsaturated and shallow groundwater zones (Chen et al., 2017; Clark and Fritz, 1997; Eichinger et al., 1984; Lee et al., 2007; Mueller et al., 2014). Yet, in areas where thin or no overburden exists, attenuation of the seasonal precipitation signal can be minimal prior to entering the fracture network (Gleeson et al., 2009). Through studying variation in the isotopic tracer with depth, mixing and transport processes in the shallow groundwater zone can be explored. Factors such as unsaturated zone thickness, matrix porosity and aquifer storage are key parameters that may influence the mixing and dampening of the isotopic signal in fractured rock (Clark and Fritz, 1997).

In karstic environments, some studies have observed full attenuation of the seasonal signal of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (Genty et al., 2014; Yonge et al., 1985), yet others have recorded strong seasonal variability (Andreo et al., 2004; Duan et al., 2016; Lauber and Goldscheider, 2014; Wu et al., 2014). Carbonate rock under conditions of dissolution, however, are inherently the focus of cave and karst studies, leaving knowledge gaps in the isotopic attenuation occurring in crystalline and other forms of purely-fractured sedimentary rock. Saxena (1984) explored the attenuation of the seasonal variation of $\delta^{18}\text{O}$ in a crystalline rock environment, but discrete samplers in open boreholes were used and the scale of the study was local (<

200 m). A result of the study conducted by Velderman (1994) was identification of seasonal variation in shallow and deep carbonate aquifers, however, the attenuation of this signal was not the primary focus of the study and open hole homeowner wells were used for groundwater sampling. In both studies, only one rock type was investigated.

Objectives of the following study are to 1) explore the attenuation of the seasonal $\delta^{18}\text{O}$ and $\delta^2\text{H}$ signal with depth in multiple rock types using multi-level wells and 2) compare the transport and residence time of the snowmelt tracer as it travels through the shallow (< 56 m deep) groundwater zone. Both objectives are aimed at furthering the understanding of recharge mechanisms and surface contaminant pathways in fractured rock where thin overburden exists. The study involves biweekly to monthly sampling of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ from multi-level bedrock wells over two seasonal snowmelt cycles (February 2017–September 2018). Three geologically-distinct field sites in south-eastern Ontario, Canada are used for the study and are comprised of limestone, sandstone, syenite and mafic gneiss. Two rounds of tritium sampling are coupled with the stable isotopes, transmissivity-depth profiles, hydraulic head measurements, groundwater temperature and groundwater conductivity for interpretation of the results. To trace the attenuation of the precipitation to depth, composite rain and snow samples are collected and analyzed for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ along with soil water in the overburden at depths less than 1 m along the soil-bedrock interface.

2 Site description

Groundwater was sampled from eight multi-level wells with a total of 22 multi-level intervals across three field sites in south-eastern Ontario, Canada. The location and geology of the field sites are shown in Figure 1. All three field sites have thin overburden (0–8 m of soil cover) and are situated in regions previously identified as vulnerable to contamination (Dillon Consulting Limited, 2004; Golder Associates Ltd., 2003; Krolik et al., 2013). The climate of the study area is humid continental and temperate with

fairly uniform precipitation each month. Near the Kingsford site and Kennedy Field Station (KFS) the average annual rainfall and snowfall is 810 mm and 154 cm, respectively, and 876 mm and 174 cm near the Tay River Field Site (Environment and Climate Change Canada, 2013). Note that the year prior to the study period, record low and extremely low rainfall amounts occurred between April and October 2016 across all three field sites (Agriculture and Agri-Food Canada, 2017). During this period, accumulated precipitation was less than 40% of the annual average (MNRF, 2018; QCA, 2016). In contrast, the entire study area received exceptionally high amounts of rainfall the following year between May and August 2017 (Agriculture and Agri-Food Canada, 2018, 2017). Again, in summer 2018, the study area experienced low water conditions due to low rainfall. Despite having similar climate conditions, the three sites are very distinct in geology and topography, and detailed site descriptions can be found in the following sections.

Figure 1

2.1 Tay River

The Tay River field site, henceforth referred to as the Tay site, is located approximately 10 km south-west of Perth, Ontario in Lanark County. Approximately 61% of Lanark County residents are dependent on groundwater, where nearly all wells tap bedrock aquifers (Golder Associates Ltd., 2003). The Tay site has previously been the subject of many studies resulting in a network of 21 bedrock wells and a total of 55 multi-level intervals within the 3400 ha area (Gleeson et al., 2009; Levison and Novakowski, 2012; Miles, 2013; Miles and Novakowski, 2016; Praamsma et al., 2009). The topography of the study area is typically low-lying with surface elevations ranging from 135 to 170 m above sea level (NRCan, 2011). Regional overburden consists of a discontinuous till veneer resulting in areas of exposed bedrock as well as areas of till blankets and organic deposits with thicknesses up to 8 m (Kettles, 1992). Local bulk hydraulic conductivity of the overburden ranges from 4.8×10^{-7} – 5.8×10^{-6} m/s (Gleeson et al., 2009; Miles

and Novakowski, 2016). The bedrock geology primarily consists of late Precambrian felsic plutonic rocks, specifically syenite migmatite, unconformably overlain by the Nepean Formation; a sandstone with some conglomerate (Dugas, 1952; Ontario Geological Survey, 2011; Wilson, 1930). Surface fracture mapping conducted by Gleeson (2009) indicates the dominant fracture orientation in the crystalline and sandstone aquifers strikes northeast. Periods of glacial advance has removed the weathered portions of the bedrock and glacial unloading has resulted in sheeting fractures that now dominate horizontal flow. The Nepean sandstone can be highly vulnerable to contamination and has a regional geometric mean transmissivity of $2.3 \times 10^{-4} \text{ m}^2/\text{s}$ compared to $4.8 \times 10^{-5} \text{ m}^2/\text{s}$ for the Precambrian bedrock (Singer et al., 2003).

2.2 Kennedy Field Station

The Kennedy field station is located near Tamworth, Ontario where 98% of the municipality's water supply is sourced from bedrock wells (Dillon Consulting Limited, 2004). Within the 55 ha field site there is a 65 m by 30 m well field consisting of nine monitoring wells, including one inclined borehole and one multi-level well. For a detailed description and characterization of the well network refer to (Persaud et al., 2018). Beyond the well field there are two additional multi-level wells each with three monitoring intervals. Elevations in the area range from 164 to 208 m above sea level (masl) with low-lying relief that is considered mid-range for the three field sites (NRCan, 2010). Overburden at KFS ranges from 0–4 m of stony and silty sand-textured till (Ontario Geological Survey, 2010). The site lies in complex bedrock terrain where Paleozoic carbonates and sandstones abut Precambrian basement. The well field is predominantly mafic gneiss, however, the remainder of the site contacts the Gull River (limestone) and Shadow Lake Formations (argillaceous sandstone and shale) of the Simcoe Group and carbonate metasedimentary rocks of the Grenville Supergroup (Ontario Geological Survey, 2011, 2001). Testing of the well field by Persaud et al. (2018) identified significant sub-horizontal fracture sets trending northeast-southwest, which is anticipated to influence the direction of horizontal flow in the area,

particularly in the metasedimentary, gneissic units. Transmissivity for the Simcoe Group has a geometric mean of $6.6 \times 10^{-5} \text{ m}^2/\text{s}$ (Singer et al., 2003) and transmissivity for the Precambrian rocks are similar to that of the Tay site.

2.3 Kingsford

The Kingsford site is located 25 km northwest of Napanee, Ontario where the township also relies on bedrock aquifers for 98% of potable water (Dillon Consulting Limited, 2004). Two multi-level wells have been installed within the 250 ha area with one well adjacent to the Salmon River. The valley setting has steep topographic gradients (0.18) with surface elevations ranging from 95 to 170 masl (NRCan, 2010). The area is predominantly exposed Paleozoic bedrock, however, there are localized pockets of sandy silt to silty sand-textured till and modern alluvial deposits near the banks of the river (Leyland et al., 1983). The dominant formations at the site are Gull River and Bobcaygeon, which are Middle Ordovician limestones of the Simcoe Group with complex members consisting of massive beds of semi-crystalline limestone with interbedded calcarenite and shale (Carson, 1980; Dillon Consulting Limited, 2004). The Salmon River Fault extends through the southern portion of the site where the northwestern side of the normal fault has been displaced 30 m downward (Carson, 1980; McFall, 1993). Felsic Precambrian basement also outcrops near the site. Structural controls in the area are primarily bedding plane fractures, regional faulting and local topographical relief with regional flow in the north-south direction. Transmissivity for the Simcoe Group in this area is anticipated to be similar to KFS.

3 Methods

3.1 Hydrogeological characterization

Wells KF10 and KC1 were drilled in 2016 and KC2 in 2017 for the purposes of this study with the remaining wells constructed for previous studies conducted between 2005 and 2015. Drilling, testing and

construction methods, however, remain consistent for all wells. Wells were drilled using 152 mm rotary percussion methods and rock chips were collected and logged to characterize lithology. Characterization of the wells also included borehole video to identify spacing and apparent openness of fracture features. All wells were tested continuously along the length of the borehole using constant head injection tests with straddle packers spaced 1.77–2.4 m (Elmhirst and Novakowski, 2012; Praamsma et al., 2009). Transmissivity was calculated from the Thiem equation as described in Lapcevic et al. (1999) and plotted with depth. Transmissivity profiles were used to identify high transmissivity features for the design of the multi-level intervals. The intervals were constructed using 51 mm schedule 40 slotted PVC and backfilled with coarse filter sand. A minimum of 2 m of bentonite clay was placed as a confining layer between intervals. Wells with three intervals are identified as shallow, middle and deep with an S, M and D following the well ID, respectively. To stop overflow in KC1M and KC1D (artesian conditions), custom packers were positioned 1.5 m below ground surface (mbgs) to prevent freezing in the winter, but still provide access for sampling. Slug tests were conducted for three intervals (KF5D, KC1D, TW18D) to confirm total interval transmissivity due to conflicting constant head test results and well recovery after sampling. Slug tests were analyzed using the Cooper et al. (1967) solution. To monitor water levels, pressure recording transducers were installed in all piezometers for periods throughout the study at a logging interval of 5 minutes and an accuracy of ± 3 –10 mm depending on transducer model. A barometric pressure logger was installed at each site with a 5-minute sample interval and accuracy of ± 0.05 kPa. Manual water levels were obtained on each sample date and used to correct continuous water levels for drift or adjustment to logger placement. In January 2018, loggers were deployed in TW5, TW6, TW18 and KF5 at the midpoint of each interval screen to monitor water levels and temperature changes (± 0.05 °C) during snowmelt.

3.2 Well selection and locations

Of the 21 bedrock wells available for sampling at the Tay site, only four were selected for this study. Wells TW6 and TW5 were selected as seasonal variation was previously identified in the lower sections by Praamsma et al. (2009). Wells TW16 and TW18 were selected as these wells penetrate the upper Nepean sandstone on the upstream side of TW5 and TW6 and have promising historic hydraulic-head responses from rainfall events. At KFS, KF5 was the only existing multi-level well, thus it was used for the study. The location for KF10 was chosen to investigate a higher topographic portion of the field site, which also lies adjacent to agricultural fields with uniform recharge conditions. Development of the Kingsford field area was initiated due to its proximity to the Salmon River, its highly limited overburden and to further investigate limestone bedrock.

3.3 Isotope sampling and analysis

Isotope sampling commenced 14 February 2017 and continued biweekly to monthly until 8 September 2018. Sampling during the first snowmelt event of 2017 was shorter (3-5 days) to capture rapid snowmelt input signals that may be missed at 2-week intervals. Due to limited winter access to KF10 and frozen well conditions at TW16, winter 2018 samples are limited at these locations. Sampling of KC2 occurred monthly between 21 January 2018 and 8 September 2018. At least one screen volume was purged from each well interval using dedicated tubing and foot valves prior to taking a sample. A flow cell and a YSI Pro Plus multiparameter meter was used to confirm representative purge volumes through the stabilization of field parameters, including conductivity, pH, dissolved oxygen (DO), oxidation reduction potential (ORP) and temperature. Isotope values measured at mid-purge and final-purge volumes consistently remained within analytical error, further confirming that the purge volumes provide representative samples. Based on the sampling method and limited spatial and temporal variation observed in pH, field parameters measured including DO, ORP and pH were not utilized for the development of the conceptual models, but simply to ensure that representative isotope samples were collected, as described above. At each well location one interval was randomly selected for a triplicate

sample, where the sample was homogenized prior to being divided into three 50 mL HDPE sample tubes and then stored at 4°C until $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analysis. On 19 March 2018, samples from each interval of TW6, KF5 and KC1 were collected in 500 mL HDPE bottles for tritium analysis. All wells, including TW6, KF5 and KC1, were sampled for tritium on 7 August 2018.

A tipping bucket rain gauge and rain collector were deployed at all three sites with locations shown in Figure 1. The tipping bucket has a resolution of 0.2 mm and recorded every 15 minutes or during rain events. The rain collector consisted of a 1 L HDPE Nalgene bottle with funnel-ball mechanism as well as 1 cm of inert, light mineral oil in the bottle to prevent sample evaporation (IAEA, 1983). Rain was collected as a composite sample during the period between sampling dates. Composite snow samples were cored through the full snow pack, placed in a plastic bag to melt and homogenize and then transferred into the 50 mL sample tubes. Sample tubes were filled to the top in all cases to prevent sample evaporation while in storage.

Two sets of porous-cup lysimeters were installed at the Tay site and KFS. No lysimeters were installed at Kingsford due to unrestricted public access to the site and limited soil for installation. Lysimeter locations are shown in Figure 1a and 1c. The lysimeters were installed in shallow and deep pairs by augering 51 mm diameter holes until refusal at bedrock. The shallow lysimeter of KFL2 never produced water, either from lack of permeability or a faulty seal. The depths of the lysimeters can be found in Table 1. The lysimeters were sampled using a vacuum pump and Erlenmeyer flask and then placed under 60 centibars of suction until the next sample date.

Table 1. Lysimeter depth and bulk soil characterization from installation.

Lysimeter Name	Depth (cm)	Soil Description	Munsell Soil Colour
KFL1S	48.0	Silty-Sand	Brown
KFL1D	65.5	Silty-Sand	Brown
KFL2S*	48.0	Fine grained sand	Brown
KFL2D*	98.0	Fine grained sand	Brown
TWL1S	30.5	Silty-Sand	Very Dark Brown
TWL1D	43.0	Silty Sand and very fine sand	Light brown
TWL2S	25.4	Silty Sand	Dark Brown
TWL2D	30.5	Clayey-sand and silt	Very dark brown

*Lysimeters were not constructed to bedrock

Samples were analyzed using a Los Gatos Research liquid water isotope analyzer that utilizes Off-Axis Integrated Cavity Output Spectroscopy with values reported relative to Vienna Standard Mean Ocean Water (VSMOW). Three to five known standards were used to calibrate samples with every run. The samples were filtered using a 13 mm syringe filter with a 0.45 μm PTFE membrane. The estimated error associated with isotopic measurement based on field triplicates, in-run duplicates and across-run samples is $\pm 0.15\text{‰}$ and $\pm 1\text{‰}$ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively. The enriched tritium analysis was conducted at the Environmental Isotope Laboratory at the University of Waterloo in Waterloo, Ontario. Samples were enriched 15 times by electrolysis for an improved detection limit of 0.8 ± 0.8 TU.

4 Results

Table 2 includes the well characterization details of the intervals sampled in the study. The aquifer type has been estimated based on barometric response functions (BRF) of each interval. BRFs were determined through software developed by the Kansas Geological Survey (Bohling et al., 2011) using the methods discussed in Butler et al. (2011) and the transducer measurements obtained for this study during periods with no precipitation or pumping influences. Interpretation of the BFR was guided by Rasmussen and Crawford (1997) and Spaine (2002) with plots included in Supplementary Material. Cumulative

transmissivity from constant head tests for each interval is presented along with the range in water table fluctuations observed throughout the whole study period, unless otherwise noted.

Table 2. Hydrogeological characteristics of the well intervals sampled in the study. The designation S, M, D in the Well ID refers to shallow, mid-depth, and deep. Negative values indicate artesian conditions measured in meters above ground surface.

Well ID	Screened interval (mbgs)	Dominant rock type	Drift thickness (m)	Aquifer Type	T (m ² /s)	Water table range (mbgs)
KF5S	2.60–12.47	Mafic gneiss	0.5	Unconfined	2.48×10^{-4}	3.56–0.73
KF5M	14.87–19.67	Mafic gneiss	0.5	Unconfined	5.38×10^{-5}	3.58–0.55
KF5D ^a	24.47–36.47	Mafic gneiss	0.5	Unconfined	4.37×10^{-6}	3.70–2.25
KF10S	4.30–14.78	Limestone	3.6	Unconfined	8.65×10^{-5}	12.18–6.86
KF10M	18.69–27.56	Mafic gneiss	3.6	Unconfined	2.02×10^{-6}	24.13–18.59
KF10D	31.21–45.54	Mafic gneiss	3.6	Unconfined/Semi-confined	2.47×10^{-6}	13.30–11.7
KC1S	4.14–9.78	Limestone	2	Confined	3.71×10^{-6}	3.25–2.34 ^b
KC1M	12.37–19.69	Limestone	2	Confined	9.15×10^{-5}	-4.02–6.31 ^c
KC1D ^a	23.83–38.31	Limestone	2	Confined	8.28×10^{-7}	-3.13–5.45 ^c
KC2S	2.40–13.90	Limestone	0	Unconfined/Semi-confined	9.28×10^{-6}	7.87–3.87 ^d
KC2M	16.70–28.60	Limestone	0	Unconfined	3.07×10^{-5}	11.6–3.43 ^d
KC2D	31.01–42.80	Limestone	0	Unconfined	2.99×10^{-5}	12.43–6.07 ^d
TW5S	4.27–13.32	Syenite	4.3	Unconfined	3.17×10^{-4}	5.30–3.10
TW5M	15.12–24.02	Syenite	4.3	Unconfined	1.55×10^{-5}	4.90–2.26
TW5D	37.42–55.62	Syenite	4.3	Unconfined	9.59×10^{-6}	4.88–2.39
TW6S	4.57–16.12	Syenite	4	Unconfined	1.66×10^{-3}	4.79–2.17
TW6M	17.92–26.72	Syenite	4	Unconfined/Semi-Confined	3.26×10^{-4}	4.69–2.14
TW6D	38.92–49.12	Syenite	4	Semi-confined/Confined	3.33×10^{-4}	4.95–2.26
TW16S	4.80–12.89	Sandstone	2.4	Unconfined	6.73×10^{-4}	0.52–0.205
TW16D	22.60–35.80	Syenite	2.4	Semi-confined/confined	4.40×10^{-7}	0.55–0.01
TW18S	2.64–9.23	Sandstone	0.2	Unconfined	1.56×10^{-3}	1.83–0.56
TW18D ^a	11.16–27.03	Syenite	0.2	Confined	2.96×10^{-9}	1.85–1.36

^a Transmissivity calculated from interval slug test after multi-level construction

^b Water levels measured between 17 February and 4 March 2017

^c Water levels measured between 5 November 2016 to 8 April 2017

^d Water levels measured between 20 January to 8 September 2018

4.1 Stable isotopes

4.1.1 Precipitation and Lysimeters

The global meteoric water line (GMWL) and local meteoric water lines (LMWL) for the three sites are presented in Figure 2 along with the Ottawa LMWL (IAEA/WMO, 2018). Ottawa station data from the Global Network of Isotopes in Precipitation (GNIP) since the year 2000 was used to calculate a LMWL with comparable climate conditions to that of the study period. The LMWLs obtained from this study are based on a least-squares regression (LSR) of all precipitation data and average snow core samples. The precipitation-weighted least-squares regression (PWLSR) method described in Hughes and Crawford (2012) was applied to the data as a comparison. An amount weighting could not be applied to the snow melt samples resulting in winter precipitation being underrepresented in the PWLSR calculation. Additionally, precipitation amount effects tend to be limited in humid temperate climates where temperature effects dominate (Clark, 2015; Harvey, 2001), thus the LSR LMWL is presented here. Slope and intercept values of the two regression methods, however, generally fall within the error of one another.

Figure 2

Snow cores were collected throughout the first snowmelt event of 2017 at multiple locations at each site. These samples exhibit progressive isotopic enrichment throughout the melting period (Supplementary Material). This pattern is spatially consistent at each site and has been well described by Taylor et al. (2001). Maximum deuterium enrichment observed over 11 days for the Tay site, KFS and Kingsford are 49‰, 24‰ and 41‰, respectively.

Lysimeter data from Kennedy and Tay River are shown in Figure 3. Winter samples are limited due to frozen ground or from soil water freezing in the collection tube. Due to drought conditions in Summer

2018, many lysimeters were dry during this period. Seasonal variation is evident in all lysimeters with the greatest changes observed in early spring. For both Tay and KFS, isotope values are stratified in early spring, but stabilize around similar values in late summer and throughout the fall. Lysimeter values plotted on cross plots of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ typically remain to the left of the GMWL, however, some summer and early fall samples plot to the right.

Figure 3

4.1.2 Groundwater

Results of $\delta^2\text{H}$ over time for all study wells are displayed in Figure 4. The transmissivity profile, multi-level design and lithology of the well are adjacent to the isotopic results. Seasonal variation can be identified by cyclical behaviour of deuterium over time. Most intervals, regardless of seasonal variation or not, demonstrate unique isotopic values from other intervals within the same borehole. When $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of groundwater samples are plotted against one another (Figure 5), values remain to the left of the GMWL, except for TW18D, which straddles both sides of the GMWL.

Figure 4

Figure 5

The trendlines for isotope results in Figure 4 were generated based on polynomial model fitting where the chi-squared value, Akaike Information Criterion (AIC) and R^2 values were optimized such that trendlines were not overfitted. A p-value based on an F-test was also used to determine significance. Where polynomial trendlines remained within analytical error, a horizontal trend is applied to signify no seasonal

variation. Lomb (1976) periodograms for unevenly spaced data were also used for confirmation of significant periodic trends in $\delta^2\text{H}$. Table 3 displays results for wells with p-values below the 0.1 level. Well intervals of KC2 were not analyzed for seasonal trends as sampling occurred over less than a year.

Table 3. Periodogram results for well intervals displaying periodic trends at p-values below the 0.1 level. Deuterium values were detrended prior to analysis.

Well ID	Period (days)	p-value
TW6S	325	0.064
TW6M	414	0.015
TW5S	303	0.003
KF5S	326	0.001
KF5M	457	0.002
KC1S	380	0.069
KC1D	502	0.026

Table 4 contains the results of the enriched tritium analysis conducted in spring and summer 2018.

Between February 2016 and February 2018, the average measurement of tritium in precipitation at the nearby Ottawa GNIP station was 13.7 TU (IAEA/WMO, 2018). Since tritium measurements of precipitation in the last 20 years range anywhere between 5 and 78 TU, attempts at dating the groundwater would have little meaning for recent recharge events. Instead, tritium values are used to indicate distinctions between intervals within the same well, act as a tracer relative to recent (2016-2018) precipitation measurements, and provide insight into groundwater dating prior to the 1960's when tritium is zero (Clark and Fritz, 1997).

Table 4. Enriched tritium results.

Well ID	Tritium (TU)	$\pm 1\sigma$	Tritium (TU)	$\pm 1\sigma$
Sample Date	19/03/2018		07/08/2018	
TW6S	10.9	0.9	12.3	0.9
TW6M	11.1	0.9	12.0	0.9
TW6D	11.2	0.9	11.0	0.8
TW5S			9.4	0.7
TW5M			5.8	0.5
TW5D			3.6	0.4
TW16S			6.3	0.5
TW16D			5.4	0.5
TW18S			12.0	1.0
TW18D			8.1	0.7
KF5S	14	1.1	13.9	1.1
KF5M	13.2	1	14.2	1.1
KF5D	12.1	1	13.4	1.1
KF10S			8.5	0.7
KF10M			4.7	0.6
KF10D			7.1	0.7
KC1S	14.2	1.1	12.3	1.0
KC1M	5.1	0.5	3.6	0.5
KC1D	0.9	0.3	<0.8	0.3
KC2S			3.7	0.5
KC2M			5.5	0.6
KC2D			3.6	0.5

4.2 Hydraulic head and temperature

Figure 6 displays the manual and pressure transducer data for all wells in the study. Most well intervals exhibit increases in hydraulic head in alignment with precipitation events, however, observations in KC1S, KC1D and KF10M are limited. Some wells, such as TW6 and TW16 exhibit uniform hydraulic head measurements in all intervals, whereas KC1 and KF10 have fully stratified heads with depth.

Figure 6

The hydraulic heads of each interval in TW6 all increase fairly uniformly to potential infiltration events, including rainfall and snowmelt (Figure 7a). During periods of snowmelt, hydraulic head increases and is accompanied by drops in temperature in the shallow interval (Figure 7b). This response also occurs in the shallow intervals of TW5, TW18 and KF5. The largest temperature drop seen in KC2S was 0.098°C , which is outside the accuracy of the logger of $\pm 0.05^{\circ}\text{C}$, however, it consistently exhibits peaks in hydraulic head associated with drops in temperature during spring 2018 melt.

Figure 7

4.3 Correlation of specific conductance and isotopes

Specific conductance is used as an additional line of evidence for recent recharge, where conductance is inversely related to recharge events. Similarly, the snowmelt isotopic signal shares this same relationship. The correlation between conductance and isotope value can reinforce the seasonal isotopic evidence of recharge and flow. Spearman correlation coefficients calculated between specific conductance and deuterium value for well intervals are given in Table 5, where 'n' indicates the number of samples used for the analysis. Correlations for KF10 were not determined due to possible bentonite contamination from well construction. Intervals with isotopic variation within analytical error were not used for the correlation analysis.

Table 5. Correlation coefficients and p-values for relationship between deuterium and specific conductance. Wells exhibiting strong and moderate correlations are identified in bold. Remaining wells have non-significant weak or very weak relationships. A negative correlation coefficient indicates a negative relationship. Specific conductance and deuterium values were detrended by subtraction of a linear regression line prior to calculating correlation coefficients.

Well ID	Spearman's correlation coefficient	p-value	n
TW6S	0.75	9.3E-06	26
TW6M	0.53	4.8E-03	27
TW6D	-0.22	2.8E-01	26
TW5S	0.79	5.5E-06	24
TW5M	0.05	8.1E-01	24
TW18S	0.78	1.3E-05	27
KF5S	0.59	8.6E-04	28
KF5M	0.24	2.2E-01	27
KF5D	0.23	2.4E-01	27
KC1S	0.07	7.4E-01	24
KC1D	-0.18	4.4E-01	21
KC2S	-0.29	2.4E-01	10
KC2M	-0.53	1.2E-01	10
KC2D	-0.67	3.3E-02	10

5 Discussion

The calculated slopes and intercepts for the LMWLs are generally within one standard deviation of each other. There are slight differences in slope and intercept between the study LWMLs and that of Ottawa, particularly when all available data (1972–2018) is included. Closer alignment of Ottawa and study values is achieved when only data dating back to 2000 is included in the calculations (Figure 2b). This period more closely reflects the climate conditions that occurred during the study period, yet still provides nearly two decades of monthly isotope samples. Differences remaining between the LMWLs may be attributed to elevation and humidity differences between Ottawa and the study sites as similarly noted in a regional report by Golder Associates Ltd. (2003).

Groundwater sampled in this study generally falls along the LMWL (Figure 5), which indicates recent recharge from precipitation and that other fractionation processes, such as evaporation or water-rock exchange are not at play. A slight evaporative enrichment signal in TW18D may indicate a distal connection to a surface body of water, such as the Tay River or mixing with older groundwater from different climatic conditions.

In the summer months of 2017, lysimeters display slight evaporative enrichment (Figure 3c-d). This is common in shallow (< 1m) soils during warm months (Brutsaert, 2005). Lysimeter pair TWL1 had the most isotopically evaporated samples of the lysimeters in summer 2017, which may be due to the lack of tree coverage in combination with a sandier soil compared to other study lysimeters (Table 1). The evaporative signal observed in the lysimeter samples did not appear in the groundwater, suggesting little recharge through the overburden during hot summer months. Soil water displays little variation in late summer/early fall (Figure 3a-b), further suggesting little recharge through overburden during these times. Recharge in areas of exposed bedrock, however, may still be possible during these months.

5.1 Isotope response from climate conditions

Wells that exhibit a strong seasonal variation in deuterium (TW5S, TW6, TW18S, KC1S, and KF5) also display a decreasing underlying trend. The isotope values first measured in TW6 and TW5S in early 2017 are higher than previously measured at the site (Gleeson et al., 2009; Praamsma et al., 2009). The cause for this initial isotopic enrichment and subsequent depletion could be due to several factors, including the “amount effect” first described by Dansgaard (1964). The amount effect results in higher $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in small precipitation events and lower isotopic ratios in larger events. Based on the evidence of good surface connection in the identified intervals, the amount effect could have generated the $\delta^2\text{H}$ -enriched precipitation during the 2016 drought year resulting in the lingering effects being measured in the

groundwater early 2017. Similar observations were made by Andreo et al. (2004) in karstic environments with strong surface connection. The amount effect was not apparent in precipitation from the Ottawa GNIP station during 2016, however, $\delta^2\text{H}$ measured in summer 2018 precipitation was 10–15‰ higher at the Tay site than 2017 flood year. Shallow intervals of TW5, KF5 and KC1 exhibit steep increases in deuterium following the 2018 drought compared to the 2017 flood. It is hypothesized with continued sampling, the values in these wells and TW6S would continue to increase in response to the drought conditions but may not return to levels initially measured in early 2017 due to lower drought severity.

An alternative explanation is that the high $\square^2\text{H}$ and $\square^{18}\text{O}$ measured in early 2017 more closely reflects background conditions, and high intensity rainfalls in 2017 prevented the well from returning to background values. During drought conditions, little recharge occurs, as supported by the hydraulic head data, and the well rebounds to higher background conditions more quickly. The isotope cyclicity seen in the wells may not be due to $\square^2\text{H}$ -depleted snowmelt, followed by $\square^2\text{H}$ -enriched rain, but instead it is due to the snowmelt pulse entering and leaving the interval. This would allow conditions to return to background levels in the summer when little recharge occurs. This pulse of snowmelt is similar to the observations from Gleeson et al. (2009) and Deiana et al. (2017), however the residence time of the pulse in this case is several months compared to several weeks in those studies. The rate at which the aquifer rebounds to prior isotopic conditions, may be an indication of storage and vulnerability to extreme climate events, as this observation is more pronounced in crystalline rock where storage is very low.

In addition to drought conditions, the snowpack dynamics of each snowmelt season likely play a role in the isotopic measurements in the wells. When a snowmelt event takes place and the overburden is still frozen (i.e. mid-winter), recharge will likely occur in areas of thin overburden or exposed bedrock where it can infiltrate along unfrozen (Woo and Marsh, 2005), preferential fractures (Reisch and Toran, 2014).

These recharge events will input higher volumes of $\delta^2\text{H}$ -depleted waters, thereby strengthening the tracer observed in the well. Thus, in the case of KC1S where more melt events occurred earlier in the year in 2018 compared to 2017, a stronger signal was observed. Between the two years, there was approximately 18% more snowfall in 2018 than 2017 (Environment and Climate Change Canada, 2018), which may also contribute to the more pronounced isotopic response.

5.2 Attenuation of seasonal variation

Progressive isotopic enrichment of the snowpack was observed at all sites, which has implications on quantifying the attenuation of the snowmelt tracer prior to infiltration. The final composition of snow after melt metamorphism can result in isotope values that may be closer to rainfall, resulting in the miscalculation of recharge attributed to snowmelt (Earman et al., 2006). During the 2017 snowmelt, the most $\delta^2\text{H}$ -enriched snow core sample was -92‰ at KFS, with the remaining snow core values staying below -100‰. $\delta^2\text{H}$ measured in rain during this melt period remained above -67‰, suggesting misidentification of snowmelt recharge from this event would be unlikely.

Figure 8 shows the total range in deuterium measured throughout the study. The deuterium range measured in precipitation is attenuated by nearly 50% in deep soils at both the Tay site (43 cm depth) and KFS (98 cm depth). The high percentage of attenuation seen at relatively shallow depths implies that little signal would enter the bedrock at depths of 4 m, for example, which overlies TW5 and TW6. Yet, seasonal responses were observed in these wells, which is evidence for more distal recharge on or near areas of exposed bedrock.

Figure 8

5.2.1 Crystalline rock

Unconfined and semi-confined wells in crystalline rock retain the greatest percentage of seasonal isotope signal with depth compared to the other rock types, which is most likely due to low matrix porosity. The 2017 snowmelt pulse enters the shallow interval first, followed by a phase shifted and dampened pulse in the middle and finally deep sections. This pattern is strongest in TW6 where transmissivity is high and fairly uniform in all intervals (Figure 4). Intervals of KF5 exhibit similar behaviour, however, the phase shifting and dampening with depth is less pronounced. This may be due to lower transmissivity values in all intervals compared to TW6 or longer flow paths from the area of recharge. Saxena (1984) observed dampening with depth, but reported no phase shift in a fractured granodiorite, which may be due to a difference in fracture network properties, irregular sampling intervals or mixing in open-borehole conditions.

Milloy (2007) applied the water table fluctuation method to calculate recharge in the syenite found at the Tay site. The estimated recharge amount was approximately 1% of precipitation that fell during the autumn study period. Substantial reductions in the isotopic precipitation signal measured in shallow intervals are likely due to very low volumes of water entering the saturated fracture network, instead of attenuation occurring in the unsaturated fractured rock zone.

Despite BRFs indicating unconfined conditions in all intervals of TW5, only the shallow interval displays seasonal variation of $\delta^2\text{H}$ and $\delta^{18}\text{O}$. There is also a disconnect between the shallow and lower intervals in the hydraulic head (Figure 6) and tritium measurements (Table 4). Minimal seasonal variation in lower sections suggests more distal recharge areas or areas with thicker overburden, which increases mixing and attenuating processes. Similar interpretations can be applied to KF10M and KF10D, however, unsaturated zones are substantial (~24 m and 12 m) in these intervals, which would also reduce or eliminate the

isotopic signal reaching the water table. The confined intervals of TW16D and TW18D in crystalline rock exhibit little seasonal variation, which can be attributed to the very low values of transmissivity in both intervals.

5.2.2 Sandstone

The shallow intervals of TW18 and TW16 both have unconfined responses to barometric effects and have similar lithologic and transmissivity profiles, yet only TW18S displays variation in $\delta^2\text{H}$ and $\delta^{18}\text{O}$. In TW16S, unconfined conditions suggest there is a surface connection, but the low tritium values and relatively constant stable isotopes indicate substantial mixing and attenuating processes are occurring. Locally, overburden is over 2-m thicker at TW16 than TW18, which implies overburden plays a significant role in attenuating the isotopic signal. Despite having minimal overburden, the isotope values observed in TW18S are still substantially attenuated relative to the precipitation input signal, which may be attributed to higher matrix porosities and storage in the sandstone unit compared to crystalline bedrock or due to more distal areas of recharge.

5.2.3 Limestone

Seasonal variation is further attenuated relative to sandstone and crystalline rock in limestone under unconfined and semi-confined conditions with no overburden (KC2) as illustrated in Figure 8. Based on observed hydraulic responses and no local overburden, substantial isotopic recharge signals should be occurring in all intervals of KC2, yet this is not the case. The low tritium values in all intervals would suggest the surface connections identified through the BRFs are distal and recharge is well integrated with older groundwater. This well also has the greatest water table fluctuations of all the study wells, resulting in very thick unsaturated zones (7.8–12.4 m), which in combination with high matrix porosities, may further attenuate isotopic signals. The seasonal signals that do enter the shallow and middle intervals of

KC2 do not appear to be phase shifted or substantially dampened with depth, contrary to unconfined crystalline rock. The deep interval, however, receives little seasonal signal despite exhibiting unconfined barometric responses, further suggesting increased mixing and attenuation in carbonate rock.

Seasonal isotopic variation and high tritium was observed in the shallow interval of KC1, even under confining conditions. No seasonal change and low tritium, however, occurred in KC1M, which is also confined. This evidence suggests that despite local hydraulic confining conditions, precipitation input signals can still occur if pathways exist upstream from the well.

Substantial $\delta^2\text{H}$ and $\delta^{18}\text{O}$ variation, primarily a decline, was measured in the confined deep interval of KC1, yet tritium was not measured above detection limits. This indicates that the groundwater predates the 1960's and the variation observed is not due to recent snowmelt recharge. This is further supported when considering the extreme attenuation processes observed in the carbonate units, and the isolation of this horizon from the more recent water in the shallow interval. This trend is thus likely due to open-borehole contamination prior to construction of the multi-level intervals caused by high matrix porosities and moderate transmissivity. The properties of this well interval may have led to a slow recovery to isotopic equilibrium at a much lower isotope value. This is primarily evidenced by the equivalent starting point in $\delta^2\text{H}$ for KC1M and KC1D, the former of which has an artesian head greater than KC1D and would have generated mixing into the lower interval. Based on the low, declining value of $\delta^2\text{H}$, this may represent water from a colder climate (Clark, 2015). Specific conductance in this interval ranges from 7,300–13,000 $\mu\text{S}/\text{cm}$, which also implies older groundwater that has had little dilution with recent recharge. The values of tritium, deuterium and conductivity observed in this interval are similar to measurements by Zanini et al. (2000) in a highly confined dolostone aquifer in Smithville, Ontario. These measurements took place at similar depths and within a similar range in transmissivity as KC1D

(dolomitic limestone), suggesting the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in bedrock groundwater may be related to rock type and transmissivity.

5.3 Conceptual models for flow and recharge

5.3.1 Crystalline rock

Fairly uniform tritium and transmissivity values in all intervals of KF5 and of TW6 support the interpretation of good surface connectivity extending to deep intervals of these wells. Periodogram results (Table 3) indicate just under a yearly cycle in KF5S and nearly the same cycle in TW6S. The period of TW6S is not statistically significant at the 0.05 level, but it is hypothesized that with continued sampling, significance would improve based on similar responses as TW5S. The middle intervals of TW6 and KF5 are both over a yearly cycle, indicating longer flow paths and increased residence time with increased depth. Isotopic dampening and long periodicity may prevent strong periodic trends from being calculated in the deep intervals, however, visual trends of dampening and phase shifting can be identified.

The common periods of TW6 and KF5 indicate that flow and recharge in crystalline rock with thin overburden can behave similarly despite differences in location and the type of crystalline rock (i.e. syenite versus gneiss). In contrast, the isotopic patterns in TW5 and TW6, are markedly different in lower sections despite being short distances apart (150 m) and in the same syenite. Where $\delta^2\text{H}$ increases with depth in TW6, the opposite occurs in TW5. This could be caused by different mixing ratios of old and new waters. The strong isotopic variation in TW5S also causes $\delta^2\text{H}$ measurements to cross above and below the more isotopically stationary intervals, which, if only one sample were taken in time, could be misconstrued as similar behaviour to TW6.

Periodogram results in conjunction with specific conductance correlations (Table 5) indicate long flow paths and distal recharge zones in these rocks. Positive correlations indicate that the bulk of the isotope signal is derived from snowmelt rather than rainfall, since rainfall recharge would also cause the conductivity to decrease resulting in a negative correlation. Residence times of the snowmelt pulse in the shallow crystalline wells are on the order of several months, in contrast to the 3–4 weeks observed by Gleeson et al. (2009) where recharge was thought to be highly localized.

The substantial isotopic attenuation observed in the overburden emphasizes the notion of distal recharge on or near areas of exposed bedrock. The rapid drop in groundwater temperature in alignment with decreases in snowpack and increases in head observed in KF5S, TW6S and TW5S, would suggest rapid infiltration of snowmelt also occurs local to the well (Figure 7). It does not, however, significantly contribute to changing the bulk isotope value in the well as seen with high frequency sampling during the first 2017 snowmelt. Hydraulic head also rapidly responds to precipitation events, yet the underlying trend is inversely related to deuterium value. Evidence suggests low volume, rapid and local recharge is occurring in addition to large volume, slow and distal recharge. This is also supported by values of attenuated, lighter water in TW18D which although has a higher tritium value, is reflective of slower pathways governed by the very low transmissivity in this section. The higher values of $\delta^2\text{H}$ in this section reflect a period of warmer recharge that is travelling slowly through the crystalline rock at this location.

A conceptual model for flow and recharge in a crystalline formation is presented in Figure 9a. Recharge can be seen to have the strongest isotopic value (coloured black) in areas of exposed bedrock and little to no signal (light grey) where overburden increases. Due to significantly lower matrix porosities, the crystalline model has the lowest diffusive influences on the isotopically depleted snowmelt signal relative to the sedimentary rock types. Fracture connectivity dictates confined or unconfined conditions.

5.3.2 Sandstone

Short flow paths in the sandstone of TW18 are evidenced by erratic changes in $\delta^2\text{H}$ (Figure 4) and rapid drops in temperature in response to snowmelt events (same behaviour as Figure 7). Unlike crystalline rock, short flow paths in sandstone do appear to contribute high enough volumes of recharge to change the bulk isotopic composition of the well, which is seen by pronounced changes in deuterium over short time frames. No significant periodicity was calculated for this interval (Table 3) due to erratic precipitation responses, opposed to slow, well mixed seasonal responses observed in the crystalline wells. This may also indicate multiple recharge inputs and less homogenization occurring in the shallow flow system from surface. Strong correlations in specific conductance and deuterium (Table 5) support seasonal recharge trends dominated by snowmelt events.

The hydraulic head measurements in both shallow and deep intervals in TW16 and TW18 are very similar and track together suggesting there is vertical connection, but based on the stable isotopes and low transmissivity, there is not much mixing from above. The higher tritium (Table 4) measured in TW18D, however, may be an indication of distal surface connections with subsequent mixing along flow paths attenuating the seasonal variation of $\delta^2\text{H}$ and $\delta^{18}\text{O}$. Figure 9b illustrates the conceptual model for snowmelt recharge and flow in a sandstone unit. High porosities result in snowmelt signals becoming immediately dampened, limiting the signal reaching semi-confined and confined areas (lower syenite).

5.3.3 Limestone

Similar processes as described for the sandstone are illustrated in the conceptual model for limestone (Figure 9c). Direct surface connections to deeper portions of the aquifer are illustrated in unconfined conditions because of the lack of phase shift observed in KC2 shallow and middle sections. Subvertical

fractures connected to surface may also bypass shallower portions of the aquifer and extend to deeper areas allowing for unconfined conditions to underly semi-confined/confined conditions. This is supported by BRFs and fairly stable water levels in KC2S during low water conditions in 2018, while steep water level declines occurred in the lower sections.

A strong, negative and significant correlation between specific conductance and deuterium were calculated for KC2D (Table 5), which was the only significant negative relationship of all the wells. In this interval, hydraulic head rises many meters in response to snowmelt events (Figure 6), suggesting the negative relationship is not caused by a rain dominated system. Alternatively, the influx of snowmelt may increase sediment transport from surface, such as winter road salts (Reisch and Toran, 2014), or increase erosion of preferential pathways, which in turn would increase the conductivity during this time. Weak and moderate negative relationships were observed in the shallow in middle intervals, respectively, but they were not statistically significant at the 0.05 level. Further sampling would be required to determine if the negative relationships seen in all intervals persist.

A significant yearly deuterium cycle was determined for KC1S suggesting longer flow paths distally connected to the surface are allowing recharge into the confined area down-gradient. Under confined conditions, such as KC1M, no snowmelt signal reaches the interval, likely due to dominant horizontal flow paths and the absence of subvertical connections to upper aquifers. Increased matrix diffusion and mixing is illustrated in the conceptual model because of the high attenuation of the snowmelt signal observed.

Figure 9

6 Conclusions

Sampling of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ from multi-level wells at three distinct geological field sites was conducted between February 2017 and September 2018. Hydraulic head measurements, specific conductance, groundwater temperature and borehole transmissivity profiles were used in combination with the stable isotope results for interpretation of the mechanisms of groundwater recharge, flow and isotopic attenuation. From the study conducted, the following conclusions can be made:

- There is unquestionable value in the use of multi-level wells in these settings as the periodicity observed likely would not have been detected and distinct horizons could not have been identified. The use of multi-level wells also highlights the importance of temporal sampling from discrete zones in saturated fractured rock for site characterization.
- The isotopic periodicity observed in all interval depths indicates there are strong connections to the surface and recent recharge is occurring in all rock types. The long-term underlying trends, however, indicate influences from interannual climatic conditions in all rock types and in all depth horizons in crystalline rock. The oldest water occurs in strongly confined bedded limestones and may reflect water from colder climates.
- Substantial isotopic attenuation observed in the overburden indicates that the strong snowmelt signal measured in groundwater stems from water infiltrating through areas with thin or no overburden. The isotopic composition of groundwater and the degree of seasonal attenuation throughout the saturated zone is related to rock type, transmissivity and vertical connectivity. Sedimentary rock with higher matrix porosity increases attenuation of the isotopic snowmelt signal.
- There are multiple lines of evidence in all rock types for short flow paths that result in rapid, but low volume recharge, in combination with long flow paths that slowly contribute to bulk water table rises. In crystalline rock, flow paths and snowmelt residence time increase with depth. In

sedimentary rock types, horizontal flow paths can be dominant with limited vertical exchange between horizons. Snowmelt during early spring significantly contributes to recharging all types of bedrock aquifers in temperate, low-lying areas.

- The attenuation mechanisms and residence time of the isotopic snowmelt tracer are clues to surface contaminant behaviour in these kinds of systems. This study shows that bedrock aquifers can either be highly susceptible to surface contaminants extending to depths of 50 m, or under certain confining conditions and limited fracture connectivity, they can be highly resistant to surface impacts.

This study continues to contribute to the body of work that attempts to understand the complexities of fractured rock environments. Multiple rock types have directly been compared to identify similarities and differences in flow and recharge. It has been seen, however, that highly contrasting responses can occur in wells with similar hydrogeological characteristics. This emphasizes the need for larger, detailed studies that employ the methods used in this study.

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References

- Abbott, M.D., Lini, A., Bierman, P.R., 2000. $\delta^{18}\text{O}$, δD and ^3H measurements constrain groundwater recharge patterns in an upland fractured bedrock aquifer, Vermont, USA. *J. Hydrol.* 228, 101–112. [https://doi.org/10.1016/S0022-1694\(00\)00149-9](https://doi.org/10.1016/S0022-1694(00)00149-9)
- Agriculture and Agri-Food Canada, 2018. Departure From Average Precipitation (mm) in past 365 days, as of January 8, 2018 [WWW Document]. Agroclimate - Curr. Cond. URL <http://www.agr.gc.ca/drought> (accessed 1.15.18).
- Agriculture and Agri-Food Canada, 2017. 2016 Annual Report of Agroclimate Conditions Across Canada [WWW Document]. URL <http://www.agr.gc.ca/eng/programs-and-services/list-of-programs-and-services/drought-watch/2016-annual-report-of-agroclimate-conditions-across-canada/?id=1487809939662#a3> (accessed 1.15.18).
- Andreo, B., Liñán, C., Carrasco, F., Jiménez de Cisneros, C., Caballero, F., Mudry, J., 2004. Influence of rainfall quantity on the isotopic composition (^{18}O and ^2H) of water in mountainous areas. Application for groundwater research in the Yunquera-Nieves karst aquifers (S Spain). *Appl. Geochem.* 19, 561–574. <https://doi.org/10.1016/j.apgeochem.2003.08.002>
- Appels, W.M., Graham, C.B., Freer, J.E., McDonnell, J.J., 2015. Factors affecting the spatial pattern of bedrock groundwater recharge at the hillslope scale. *Hydrol. Process.* 29, 4594–4610. <https://doi.org/10.1002/hyp.10481>
- Banks, E.W., Simmons, C.T., Love, A.J., Shand, P., 2011. Assessing spatial and temporal connectivity between surface water and groundwater in a regional catchment: Implications for regional scale water quantity and quality. *J. Hydrol.* 404, 30–49. <https://doi.org/10.1016/j.jhydrol.2011.04.017>
- Bohling, G.C., Jin, W., Butler, J.J., 2011. Barometric Response Function Software. Kansas Geological Survey, Lawrence, KS.
- Brutsaert, W., 2005. *Hydrology: An Introduction*, 1st ed. Cambridge University Press.

- Butler, J.J., Jin, W., Mohammed, G.A., Reboulet, E.C., 2011. New Insights from Well Responses to Fluctuations in Barometric Pressure. *Groundwater* 49, 525–533. <https://doi.org/10.1111/j.1745-6584.2010.00768.x>
- Cai, Z., Ofterdinger, U., 2016. Analysis of groundwater-level response to rainfall and estimation of annual recharge in fractured hard rock aquifers, NW Ireland. *J. Hydrol.* 535, 71–84. <https://doi.org/10.1016/j.jhydrol.2016.01.066>
- Carson, D.M., 1980. Paleozoic Geology of the Kaladar - Tweed Area, Southern Ontario. Geological Series.
- Cartwright, I., Weaver, T.R., Cendón, D.I., Fifield, L.K., Tweed, S.O., Petrides, B., Swane, I., 2012. Constraining groundwater flow, residence times, inter-aquifer mixing, and aquifer properties using environmental isotopes in the southeast Murray Basin, Australia. *Appl. Geochem.* 27, 1698–1709. <https://doi.org/10.1016/j.apgeochem.2012.02.006>
- Chen, H., Hu, K., Nie, Y., Wang, K., 2017. Analysis of soil water movement inside a footslope and a depression in a karst catchment, Southwest China. *Sci. Rep.* 7, 2544. <https://doi.org/10.1038/s41598-017-02619-x>
- Clark, I., 2015. *Groundwater Geochemistry and Isotopes*. Taylor & Francis Group.
- Clark, I.D., Fritz, P., 1997. *Environmental isotopes in hydrogeology*. CRC Press, Boca Raton, FL.
- Cook, P.G., Herczeg, A.L. (Eds.), 2000. *Environmental Tracers in Subsurface Hydrology*. Springer US.
- Cooper, H.H., Bredehoeft, J.D., Popadopoulos, I.S., 1967. Response of a finite-diameter well to an instantaneous charge of water. *Water Resour. Res.* 3, 263–269. <https://doi.org/10.1029/WR003i001p00263>
- Craig, H., 1961. Standard for Reporting Concentrations of Deuterium and Oxygen-18 in Natural Waters. *Science* 133, 1833–1834.
- Dansgaard, W., 1964. Stable Isotopes in Precipitation. *Tellus* 16, 436–468.

- Deiana, M., Mussi, M., Ronchetti, F., 2017. Discharge and environmental isotope behaviours of adjacent fractured and porous aquifers. *Environ. Earth Sci.* 76, 595. <https://doi.org/10.1007/s12665-017-6897-x>
- Dillon Consulting Limited, 2004. Quinte Regional Groundwater Study. London, Ontario.
- Doveri, M., Mussi, M., 2014. Water Isotopes as Environmental Tracers for Conceptual Understanding of Groundwater Flow: An Application for Fractured Aquifer Systems in the “Scansano-Magliano in Toscana” Area (Southern Tuscany, Italy). *Water* 6, 2255–2277.
- Duan, W., Ruan, J., Luo, W., Li, T., Tian, L., Zeng, G., Zhang, D., Bai, Y., Li, J., Tao, T., Zhang, P., Baker, A., Tan, M., 2016. The transfer of seasonal isotopic variability between precipitation and drip water at eight caves in the monsoon regions of China. *Geochim. Cosmochim. Acta* 183, 250–266. <https://doi.org/10.1016/j.gca.2016.03.037>
- Dugas, J., 1952. Geology of the Perth Map-Area Lanark and Keeds Counties, Ontario. McGill University, Montreal, Quebec.
- Earman, S., Campbell, A.R., Phillips, F.M., Newman, B.D., 2006. Isotopic exchange between snow and atmospheric water vapor: Estimation of the snowmelt component of groundwater recharge in the southwestern United States. *J. Geophys. Res. Atmospheres* 111, D09302. <https://doi.org/10.1029/2005JD006470>
- Eichinger, L., Merkel, B., Nemeth, G., Salvamoser, J., Stichler, W., 1984. Seepage velocity determinations in unsaturated quarternary gravel, in: *Recent Investigations in the Zone of Aeration*. Munich, pp. 303–313.
- Elmhirst, L.M., Novakowski, K.S., 2012. The analysis of pulse interference tests conducted in a fractured rock aquifer bounded by a moving free surface. *Adv. Water Resour.* 35, 20–29. <https://doi.org/10.1016/j.advwatres.2011.10.002>

Environment and Climate Change Canada, 2018. Historical Data [WWW Document]. URL

http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=4268&autofwd=1 (accessed 1.15.18).

Environment and Climate Change Canada, 2013. Canadian Climate Normals 1981-2010 Station Data [WWW Document]. URL

http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=4268&autofwd=1 (accessed 1.15.18).

Ettayfi, N., Bouchaou, L., Michelot, J.L., Tagma, T., Warner, N., Boutaleb, S., Massault, M., Lgourna, Z., Vengosh, A., 2012. Geochemical and isotopic (oxygen, hydrogen, carbon, strontium) constraints for the origin, salinity, and residence time of groundwater from a carbonate aquifer in the Western Anti-Atlas Mountains, Morocco. *J. Hydrol.* 438–439, 97–111.
<https://doi.org/10.1016/j.jhydrol.2012.03.003>

Gburek, W.J., Folmar, G.J., 1999. A groundwater recharge field study: site characterization and initial results. *Hydrol. Process.* 13, 2813–2831. [https://doi.org/10.1002/\(SICI\)1099-1085\(19991215\)13:17<2813::AID-HYP901>3.0.CO;2-6](https://doi.org/10.1002/(SICI)1099-1085(19991215)13:17<2813::AID-HYP901>3.0.CO;2-6)

Genty, D., Labuhn, I., Hoffmann, G., Danis, P.A., Mestre, O., Bourges, F., Wainer, K., Massault, M., Van Exter, S., Régnier, E., Orengo, P., Falourd, S., Minster, B., 2014. Rainfall and cave water isotopic relationships in two South-France sites. *Geochim. Cosmochim. Acta* 131, 323–343.
<https://doi.org/10.1016/j.gca.2014.01.043>

Gleeson, T., 2009. Groundwater recharge, flow and discharge in a large crystalline watershed (Thesis).

Gleeson, T., Novakowski, K., Kurt Kyser, T., 2009. Extremely rapid and localized recharge to a fractured rock aquifer. *J. Hydrol.* 376, 496–509. <https://doi.org/10.1016/j.jhydrol.2009.07.056>

Golder Associates Ltd., 2003. Renfrew County - Mississippi- Rideau Groundwater Study. Ottawa, Ontario.

- Harvey, F.E., 2001. Use of NADP Archive Samples to Determine the Isotope Composition of Precipitation: Characterizing the Meteoric Input Function for Use in Ground Water Studies. *Groundwater* 39, 380–390. <https://doi.org/10.1111/j.1745-6584.2001.tb02322.x>
- Hughes, C.E., Crawford, J., 2012. A new precipitation weighted method for determining the meteoric water line for hydrological applications demonstrated using Australian and global GNIP data. *J. Hydrol.* 464–465, 344–351. <https://doi.org/10.1016/j.jhydrol.2012.07.029>
- Hugman, R., Stigter, T.Y., Monteiro, J.P., Nunes, L., 2012. Influence of aquifer properties and the spatial and temporal distribution of recharge and abstraction on sustainable yields in semi-arid regions. *Hydrol. Process.* 26, 2791–2801. <https://doi.org/10.1002/hyp.8353>
- Huijgevoort, M.H.J., Tetzlaff, D., Sutanudjaja, E.H., Soulsby, C., 2016. Using high resolution tracer data to constrain water storage, flux and age estimates in a spatially distributed rainfall-runoff model. *Hydrol. Process.* 30, 4761–4778. <https://doi.org/10.1002/hyp.10902>
- IAEA, 1983. Guidebook on Nuclear Techniques in Hydrology. IAEA Technical Report Series No. 91.
- IAEA/WMO, 2018. Global Network of Isotopes in Precipitation [WWW Document]. URL <https://nucleus.iaea.org/wiser>
- Jódar, J., Custodio, E., Lambán, L.J., Martos-Rosillo, S., Herrera-Lameli, C., Sapriza-Azuri, G., 2016. Vertical variation in the amplitude of the seasonal isotopic content of rainfall as a tool to jointly estimate the groundwater recharge zone and transit times in the Ordesa and Monte Perdido National Park aquifer system, north-eastern Spain. *Sci. Total Environ.* 573, 505–517. <https://doi.org/10.1016/j.scitotenv.2016.08.117>
- Kettles, I., 1992. Surficial Geology, Perth, Ontario, Geological Survey of Canada, “A” Series Map 1800A.
- Krolik, J., Maier, A., Evans, G., Belanger, P., Hall, G., Joyce, A., Majury, A., 2013. A spatial analysis of private well water *Escherichia coli* contamination in southern Ontario. *Geospatial Health* 8, 65. <https://doi.org/10.4081/gh.2013.55>

- Lapcevic, P.A., Novakowski, K.S., Sudicky, E.A., 1999. Groundwater Flow and Solute Transport in Fractured Media, in: Handbook of Groundwater Engineering. Springer-Verlag, Berlin Heidelberg.
- Lauber, U., Goldscheider, N., 2014. Use of artificial and natural tracers to assess groundwater transit-time distribution and flow systems in a high-alpine karst system (Wetterstein Mountains, Germany). *Hydrogeol. J.* 22, 1807–1824. <https://doi.org/10.1007/s10040-014-1173-6>
- Lee, K.-S., Kim, J.-M., Lee, D.-R., Kim, Y., Lee, D., 2007. Analysis of water movement through an unsaturated soil zone in Jeju Island, Korea using stable oxygen and hydrogen isotopes. *J. Hydrol.* 345, 199–211. <https://doi.org/10.1016/j.jhydrol.2007.08.006>
- Levison, J., Novakowski, K., 2009. The impact of cattle pasturing on groundwater quality in bedrock aquifers having minimal overburden. *Hydrogeol. J.* 17, 559–569. <https://doi.org/10.1007/s10040-008-0385-z>
- Levison, J.K., Novakowski, K.S., 2012. Rapid transport from the surface to wells in fractured rock: A unique infiltration tracer experiment. *J. Contam. Hydrol.* 131, 29–38. <https://doi.org/10.1016/j.jconhyd.2012.01.001>
- Leyland, J.G., Mihychuk, M., Assistants, 1983. Quaternary Geology, Tweed Area, Southern Ontario.
- Lomb, N.R., 1976. Least-squares frequency analysis of unequally spaced data. *Astrophys. Space Sci.* 39, 447–462. <https://doi.org/10.1007/BF00648343>
- Lubianetzky, T.A., Dickson, S.E., Guo, Y., 2015. Proposed method: incorporation of fractured rock in aquifer vulnerability assessments. *Environ. Earth Sci.* 74, 4813–4825. <https://doi.org/10.1007/s12665-015-4471-y>
- McFall, G., 1993. Structural Elements and Neotectonics of Prince Edward County, Southern Ontario. *Géographie Phys. Quat.* 47, 303–312. <https://doi.org/10.7202/032959ar>
- Miles, O., 2013. Processes governing rapid recharge events in a shallow fractured rock aquifer having minimal overburden cover (Thesis). Queen's University, Kingston, ON.

- Miles, O.W., Novakowski, K.S., 2016. Large water-table response to rainfall in a shallow bedrock aquifer having minimal overburden cover. *J. Hydrol.* 541, 1316–1328.
<https://doi.org/10.1016/j.jhydrol.2016.08.034>
- Milloy, C.A., 2007. Measurement of hydraulic head for the evaluation of groundwater recharge to discrete fracture zones in a crystalline bedrock aquifer (Thesis). Queen's University, Kingston, ON.
- MNRF, 2018. Low Water Response Program [WWW Document]. Ontario.ca. URL <https://www.ontario.ca/page/low-water-response-program>
- Mueller, M.H., Alaoui, A., Kuells, C., Leistert, H., Meusburger, K., Stumpp, C., Weiler, M., Alewell, C., 2014. Tracking water pathways in steep hillslopes by $\delta^{18}\text{O}$ depth profiles of soil water. *J. Hydrol.* 519, 340–352. <https://doi.org/10.1016/j.jhydrol.2014.07.031>
- Negrel, P., Pauwels, H., Dewandel, B., Gandolfi, J.M., Mascré, C., Ahmed, S., 2011. Understanding groundwater systems and their functioning through the study of stable water isotopes in a hard-rock aquifer (Maheshwaram watershed, India). *J. Hydrol.* 397, 55–70.
<https://doi.org/10.1016/j.jhydrol.2010.11.033>
- Nimmo, J.R., Horowitz, C., Mitchell, L., 2015. Discrete- Storm Water- Table Fluctuation Method to Estimate Episodic Recharge. *Groundwater* 53, 282–292. <https://doi.org/10.1111/gwat.12177>
- NRCan, 2011. Perth, Ontario. Canadian topographic maps 1915-885831-C/16.
- NRCan, 2010. Tweed, Ontario. Canadian topographic maps 1915-885831-C/6.
- Nunes, M.A., Aravena, R., Parker, B.L., Clark, I., 2017. Geochemical and Isotopic Study of Bedrock Groundwater in the City of Guelph, Canada. *Procedia Earth Planet. Sci.*, 15th Water-Rock Interaction International Symposium, WRI-15 17, 921–923.
<https://doi.org/10.1016/j.proeps.2017.01.018>
- Ontario Geological Survey, 2011. 1:250 000 scale bedrock geology of Ontario. Miscellaneous Release---Data 126-Revision 1.

- Ontario Geological Survey, 2010. Surficial Geology of Southern Ontario. Miscellaneous Release--Data 128-REV.
- Ontario Geological Survey, 2001. Precambrian Geology: Kaladar Area.
- Oxtobee, J.P.A., Novakowski, K., 2002. A field investigation of groundwater/surface water interaction in a fractured bedrock environment. *J. Hydrol.* 269, 169–193. [https://doi.org/10.1016/S0022-1694\(02\)00213-5](https://doi.org/10.1016/S0022-1694(02)00213-5)
- Padilla, C., Onda, Y., Iida, T., 2015. Interaction between runoff – bedrock groundwater in a steep headwater catchment underlain by sedimentary bedrock fractured by gravitational deformation. *Hydrol. Process.* 29, 4398–4412. <https://doi.org/10.1002/hyp.10498>
- Persaud, E., Levison, J., Pehme, P., Novakowski, K., Parker, B., 2018. Cross-hole fracture connectivity assessed using hydraulic responses during liner installations in crystalline bedrock boreholes. *J. Hydrol.* 556, 233–246. <https://doi.org/10.1016/j.jhydrol.2017.11.008>
- Praamsma, T., Novakowski, K., Kyser, K., Hall, K., 2009. Using stable isotopes and hydraulic head data to investigate groundwater recharge and discharge in a fractured rock aquifer. *J. Hydrol.* 366, 35–45. <https://doi.org/10.1016/j.jhydrol.2008.12.011>
- QCA, 2016. Level 3 Low Water Condition [WWW Document]. Quinte Conserv. URL http://quinteconservation.ca/site/index.php?option=com_content&task=view&id=305&Itemid=68 (accessed 7.4.18).
- Rasmussen, T.C., Crawford, L.A., 1997. Identifying and Removing Barometric Pressure Effects in Confined and Unconfined Aquifers. *Groundwater* 35, 502–511. <https://doi.org/10.1111/j.1745-6584.1997.tb00111.x>
- Regan, S., Goodhue, R., Naughton, O., Hynds, P., 2017. Geospatial drivers of the groundwater $\delta^{18}\text{O}$ isoscape in a temperate maritime climate (Republic of Ireland). *J. Hydrol.* 554, 173–186. <https://doi.org/10.1016/j.jhydrol.2017.09.017>

- Reilly, T.E., Franke, O.L., Bennett, G.D., 1989. Bias in Groundwater Samples Caused by Wellbore Flow. *J. Hydraul. Eng.* 115, 270–276. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1989\)115:2\(270\)](https://doi.org/10.1061/(ASCE)0733-9429(1989)115:2(270))
- Reisch, C.E., Toran, L., 2014. Characterizing snowmelt anomalies in hydrochemographs of a karst spring, Cumberland Valley, Pennsylvania (USA): evidence for multiple recharge pathways. *Environ. Earth Sci.* 72, 47–58. <https://doi.org/10.1007/s12665-013-2935-5>
- Rodhe, A., Bockgård, N., 2006. Groundwater recharge in a hard rock aquifer: A conceptual model including surface-loading effects. *J. Hydrol.* 330, 389–401. <https://doi.org/10.1016/j.jhydrol.2006.03.032>
- Saha, D., Dwivedi, S.N., Roy, G.K., Reddy, D.V., 2013. Isotope-based investigation on the groundwater flow and recharge mechanism in a hard-rock aquifer system: the case of Ranchi urban area, India. *Hydrogeol. J.* 21, 1101–1115. <https://doi.org/10.1007/s10040-013-0974-3>
- Saxena, R.K., 1984. Surface and groundwater mixing and identification of local recharge-discharge zones from seasonal fluctuations of Oxygen-18 in groundwater in fissured rock. *IAHS Press* 150, 419–428.
- Shapiro, A.M., 2002. Cautions and Suggestions for Geochemical Sampling in Fractured Rock. *Ground Water Monit. Remediat.* 22, 151–164. <https://doi.org/10.1111/j.1745-6592.2002.tb00764.x>
- Singer, S.N., Cheng, C., Scafe, M.G., 2003. The hydrogeology of Southern Ontario - Second Edition, Hydrogeology of Ontario Series. Ministry of the Environment, Toronto Ontario.
- Singhal, B.B.S., Gupta, R.P., 2010. Applied hydrogeology of fractured rocks, 2nd ed. ed. Springer, Dordrecht ; New York.
- Spane, F.A., 2002. Considering barometric pressure in groundwater flow investigations. *Water Resour. Res.* 38, 14-1-14–18. <https://doi.org/10.1029/2001WR000701>
- Sterling, S.N., Parker, B.L., Cherry, J.A., Williams, J.H., Lane, J.W., Haeni, F.P., 2005. Vertical Cross Contamination of Trichloroethylene in a Borehole in Fractured Sandstone. *Groundwater* 43, 557–573. <https://doi.org/10.1111/j.1745-6584.2005.0087.x>

- Taylor, S., Feng, X., Kirchner, J.W., Osterhuber, R., Klaue, B., Renshaw, C.E., 2001. Isotopic evolution of a seasonal snowpack and its melt. *Water Resour. Res.* 37, 759–769.
<https://doi.org/10.1029/2000WR900341>
- Tweed, S.O., Weaver, T.R., Cartwright, I., 2004. Distinguishing groundwater flow paths in different fractured-rock aquifers using groundwater chemistry: Dandenong Ranges, southeast Australia. *Hydrogeol. J.* 13, 771–786. <https://doi.org/10.1007/s10040-004-0348-y>
- Velderman, B.-J., 1994. Groundwater recharge and contamination: Sensitivity analysis for carbonate aquifers in south-eastern Ontario. The Jock River Basin study. (Thesis). University of Ottawa (Canada).
- Weeks, E.P., 2002. The Lisse Effect Revisited. *Groundwater* 40, 652–656. <https://doi.org/10.1111/j.1745-6584.2002.tb02552.x>
- Wilson, M.E., 1930. Perth Lanark and Leeds Counties Ontario.
- Winograd, I.J., Riggs, A.C., Coplen, T.B., 1998. The relative contributions of summer and cool-season precipitation to groundwater recharge, Spring Mountains, Nevada, USA. *Hydrogeol. J.* 6, 77–93.
<https://doi.org/10.1007/s100400050135>
- Woo, M.-K., Marsh, P., 2005. Snow, frozen soils and permafrost hydrology in Canada, 1999–2002. *Hydrol. Process.* 19, 215–229. <https://doi.org/10.1002/hyp.5772>
- Wu, X., Zhu, X., Pan, M., Zhang, M., 2014. Seasonal variability of oxygen and hydrogen stable isotopes in precipitation and cave drip water at Guilin, southwest China. *Environ. Earth Sci.* 72, 3183–3191. <https://doi.org/10.1007/s12665-014-3224-7>
- Yonge, C.J., Ford, D.C., Gray, J., Schwarcz, H.P., 1985. Stable isotope studies of cave seepage water. *Chem. Geol. Isot. Geosci. Sect.* 58, 97–105. [https://doi.org/10.1016/0168-9622\(85\)90030-2](https://doi.org/10.1016/0168-9622(85)90030-2)
- Zanini, L., Novakowski, K.S., Lapcevic, P., Bickerton, G.S., Voralek, J., Talbot, C., 2000. Ground Water Flow in a Fractured Carbonate Aquifer Inferred from Combined Hydrogeological and

Tay

Kennedy Field Station

Hydraulic Head (mbtoc)

Precipitation (mm/cm)

(a) Crystalline

(b) Sandstone

(c) Limestone

Unconfined

Semi-confined

Confined

High
Low

Strength of isotopic
snowmelt signal

Isotopic
diffusive halo

Major fracture
Minor fracture

Geochemical Measurements. Groundwater 38, 350–360. <https://doi.org/10.1111/j.1745-6584.2000.tb00220.x>

Figure 10. Regional geologic map of the study area and field site locations. (a-c) Detailed field site maps, where contour lines are in meters above sea level spaced at 10 m increments. (d) Location of the study relative to Canada.

Figure 11. (a) LMWLs for the study sites, Ottawa GNIP station and the GMWL. (b) LMWLs zoomed to a scale reflective of groundwater values measured in the study. Error bars are approximately the size of data symbols.

Figure 12. (a) Temporal deuterium results for lysimeters at the Tay site. (b) Temporal deuterium results for lysimeters at KFS (c) Cross-plots for lysimeters at the Tay site. (d) Cross-plots for lysimeters at KFS. Error bars are approximately the size of the data symbol.

Figure 13. Temporal deuterium results for all wells. Note, for direct comparison the vertical scale for deuterium is consistent for all wells except for KC1. The temporal scale is uniform across all wells with uniform axes. To the right of each isotope plot is the corresponding transmissivity profile and multi-level well diagram. Transmissivity is represented as a logarithmic value. Note that the error bar for each plot is illustrated in the lower left corner of the diagram.

Figure 14. Cross plots of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ for all study wells with respective LMWLs. Note the error bar is shown in the upper left corner of each diagram.

Figure 15. Manual measurements and pressure transducer data for hydraulic head in meters below top of casing (mbtoc) for each well. Snowpack thickness and rainfall data is included in the lower well plot for each of the three sites and all well plots maintain horizontal scale. Negative values in KC1 represent artesian conditions measured above top of casing (toc).

Figure 16. Example plots of hydraulic head and temperature response to snowmelt events. (a) Hydraulic head data for TW6 during spring melt, 2018 where logger data has been corrected with manual water level measurements and influences on water level from sampling has been removed. (b) Groundwater temperature measured at the midpoint of TW6 intervals and rainfall and snowpack thickness from Drummond Centre climate station approximately 15 km north of the site (Environment and Climate Change Canada, 2018). A moving average of three hours has been applied to the shallow temperature data to reduce noise.

Figure 17. Ranges of deuterium values of precipitation, lysimeters and wells for (a) the Tay site and (b) the Kennedy Field Site and Kingsford. Shallow (LS) and deep (LD) lysimeter results are a combination of multiple lysimeters at the site.

Figure 18. Conceptual models for groundwater recharge and seasonal isotopic attenuation for (a) crystalline, (b) sandstone and (c) limestone rock types based on results of the study. Vertical scale is exaggerated, and fracture features are emphasized for clarity. Figures are horizontally-exaggerated to an arbitrary scale. The water table sits just below the surface indicated with a white dashed line. The strength

and direction of flow is denoted with arrows where black is the isotopic input signal and light grey represents background conditions. For clarity, only select flow paths and diffusive halos are included along example fractures.

ACCEPTED MANUSCRIPT

Highlights

- Multi-level wells in multiple rock types were temporally sampled for $\delta^2\text{H}$ and $\delta^{18}\text{O}$
- Isotopic periodicity in all rock types indicates strong surface connections
- Isotopic attenuation is highest with increased depth and matrix porosity
- Snowmelt recharge occurs through both long, slow and short, rapid flow paths
- Multi-level wells are vital for resolving flow and recharge processes in bedrock