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Journal of Hydrology 269 (2002) 169–193

Journal of Hydrology

www.elsevier.com/locate/jhydrol

A field investigation of groundwater/surface water interaction in a fractured bedrock environment

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Received 5 October 2001; revised 2 July 2002; accepted 12 July 2002

Abstract

To facilitate a better understanding of the exchange processes between a fractured rock aquifer and a bedrock stream, a study of groundwater/surface water interaction between Twenty Mile Creek and the local aquifer in Smithville, Ont. was completed. The points of interaction between the creek and the local aquifer were identified and quantified through the use of air-photo interpretation, detailed stream surveys, electrical conductivity and temperature surveys, isotopic analysis, mixing calculations, and point measurements of hydraulic head and discharge obtained using mini-piezometers, seepage meters and weirs. The results indicate that the interaction between Twenty Mile Creek and the local aquifer is extremely limited with greater than 95% of the groundwater within the study area underflowing the creek completely during baseflow conditions. In addition, it was observed that groundwater discharge in a bedrock stream environment occurs primarily through discrete point sources associated with open fractures, as compared to more diffuse, or continuous seepage zones often observed in a porous media environment. The small quantity of groundwater discharging into Twenty Mile Creek through these features has an electrical conductivity and isotopic signature consistent with shallow groundwater and most likely originates in the upper 3–7 m of bedrock. Although previous investigations have identified potentially open vertical fractures within the study area, it is apparent that the fracture network has extremely poor vertical connections, limiting groundwater exchange in the vicinity of the creek. In addition, the low velocity and discharge rate within the creek does not allow for incising into the bedrock. As a result, horizontal fractures do not play a significant role in the exchange process within the study area.

Keywords: Groundwater discharge; Groundwater/surface water interaction; Isotopes; Field study; Fractured rock

1. Introduction

Understanding the interaction between groundwater and surface water can be important for water resources management, and in the determination of migration pathways for contaminants. The degree of interaction can depend on a number of factors including topography, underlying geology, subsurface hydraulic properties, temporal variation in precipitation, and local groundwater flow patterns (Cey et al., 1998).

In many watersheds, it is commonly assumed that groundwater makes up the majority of stream flow during periods of baseflow (Freeze and Cherry, 1979). However, this concept is defined for streams

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0022-1694/02/$ - see front matter © 2002 Published by Elsevier Science B.V.
PII: S0022-1694(02)00213-5

underlain by porous media, not fractured rock. When sedimentary or crystalline rock constitutes the principal aquifer, and the stream flows directly on the bedrock, the nature of the exchange between the surface water and local aquifer can become extremely complex (Novakowski et al., 2000).

To assist in quantifying the interaction between a groundwater flow system, and stream environment, field investigations are often conducted to measure the exchange. Detailed measurements of stream discharge at the upstream and downstream end of the study area can be used to estimate groundwater contributions (Devito et al., 1996; Cey et al., 1998). Once all fluxes into (agricultural runoff, tile drains, etc.), or out of the stream are accounted for, with the exception of groundwater/surface water exchange, an estimate of net groundwater flux can be obtained through mass balance.

Seepage meters and mini-piezometers are simple devices that allow for the collection of hydraulic data directly from the streambed (Lee, 1978; Lee and Cherry, 1978; Woessner and Sullivan, 1984; Shaw and Prepas, 1990; Cey et al., 1998). Mini-piezometers provide information on the hydraulic gradient, while seepage meters allow for the direct measurement of seepage flux between the groundwater system and the overlying surface water. Both instruments provide a means for collecting samples for electrical conductivity and isotopic analysis.

In many study areas, groundwater displays a distinctive isotopic signature compared to surface water (Jacobson et al., 1991; Space et al., 1991; McCarthy et al., 1992; Acheampong and Hess, 2000). Once these signatures have been established through stable isotope analysis (Oxygen-18 and deuterium), sampling results can be used to help locate, and confirm groundwater discharge points.

Groundwater discharge points are often characterized by sharp changes in temperature distribution and/or electrical conductivity along the sediment–water interface (Lee, 1985; Jacobson et al., 1991; Silliman and Booth, 1993; Silliman et al., 1995; Harvey et al., 1997; Zondlo, 1998). These anomalies allow for the identification of groundwater discharge points using electrical conductivity and temperature probes. This method provides a quick and inexpensive means of locating groundwater discharge points, but is ineffective in quantifying the exchange.

To date, limited fieldwork has been completed on groundwater/surface water interaction in fractured bedrock stream environments. Zondlo (1998) focused on identifying areas of groundwater discharge on the basis of differences in temperature and electrical conductivity for a field site near Oak Ridge, TN. The study concluded that using specific conductance and temperature to locate groundwater discharge would be best suited to settings where surface water flow rates are negligible to non-existent, and where surface water temperatures remained relatively constant during the time required to complete a survey. In addition, few discharge points were detected in areas where thick sediment blankets the river or creek bottom. In these areas, groundwater appears to discharge as diffuse seepage zones, or as a continuous seepage face. Conversely, more discrete, larger magnitude discharge points were detected in areas where bedrock was exposed along the river/creek bottom. The results of this study, however, were primarily observational and non-quantitative.

To develop a better understanding of the exchange processes between a fractured rock aquifer and a bedrock stream, a study of groundwater/surface water interaction between Twenty Mile Creek and the local aquifer (the Lockport Formation) in Smithville, Ont. was completed during the 1999 and 2000 field seasons. Within the study area, large portions of Twenty Mile Creek are known to bottom directly on bedrock providing potential locations for groundwater and surface water exchange. The study was conducted during baseflow conditions and during storm events using tools developed primarily for studies conducted in porous media.

2. Field setting and hydrogeology

The study area is centered around the community of Smithville, Ont. located above the Niagara Escarpment, in the middle of the Niagara Peninsula. Fig. 1 illustrates the regional setting of the study area. Based on an initial stream survey combined with air-photo analysis, an 8-km reach of Twenty Mile Creek was selected for the study. The downstream limit of the study reach is located below the confluence of

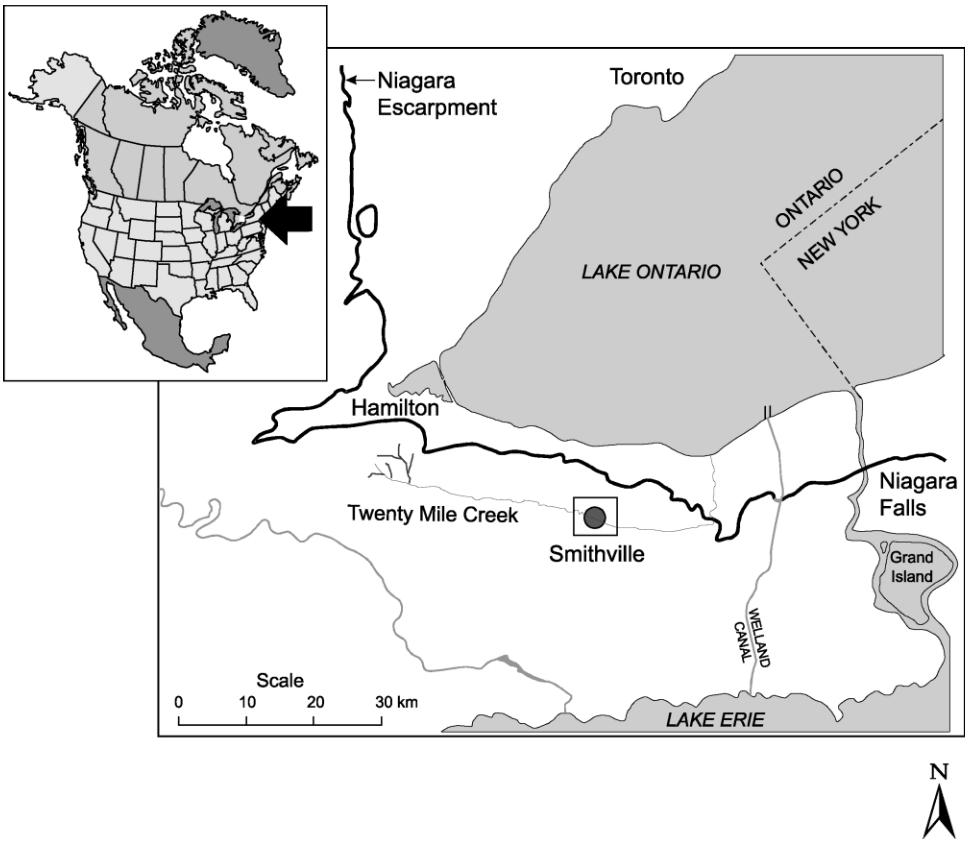

Fig. 1. Regional setting of the study area.

Twenty Mile Creek and North Creek. North Creek is a small tributary of Twenty Mile Creek draining agricultural land to the south of Smithville. Fig. 2 shows the study reaches for both creeks.

Within the study area, the depth of Twenty Mile Creek is typically less then 1 m, but can grow to a depth greater than 3 m during spring freshet or major storm events. The width of Twenty Mile Creek varies between 4 and 23 m depending on location within the study area. Wider sections are typically associated with deep, slow moving water, and are often located upstream from topographic rises. A survey of historical discharge data for Twenty Mile Creek (1987–1995) indicates the maximum recorded discharge was 80.5 m^3/s, and the minimum was 0 m^3/s, with an annual average discharge of approximately 1.66 m^3/s. In general, North Creek is similar in depth to Twenty Mile Creek, but is typically narrower, and has a much smaller watershed (approximately 34 versus 293 km^2; Tinkler, 1999).

The local topography is gently rolling to flat and ranges from approximately 200 m above sea level (masl) along the northern edge of the study area to approximately 180 masl at the banks of North Creek. Surveying indicated that the changes in relief for Twenty Mile Creek and North Creek were approximately 9 and 7.5 m, respectively, within the study area. This translates to a streambed gradient of approximately 0.001 for both streams, resulting in a low surface water velocity throughout the study area.

The study area is underlain by the Haldimand Clay Plain, and the overburden soils are predominantly poorly drained lacustrine clay to silty clay overlying clay loam till (Chapman and Putnam, 1984). The hydraulic conductivity of the intact till is 2×10^{-10} m/s, although the upper weathered till

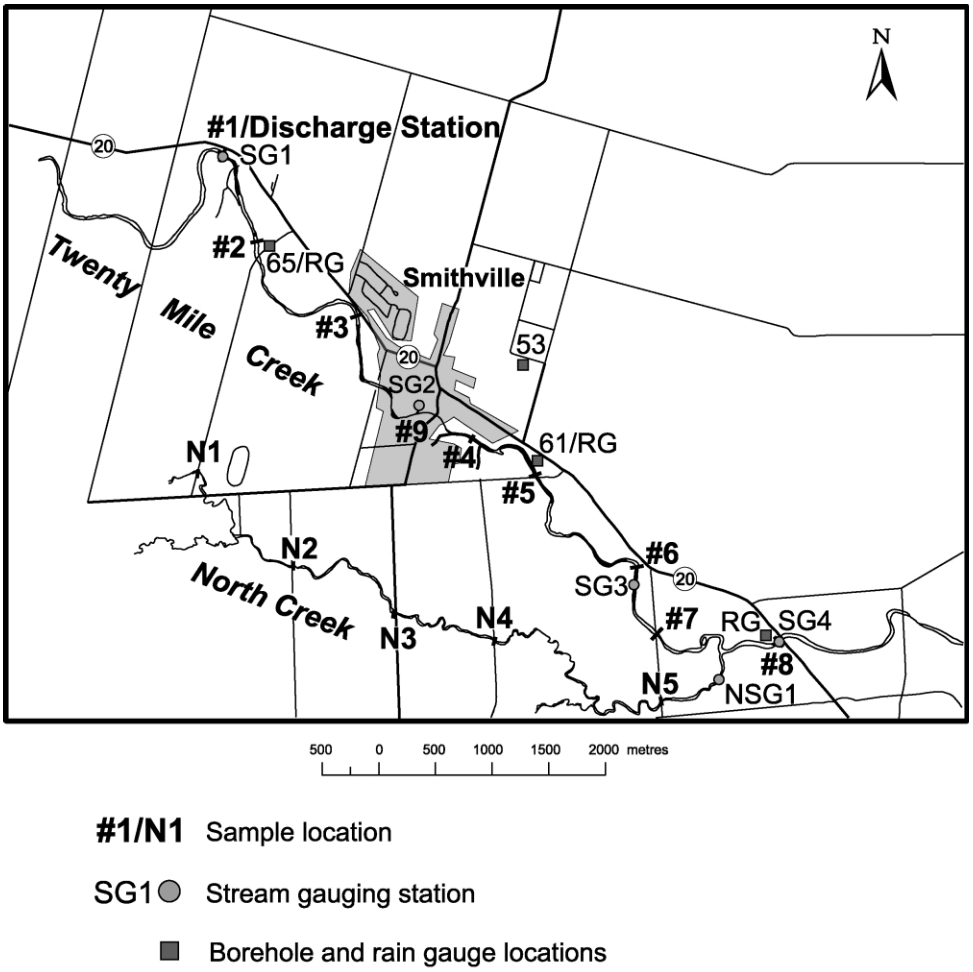

Fig. 2. Map displaying the study area, stream gauging stations, and sample locations.

may have a hydraulic conductivity 2–3 orders of magnitude higher (Ruland et al., 1991; McKay et al., 1993). The overburden thickness varies considerably in the region and generally increases to the south. Data collected from piezometers and boreholes installed in the vicinity of Twenty Mile Creek indicate the drift thickness adjacent to the creek varies from approximately 1 to 5 m.

The bedrock underlying the Smithville area consists of a sequence of flat-lying bedded dolostones having a southward regional dip between 0 and 2°. The dip varies locally according to large-scale structural elements, the presence of bioherms, and facies changes (Novakowski et al., 1999). The bedrock contacts in the Smithville area are displayed on Fig. 3. The course of Twenty Mile Creek closely follows the presumed contact between the Lockport and Guelph Formations resulting in the majority of the study area being underlain by dolostones of the Lockport Formation, while in the extreme southern portion, the Guelph Formation overlays the Lockport. The Lockport Formation is divided into four members; the Eramosa, Vinemount, Goat Island, and the Gasport, which total approximately 40 m in thickness. The Lockport is underlain by the Rochester Formation, a shale of very low permeability (Novakowski et al., 1999).

Although the surface topography in the study area is relatively flat, the bedrock surface shows greater than 30 m of relief (198–168 masl). A bedrock high is

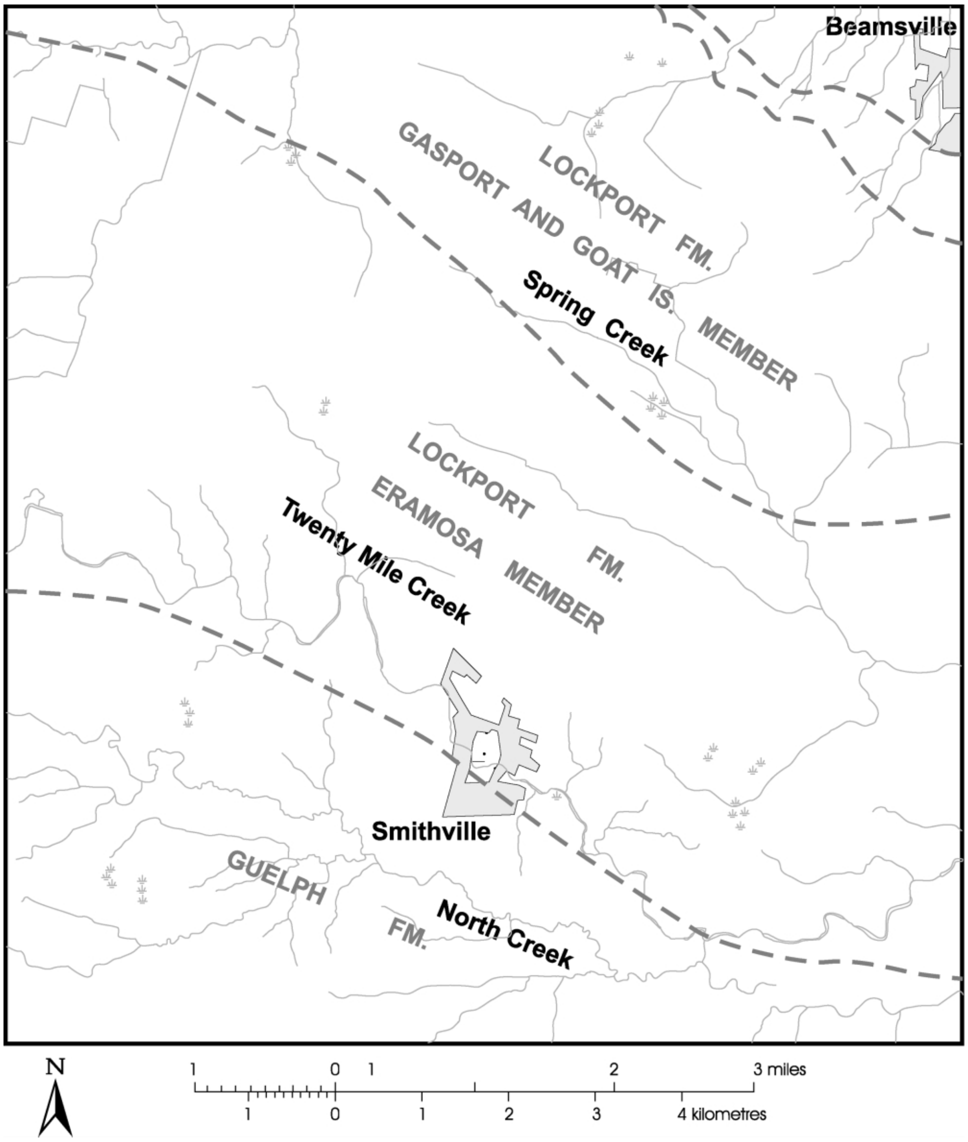

Fig. 3. Bedrock contacts in the Smithville area.

located within the study area approximately 3 km north of Twenty Mile Creek. In general, in the vicinity of the creeks, the bedrock surface is flat lying, and shows little change in elevation.

The relationship between the bedrock highs and lows defines the local recharge and discharge areas for the groundwater flow system in the Lockport Formation (Novakowski et al., 1999). A steady regional decline in the bedrock surface is observed to occur in a southerly direction across the study area. An increasingly thick layer of glacial material to the south maintains the relatively flat surface topography.

The flow of groundwater in the Lockport Formation is primarily through large-aperture horizontal fractures of significant lateral extent (Zanini et al., 2000). Overall, the direction of groundwater flow in the bedrock is controlled by the governing hydraulic gradient, and the orientation of the high permeability fractures relative to that gradient. Exchange in the vertical direction between horizontal flow paths is controlled by smaller, less frequent vertical fractures. The results of pumping tests completed using a cluster of boreholes within the study area confirmed interwell connectivity through horizontal fractures at a scale up to 125 m, and showed that the contribution of the vertical fractures to the flow system is not significant (Novakowski et al., 1999).

Within the study area, the Lockport Formation is approximately 40 m thick and can be divided into an upper and lower flow system by a 2–4 m thick, low permeability horizon located near the midpoint of the formation (Zanini et al., 2000). In the lower flow system, groundwater travels slowly suggesting poor interconnection of the fracture system at depth. The upper flow system is more active, with groundwater velocities as high as 30 m/day measured in the uppermost member (Novakowski et al., 1999).

Based on measurements obtained by Novakowski et al. (1999), the groundwater flow directions for the Upper Eramosa (immediately underlying Twenty Mile Creek) are displayed in Fig. 4. The estimated directions were based on the spring measurements of hydraulic head in all boreholes completed by within the study area. The direction of groundwater flow in the Upper Eramosa north of Twenty Mile Creek is uniformly south towards the creek.

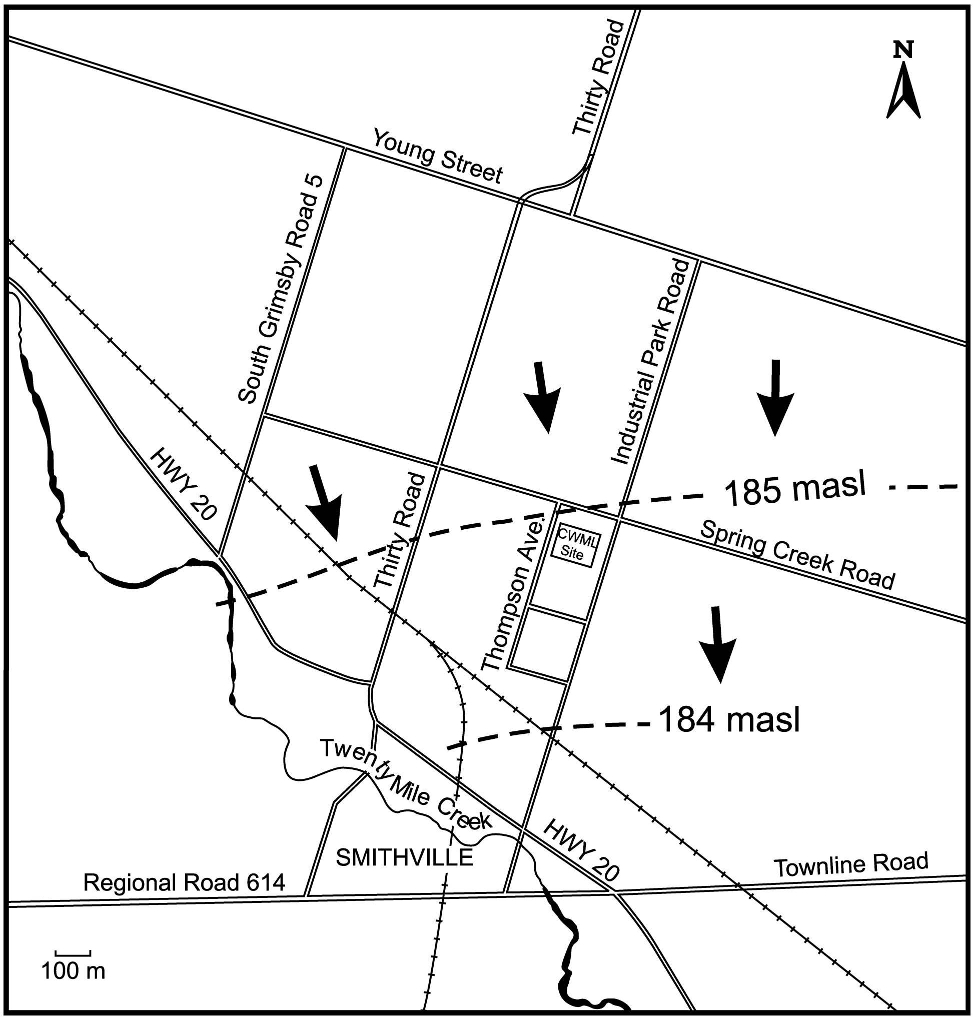

Fig. 4. Groundwater flow directions in the Upper Eramosa unit based on spring hydraulic head measurements (Novakowski et al., 1999).

Water level results obtained from a group of shallow monitoring wells (completed in the upper 1–3 m of bedrock) located on the south side of Twenty Mile Creek during 1999 indicate shallow groundwater is flowing northerly towards the creek. The positions of the shallow wells are displayed on Fig. 5. An approximate direction of the horizontal component of the hydraulic gradient for this area was determined using OW2, OW4, and OW3–5 all of which are completed at approximately the same elevation in the upper bedrock unit. The resulting groundwater flow direction assuming homogeneous, isotropic media is displayed on Fig. 5. Based on hydraulic head measurements for OW3–5 and OW3–10, the vertical component of the hydraulic gradient is interpreted as upward in the area adjacent to the creek.

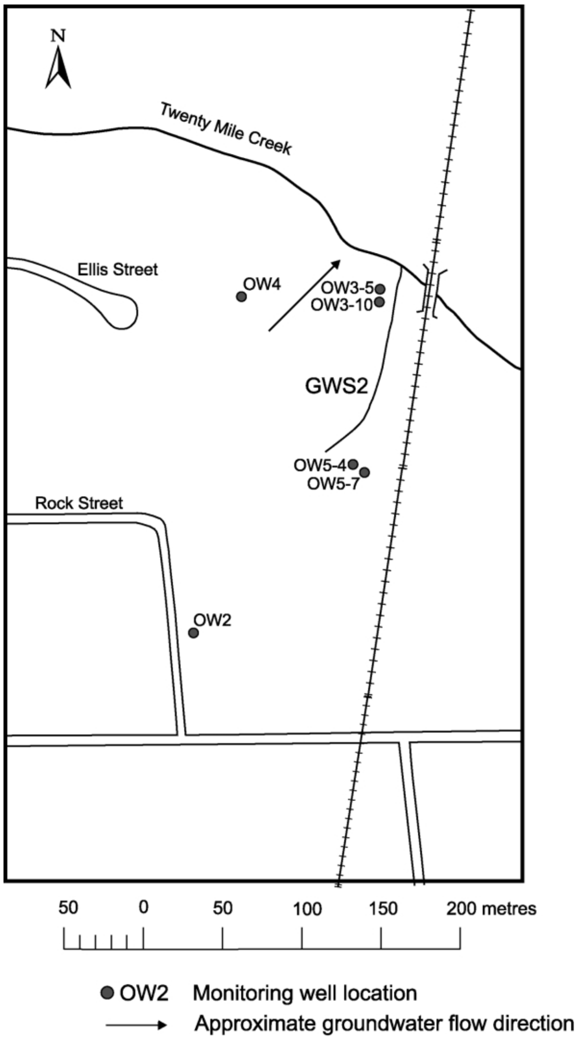

Fig. 5. Location of monitoring wells, and the approximate groundwater flow direction on the south-side of Twenty Mile Creek.

3. Field investigations

For groundwater to discharge in large volumes into Twenty Mile Creek, a direct connection between the underlying fracture network and the streambed would be required. In this environment, locating and quantifying the exchange at points where the creek is connected to the fracture network through horizontal and/or vertical fractures is the primary objective of the field investigations.

For this study, the points of interaction were identified and quantified through the use of air-photo interpretation, detailed stream surveys, electrical conductivity and temperature surveys, isotopic analysis, mixing calculations, and point measurements of hydraulic head and discharge obtained using mini-piezometers, seepage meters and weirs.

An air-photo interpretation of the study area was conducted to assist in locating natural and anthropogenic features contributing to streamflow. These can include agricultural runoff, storm water outfalls, tile drains, and local intermittent rivulets. The air-photos were completed using an infrared camera which is sensitive to ground moisture. The air-photos were produced at a scale of 1:10,000 and were interpreted using stereo pairs. The air-photo interpretation also included the identification of potential karst features, regional-scale fractures, bedrock outcrops, and assisted in defining the extent of the study area.

3.1. Stream surveys

A detailed stream survey was conducted to visually identify areas of the creek that bottom directly on bedrock, to locate major areas of water loss, and to verify features identified from air-photos. During the stream survey, potential stations for the measurement of electrical conductivity and stream discharge were also identified. In addition, an electrical conductivity meter was towed down the length of the study area to obtain continuous conductivity readings.

Historical flow values obtained from a stream gauging station located adjacent to sample location #1 in Twenty Mile Creek were plotted to identify regular, seasonal patterns. The location of the station is displayed on Fig. 2. Daily discharge measurements from January 1, 1987 to December 13, 1995 were reviewed.

Groundwater present in the Eramosa member is known to have an elevated electrical conductivity in comparison to surface water in the study area (Zanini et al., 2000). Surface water typically has an electrical conductivity below 1.0 mS/cm, while the groundwater in the Eramosa unit has an electrical conductivity between 2 and 4 mS/cm (Zanini et al., 2000). In addition, because the fieldwork was completed during the summer months, a sharp contrast in temperature between the groundwater and surface water was expected. The groundwater temperature remains relatively constant at approximately 10 °C (Zanini et al., 2000), while the surface water temperature can range between 15 and 26 °C during the late spring, and summer. As a result, both continuous and discrete electrical conductivity and temperature measurements were obtained over the course of the field seasons to locate potential groundwater discharge points.

Point measurements of electrical conductivity were obtained along an 8-km reach of Twenty Mile Creek at the nine sample locations indicated on Fig. 2. Eight sample stations were originally located and denoted #1–#8 in the downstream direction. Location #9 was added upon the discovery of a stream resurface point adjacent to the creek. The sample stations were chosen to evenly cover the study area. Sufficient water depth was required at these locations to ensure that sampling could be completed for the duration of the summer. Electrical conductivity surveys at these locations were completed on a weekly to biweekly basis over a period of 30 weeks (May 17–December 10, 1999).

Five sample locations along an 8-km reach of North Creek were selected using the same criteria as for those in Twenty Mile Creek. The location of stations N1–N5 is shown on Fig. 2. Conductivity values were obtained on a weekly to biweekly basis over a period of 28 weeks (June 7–December 10, 1999).

To provide confidence in electrical conductivity survey results, the conductivity meter was calibrated before entering the field, and a sampling plan was established whereby the same locations in the same order were measured during each survey. An error of approximately ± 0.03 mS/cm for the measurements was estimated by comparing duplicate measurements obtained during each survey.

During the summer months, several sections of Twenty Mile Creek ceased flow completely exposing long bedrock sections. During this time, two sections of exposed bedrock were mapped for the presence, and orientation of vertical fractures. The fracture trends were measured relative to north using a compass, and only fractures having a trace length greater than 2.0 m were recorded.

3.2. Oxygen-18 and deuterium analysis

Four rounds of water samples were collected from selected sample locations within the study area to investigate temporal variations in isotopic signatures related to changes in local precipitation and flow conditions, and to establish characteristic isotopic signatures of groundwater and surface water within the study area.

Water samples were collected from two shallow piezometers (OW3–5 and OW3–10) located adjacent to Twenty Mile Creek (see Fig. 5) to establish the characteristic δ^{18}O and δ^{2}H signatures for shallow groundwater in the study area. In addition, δ^{18}O and δ^{2}H results obtained by Novakowski et al. (1999) for groundwater samples collected within the study area were used for comparison. Results from electrical conductivity surveys completed weekly during May and June of 1999 within the creek indicate that no areas of elevated electrical conductivity (potentially associated with points of groundwater discharge) are present in the upstream portions of the study area. As a result, water samples were collected from locations #1 to #3 in Twenty Mile Creek, and N1 and N2 in North Creek to represent the isotopic signature of surface water in the study area. Stable isotopic analysis (δ^{2}H and δ^{18}O) was completed at the Environmental Isotope Lab at the University of Waterloo. The stable isotope compositions are reported in the δ notation where:

$$\delta = ((R_{sam} - R_{std})/R_{std})1000 \quad (3.1)$$

and R is the isotopic ratio (e.g. D/H) of the sample or the standard. All values are reported in per mil in reference to V-SMOW (Clark and Fritz, 1997). Positive δ values indicate the sample is enriched in the heavy isotope species, while negative δ values are typical in samples depleted in the heavy isotope species, compared to the standard, respectively.

3.3. Groundwater and stream discharge measurements

Stream discharge measurements were obtained to help identify areas of large-scale water loss, or gain within the study area. Four stations, SG1–SG4 (SG2 located in resurface point) were selected for discharge measurements within Twenty Mile Creek. Stream gauging station locations are shown on Fig. 2. Due to low water velocity within the creek, it was necessary to locate stream-gauging stations in narrow, shallow areas. The current meter method (Chow et al., 1988) was used to obtain water velocities, and discharge rates at these locations. Due to extremely low velocities in North Creek, only one station (NSG1; see location on Fig. 2) was used, and the measurements were conducted using a simple tracer experiment.

During 'baseflow' conditions (July, August, and September), the rate of groundwater discharge was measured at the identified groundwater discharge points within the study area. Where possible, mini-piezometers were installed to determine the specific area where upward hydraulic gradients were present, and flux measurement were obtained using seepage meters and weirs. For areas where installation of seepage meters or weirs was not possible, estimates of groundwater discharge were made using mixing calculations. The mini-piezometers and seepage meters were constructed and installed following the procedures outlined in Lee (1978). The weirs were constructed in 'V-notch' format using formed stainless steel.

3.4. Storm events

To explore the possible contribution of groundwater to Twenty Mile Creek from locations deeper in the Lockport Formation, a study of the response in hydraulic head and changes in electrical conductivity in boreholes 53, 61, and 65 (locations shown on Fig. 2) during rainfall events was conducted. Boreholes 61 and 65 are located adjacent to Twenty Mile Creek, and changes in electrical conductivity with respect to depth and time may occur during storm events due to interactions with the creek. For example, if a portion of the surface channel is connected to the subsurface, an increase in hydraulic head may be observed in the subsurface as the stream stage increases. Borehole 53 is located approximately 800 m up-gradient from Twenty Mile Creek. As a result, the borehole will not be affected by changes stream stage, and hydraulic heads obtained at borehole 53 will represent background groundwater conditions.

All three boreholes are completed through the entire Lockport Formation and are instrumented with the Westbay multi-level packer system allowing for the sampling of several distinct zones. Ground water samples were obtained using the Westbay sampling probe fitted with a 250 ml sampling chamber. Electrical conductivity and temperature were measured at ground surface after the samples were collected.

Measurements of hydraulic head were obtained daily from boreholes 61, 65, and 53 over two rainfall events, which occurred on May 22 and 24, 1999. Samples for electrical conductivity were collected from the boreholes on May 27, June 3, and June 10, spanning a time period where a significant rise in creek level (approximately 30 cm) was observed.

The response to storm events was also studied through in situ measurements of stream stage, electrical conductivity, and stream temperature obtained using two Hydrolab Datasonde 3 units. The purpose of this component of the study was to determine if an increase in groundwater discharge occurred during storm events.

A large fall storm event occurred over the period from November 2 to 3, 1999, when approximately 77 mm of rain fell in the Smithville area. During this event, one instrument was placed on the streambed at sample location #1 in Twenty Mile Creek, and the second at sample location N4 in North Creek (see locations on Fig. 2). The units were deployed on November 2, 1999, and retrieved on November 15, 1999. A sampling frequency of 15 min was used for both deployments.

3.5. Measurements of hydraulic head

Several times a week water level readings were obtained using a water level tape from monitoring wells OW3–5 and OW3–10 located immediately adjacent to Twenty Mile Creek. Both boreholes are cased through the overburden and screened in the upper bedrock. Fluctuations in water level within the wells during periods of high, or low flow in Twenty Mile Creek could potentially indicate interaction between groundwater and surface water at this location.

4. Results and discussion

4.1. Stream surveys

The location of potential agricultural runoff, storm sewer outfalls and karst features are shown on Fig. 6.

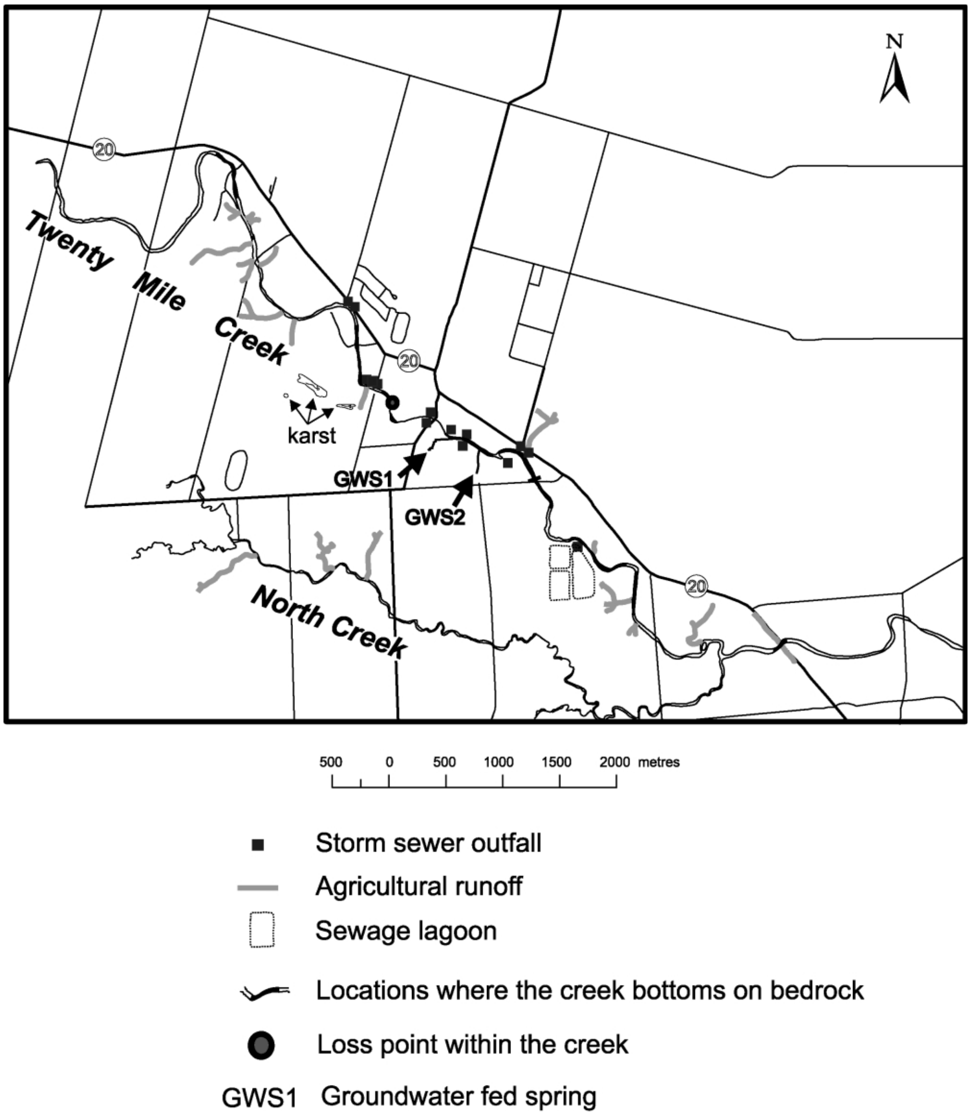

Fig. 6. Stream survey results and feature locations.

During the detailed stream survey, no bedrock shelves were observed indicating that the creek is not incising into the bedrock. Approximately 55% of the channel in Twenty Mile Creek bottoms directly on bedrock within the study area (darkened portions on Fig. 6). In the remaining portions of the creekbed, the sediment thickness ranges between 0.1 and 1 m. Storm sewer outfalls are found primarily in the middle portion of the study area as the creek passes through the center of Smithville. Areas of agricultural runoff are concentrated to the east and west of town in the rural portions of the study area. A cluster of three karst features was identified south of Twenty Mile Creek, just west of town (location shown on Fig. 6). Two groundwater fed springs which empty into Twenty Mile Creek in the central portion of the study area were identified and are also shown on Fig. 6 (labeled as GWS1 and GWS2). One major area of water loss was identified during the stream survey (location given on Fig. 6). The connection between the loss point and a resurface point (located at sample location #9 shown on Fig. 2) was established through a dilute salt tracer experiment.

The continuous electrical conductivity readings obtained during the detailed stream survey in Twenty Mile Creek (completed May 6) ranged between 0.87 and 1.05 mS/cm, and showed no zones of sharply elevated conductivity. The continuous electrical conductivity readings obtained in North Creek (completed June 3) identified one point of elevated conductivity, peaking at 3.41 mS/cm, located at sample location N4. The remainder of North Creek ranged between 0.60 and 0.73 mS/cm.

Fig. 7 shows daily stream discharge measurements obtained from a gauging station located at the upstream end of the study area for 1995. The results obtained in 1995 are typical for this section of Twenty Mile Creek. There are several large peaks in discharge associated with snowmelts and storm events, and there are significant periods over the course of the year during which no discharge is measured. According to anecdotal information obtained from town residents, it is common for large portions of Twenty Mile Creek to 'dry-up' during the summer months. This provided initial evidence that there may be very little groundwater contribution to Twenty Mile Creek within the study area during the summer months. It should be noted, during the 1999 field season, surface

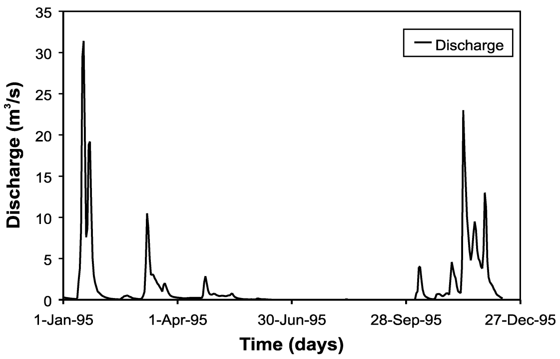

Fig. 7. Daily stream discharge measurements obtained from the gauging station located at the upper-end of the study area (within Twenty Mile Creek).

flow into the study area ceased in early July resulting in large pools separated by dry exposed bedrock sections. This marks the onset of the 'dry period', and provided ideal conditions for locating groundwater discharge points.

The results of the electrical conductivity surveys for stations 1–9 within Twenty Mile Creek for both the 'wet' and 'dry' periods are presented in Fig. 8(A) and (B), respectively. Electrical conductivity surveys completed from May 17 to June 18, 1999 (Fig. 8(A); wet period) show very little spatial or temporal variation. The conductivity consistently varies between 0.8 and 1.05 mS/cm. As expected, during the 'wet period' the flow entering Twenty Mile Creek at station #9 (the resurface point) has electrical conductivity values similar to upstream portions of the creek.

The slightly upward slope of the lines on Fig. 8(A) and (B) indicate an increase in electrical conductivity in the lower half of the study area. The increase is most obvious for surveys completed between June 28 and August 16, 1999 (dry period). This suggests that some high-conductivity groundwater is entering the stream over the study reach, or the observed increase in electrical conductivity may be a result of evaporation within the shallow disconnected pools.

Electrical conductivity surveys completed after surface flow into the study reach ceased (Fig. 8(B)) indicated three spikes at stations 5,7, and 9 within Twenty Mile Creek. The maximum electrical conductivity results were obtained during surveys completed on July 19 and 26, 1999. Stations 5 and 7 reached a peak of approximately 2.0 mS/cm, while station 9 peaked at 1.63 mS/cm. These results are well above values observed while the creek was fully connected (usually below 1 mS/cm). Once the spikes in conductivity were identified through discrete electrical conductivity surveys, a continuous survey was completed to pinpoint the sources of elevated

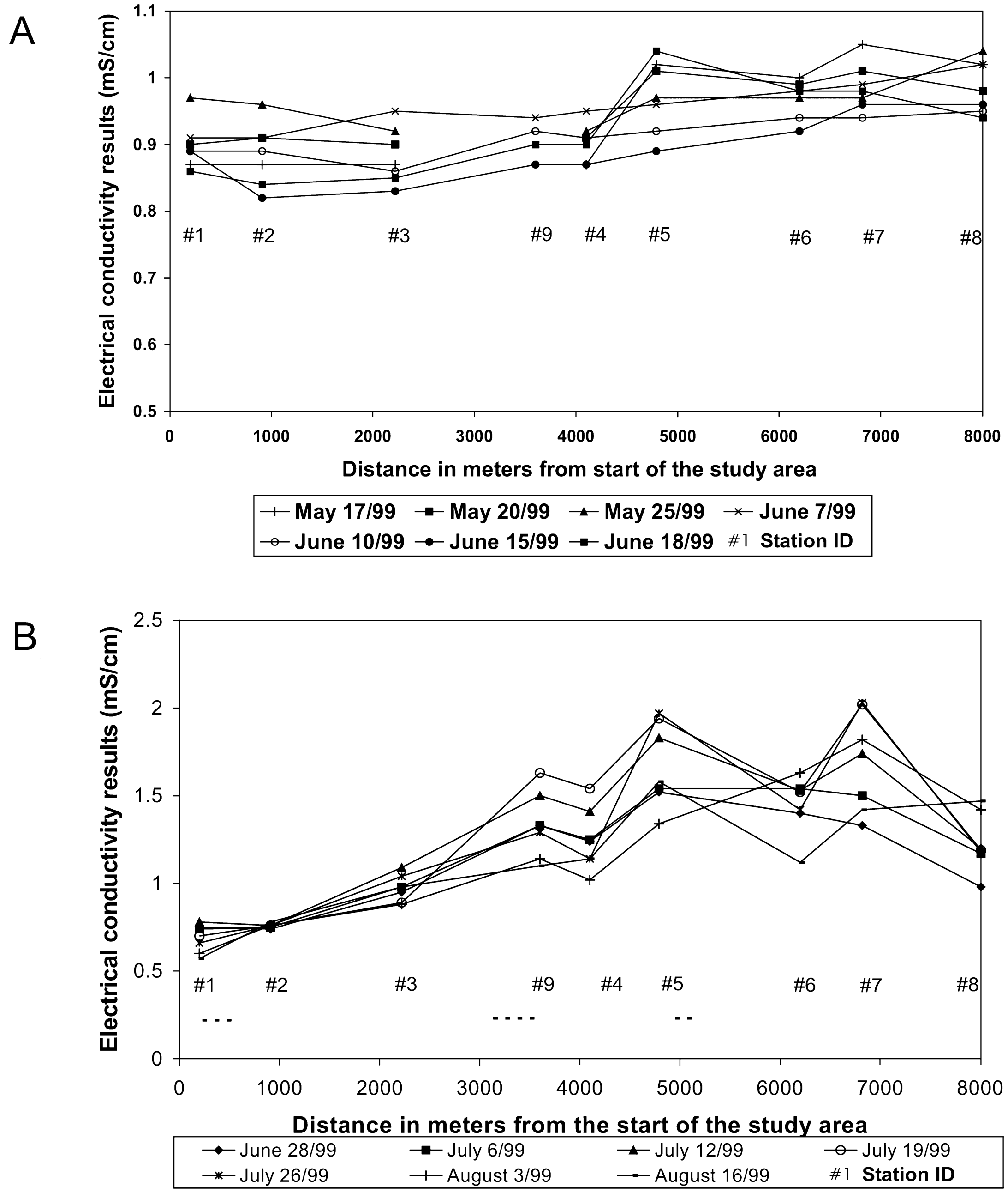

Fig. 8. Electrical conductivity results for Twenty Mile Creek during (A) the period when the creek was fully connected, and (B) the period when the creek was disconnected (dry period). Dry sections are indicated by dash lines along the bottom of the plot. Three distinct spikes in electrical conductivity are observed at stations 5, 7, and 9.

conductivity. The locations of four potential groundwater discharge points (denoted D1–D4) were identified, and are shown on Fig. 9. Each location displaying elevated electrical conductivity also displayed a corresponding decrease in water temperature on the order of 5–10 °C.

The observed increase in electrical conductivity at station #9 (resurface point; D1) during periods of extremely low flow (July 19 and 26) indicate that the flow is a mixture of surface water and groundwater at this point. The increase in electrical conductivity occurs as the contribution from the creek (relatively low conductivity water) decreases leaving only the higher conductivity groundwater portion.

With the exception of station N4, electrical conductivity values obtained within North Creek are lower than the values within Twenty Mile Creek for the same time period. The conductivity readings obtained at station N4 are consistently above 3.25 mS/cm, while values are below 1.2 mS/cm for the remainder of the creek during both the wet and dry periods. These results indicate there is only one potential groundwater discharge point in North Creek. The potential groundwater discharge location in North Creek was denoted D5, and the position is given on Fig. 9. Overall, groundwater discharge appears to be occurring primarily in the central portion of the study area.

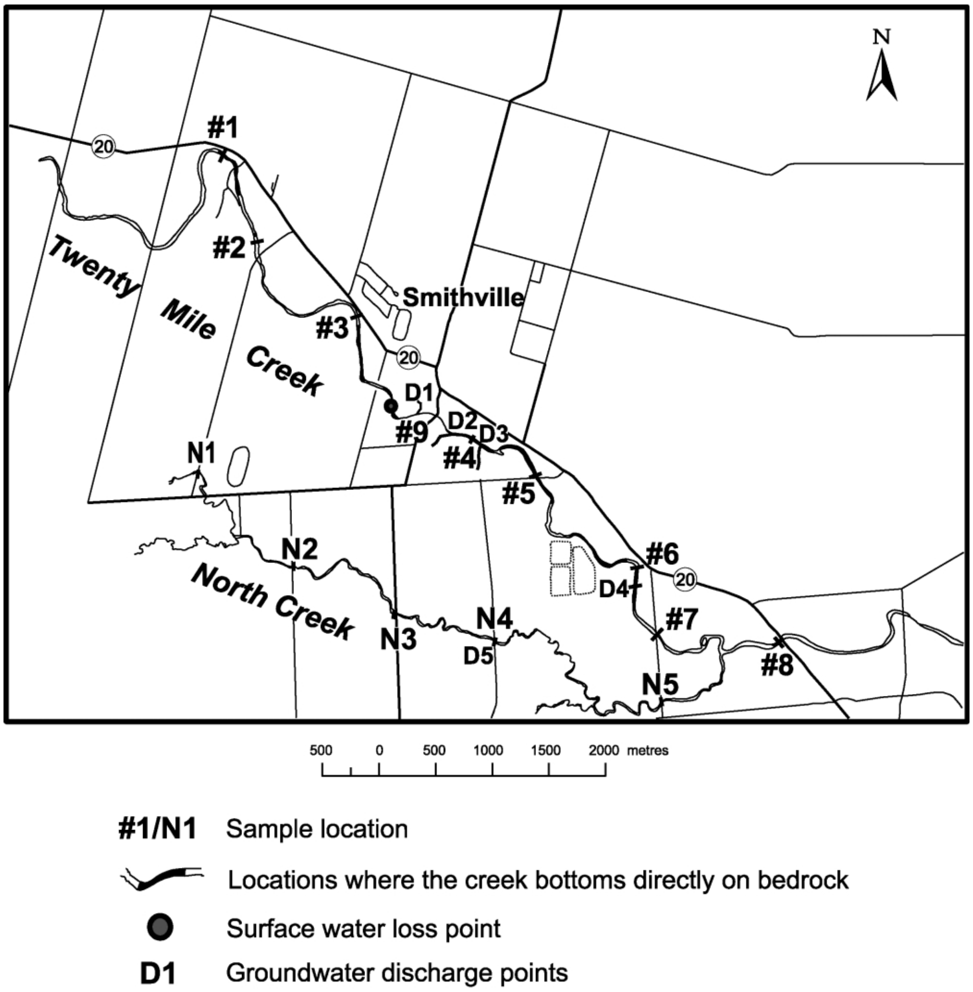

Fig. 9. Location of the potential groundwater discharge points in Twenty Mile Creek and North Creek.

During the dry period of the 1999 field season, vertical fractures appearing on two long, dry bedrock sections were mapped for fracture trends. The first section was located adjacent to sample location #1, and the second was located just upstream from sample location #9.

In the upstream bedrock section almost all identified fractures trend across the creek approximately orthogonal to the surface water flow direction. The second bedrock section displayed a bimodal distribution, with vertical fractures trending both parallel, and orthogonal to the direction of surface water flow. The vertical fractures cutting across the creek out number the parallel vertical fracture (25 to 12), and in general the trace lengths of the orthogonal fracture set was 3–4 times that of the set parallel to the trend of the creek. All vertical fractures identified in the two bedrock sections were closed features, and were not conductive to groundwater flow. This provides evidence of the poor vertical communication between the fracture network and the creek at these locations.

4.2. Oxygen-18 and deuterium analysis

After identifying the five potential groundwater discharge points (D1–D5) within the study area, isotopic analysis was performed to confirm the presence of groundwater. Before this could be completed, the characteristic isotopic signatures for surface water and groundwater within the study area were established. The $\delta^{18}O$ and $\delta^{2}H$ results for surface water, groundwater, and local precipitation for all sampling rounds are presented in Table 1.

A Local Meteoric Water Line (LMWL) for the Smithville, Ont. area, was developed using precipitation samples collected within the study area between July 1999 and May 2000. Precipitation samples were collected during individual precipitation events. The LMWL is described by the equation $\delta^2H = 7.95\delta^{18}O + 13.58$ ($R_2 = 0.9981$, $N = 8$). The precipitation results observed in Smithville are similar to historical isotope data observed in precipitation in Southern Ontario (Fritz et al., 1987). When $\delta^{18}O$ and $\delta^{2}H$ results are plotted versus the LMWL, zones characterizing the areas where surface water and groundwater samples are expected to plot for the study area can be established. $\delta^{18}O$ and $\delta^{2}H$ results for water samples collected from potential groundwater discharge points identified through electrical conductivity and temperature surveys can then be compared to the established zones to confirm, or discount the presence of groundwater.

Precipitation samples collected between July 19, 1999 and May 18, 2000 within the study area showed a wide range in isotopic composition. $\delta^{18}O$ varied from -4.5 to -21.8 and $\delta^{2}H$ varied from -24 to -162 (Table 1). Large ranges in individual precipitation events are not uncommon, and have been observed in previous studies (Njitchoua et al., 1999; Acheampong and Hess, 2000).

Stable isotope results for spring and summer precipitation samples are found on the high end of the ranges, with $\delta^{18}O$ varying from -4.5 to -6.4, and $\delta^{2}H$ from -24 to -41 (Table 1). Conversely, stable isotope results for fall and winter precipitation samples are found on the low end of the range, with $\delta^{18}O$ varying from -10.8 to -21.8, and $\delta^{2}H$ from -73 to -162 (Table 1). Due to the significant seasonal variations in $\delta^{18}O$ and $\delta^{2}H$ in precipitation in the study area, the discussion of isotopic results will be divided into spring and summer, and winter sections.

4.2.1. Spring and summer results

Water samples were collected for isotope analysis twice during the summer of 1999, and once during the spring of 2000. The first round of sampling was completed on July 12, 1999 during low-flow condition, shortly after surface water inflow into the study area ceased. Samples collected August 3, 1999 were obtained again during low-flow conditions approximately 1 month after surface water inflow into the study area ceased. Samples were also collected May 30, 2000 during high-flow conditions while both creeks were fully connected.

For surface water samples, the values of $\delta^{18}O$ range from -7.2 to 2.1 and values of $\delta^{2}H$ range from -54 to -7 (Table 1). The more enriched values of both $\delta^{18}O$ and $\delta^{2}H$ occurred during the summer sampling rounds. During this time, surface water flow was cut-off resulting in large disconnected pools, which are highly susceptible to evaporation. Groundwater samples collected during the same time period display more consistent isotopic content and less

Table 1
Oxygen-18 and deuterium results for surface water, groundwater, and local precipitation for all sampling rounds

Sample location	Spring and summer results						Winter results (February 21, 2000)							
	July 12, 1999		August 3, 1999		May 30, 2000									
	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$						
#1	−4.1	−37	−2.3	−23	−7.2	−54	−10.5	−71						
#2	−2.9	−28	0.3	−18	−7.2	−53	−10.3	−74						
#3	−5.5	−41	−4.2	−28	−7.2	−54	−10.2	−75						
N1	−2.4	−34	−1.0	−22	−5.7	−47	−10.8	−81						
N2	−0.2	−21	2.1	−7	−5.6	−46	−11.5	−76						
OW3–5	−10.5	−72	−10.2	−75	–	–	−10.3	−75						
OW3–10	−10.6	−69	−10.5	−71	–	–	−10.4	−70						
Suspected groundwater discharge points														
D2	−10.1	−68	−10.0	−68	–	–	−10.0	−73						
D3	−10.1	−69	−10.2	−70	–	–	−10.2	−69						
	August 23, 1999													
	$\delta^{18}O$	$\delta^{2}H$												
D4 (fractures in 20)	−8.7	−61												
	September 24, 1999		August 3, 2000											
	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$										
D5 (North Creek)	−9.7	−65	−8.8	−62										
	July 12, 1999		August 3, 1999		July 23, 2000		February 21, 2000							
	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$						
D1 (Resurface point)	−8.4	−58	−6.4	−40	−6.5	−48	−10.0	−73						
Precipitation results														
	July 19, 1999		August 20, 1999		October 13, 1999		November 26, 1999		January 3, 2000		February 18, 2000		May 17–18, 2000	
	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$
Rainfall	−5.4	−31	−6.4	−41	−11.6	−79	−13.4	−89	−10.8	−73	−21.8	−162	−4.6	−24

Note: (1) All ^{18}O and ^{2}H results are reported relative to VSMOW. (2) July 12, 1999: samples collected during summer low-flow conditions shortly after Twenty Mile Creek was cut-off. (3) August 3, 1999: samples collected during summer low-flow conditions after Twenty Mile Creek had been cut-off for approximately 1 month. (4) February 21, 2000: samples collected during winter low-flow conditions, the creek was iced over, but still fully connected. (5) May 30, 2000: samples collected during spring high-flow conditions.

enriched values than the surface water. The $\delta^{18}O$ values ranged from −10.6 to −10.2 and $\delta^{2}H$ values ranged from −75 to −69 (Table 1).

Fig. 10 shows a plot of the spring and summer data set versus the LMWL for Smithville, Ont. The $\delta^{18}O$ and $\delta^{2}H$ results for groundwater samples obtained throughout the Lockport Formation collected by Novakowski et al. (1999) are also displayed on Fig. 10. The division between more recent, and old, cold climate groundwater established for the study area by Novakowski et al. (1999) will be used in this study, and is illustrated on Fig. 10. It is apparent that all groundwater samples obtained during this study have isotopic signatures consistent with shallow groundwater in the region. Oxygen-18 and deuterium analysis in conjunction with tritium analysis and measurements of groundwater velocity in the upper half of the Lockport Formation (Novakowski et al., 1999) indicate shallow groundwater in the study area is post Wisconsin Glaciation in age.

The distribution of $\delta^{18}O$ and $\delta^{2}H$ results in Fig. 10 indicate all groundwater samples fall on or near the LMWL, suggesting an absence of evaporation effects. The isotopic results for surface water samples fall consistently below the LMWL due to isotopic enrichment caused by secondary evaporation. In addition, the isotopic results for surface water samples show a much larger range due to seasonal variations in local precipitation.

Surface water samples collected during connected flow (May 2000) plot closest to the LMWL, while those samples collected during mid- to late-summer (July 12 and August 3, 1999), after both creeks became disconnected show the greatest effects of secondary evaporation, and plot the further off the LMWL. The slope of the Local Evaporation Line (LEL) displayed on Fig. 10 is equal to 4.5. This is consistent with work completed by Acheampong and Hess (2000) which found evaporation occurring when the relative humidity is less than 100% will result in a LEL slope of 5 ± 2 on a $\delta^{18}O-\delta^{2}H$ plot. The angle (α) between the LEL and the LMWL will increase as the effects of secondary evaporation increase, and is a function of the relative humidity (Gonfiantini, 1986). The general trends observed on Fig. 10 were also observed in work completed by Acheampong and Hess (2000). In both studies, groundwater samples are grouped on or near the LMWL, and enriched (less negative) $\delta^{18}O$ and $\delta^{2}H$ results for surface water plot towards the upper end, and below the LMWL.

In addition, the isotopic results displayed on Fig. 10 allowed for the placement of zones characterizing the areas where surface water and groundwater samples are expected to plot. These distinctive areas will assist in interpreting isotopic results for water samples obtained from potential groundwater discharge points.

4.2.2. Winter results

Water samples representing winter conditions were collected for isotope analysis on February 21, 2000.

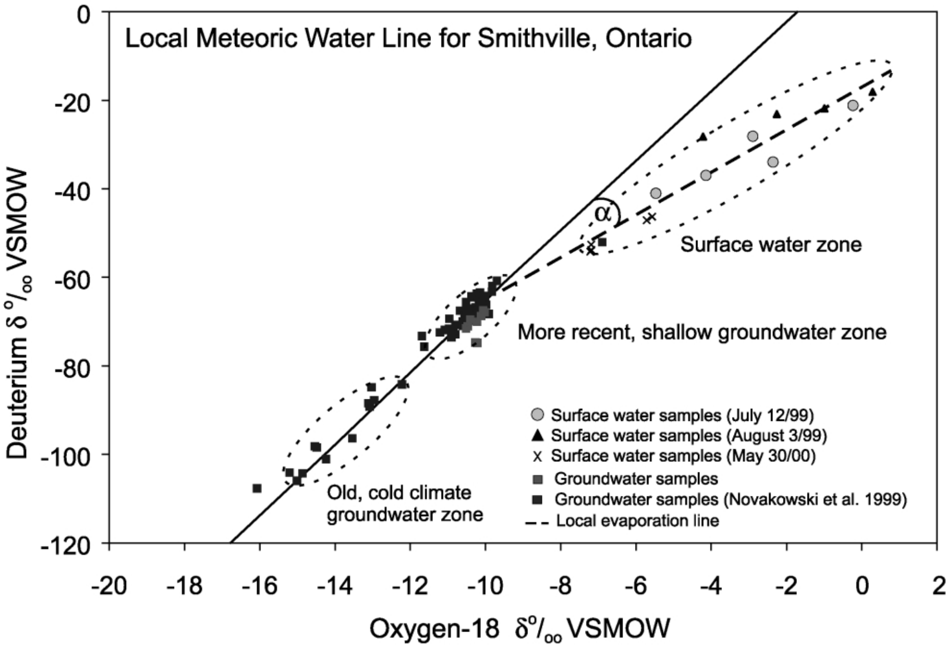

Fig. 10. A plot of the spring and summer data versus the LMWL for Smithville, Ont. $\delta^{18}O$ and $\delta^{2}H$ results for groundwater samples collected by Novakowski et al. (1999) are included to establish the division between more recent, and older groundwater samples.

At that time, both creeks were iced over, but still fully connected. For surface water samples, the values of $\delta^{18}O$ range from −11.5 to −10.2 and values of $\delta^{2}H$ range from −81 to −71 (Table 1). These results are consistently lower than the range observed for surface water samples collected during the spring and summer. This is primarily a result of significant changes in the isotopic signature of local precipitation during the fall and winter seasons. Precipitation samples collected for individual storm events during the spring and summer in the study area had an average $\delta^{18}O$ of −5.5 and an average $\delta^{2}H$ of −32 (Table 1). Precipitation samples collected during the fall and winter had an average $\delta^{18}O$ of −14.3 and an average $\delta^{2}H$ of −101 (Table 1).

Fig. 11 displays a plot of isotopic results for winter sample versus the LMWL for Smithville, Ont. Decreases in $\delta^{18}O$ and $\delta^{2}H$ in precipitation result in the surface water samples plotting in the same range as the groundwater samples. It is apparent from Fig. 11 that distinct isotopic signatures for surface water and groundwater do not exist during the winter months, and therefore, $\delta^{18}O$ and $\delta^{2}H$ results cannot be used to confirm groundwater discharge points during this time period. With this in mind, winter sample results will be excluded during the analysis of potential groundwater discharge points.

4.2.3. Potential groundwater discharge points

Five potential groundwater discharge points (D1–D5) were identified within the study area using electrical conductivity and temperature surveys during the 1999 field season (locations given on Fig. 9). The $\delta^{18}O$ and $\delta^{2}H$ results for the potential groundwater discharge points plotted versus the LMWL for Smithville, Ont. are displayed on Fig. 12.

Water samples at D1 were collected for isotope analysis on July 12, 1999, August 3, 1999 and July 23, 2000, and the results for this location are shown in Table 1. The $\delta^{18}O$ and $\delta^{2}H$ results at this location are

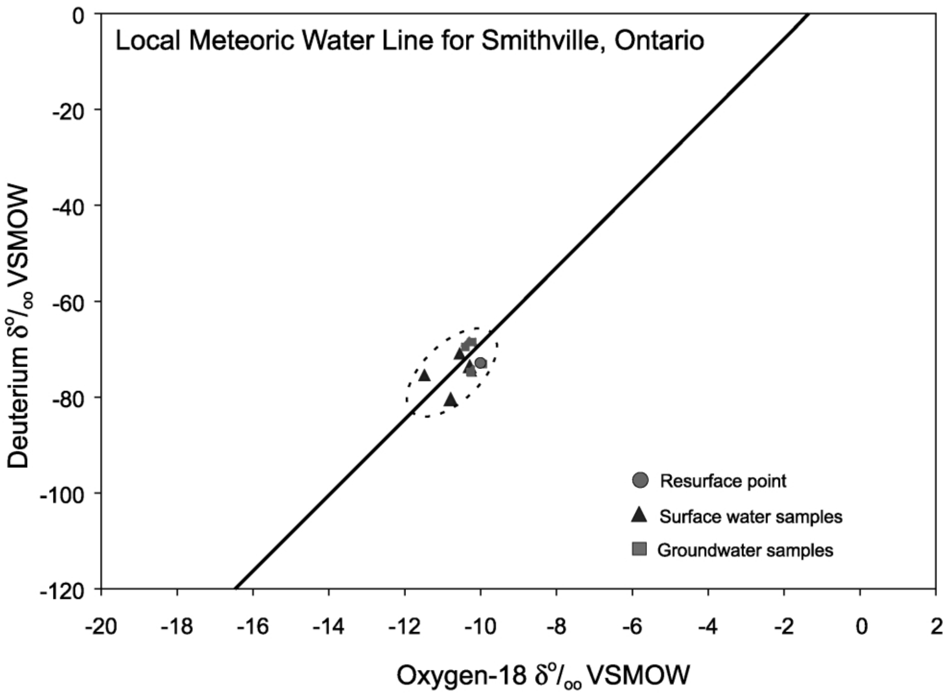

Fig. 11. A plot of isotopic results for surface water and groundwater samples collected during winter sampling versus the LMWL for Smithville, Ont.

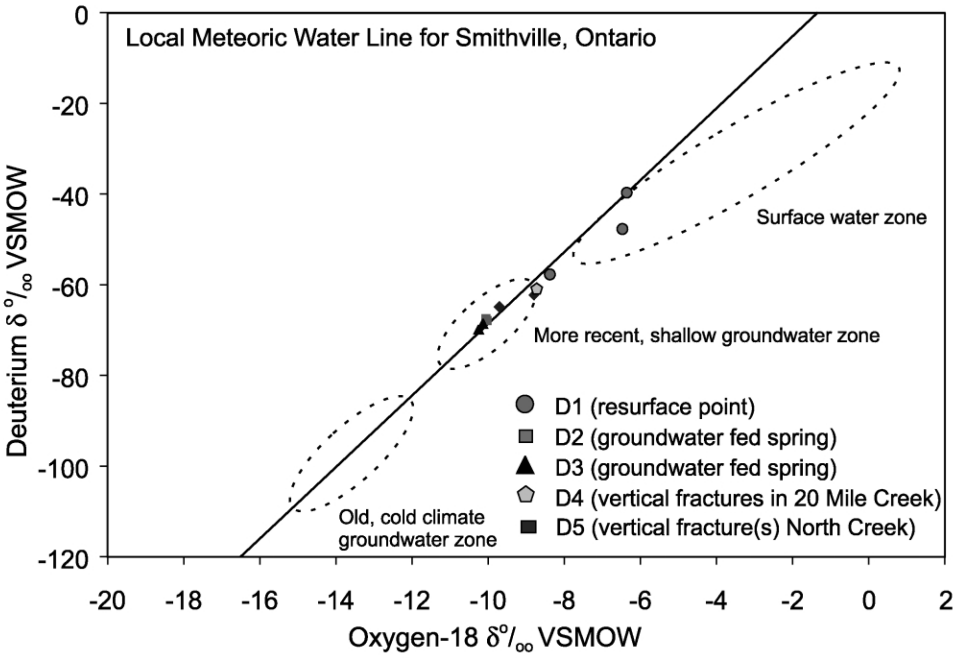

Fig. 12. A plot of isotopic results for the potential groundwater discharge points versus the LMWL for Smithville, Ont.

controlled by the water level in the creek as indicated by the wide range in values observed with time.

The first sample collected on July 12, 1999 had an δ^{18}O value of -8.4 and a δ^{2}H value of -58 (Table 1). The result plots between the areas defined for recent groundwater and surface water. This indicates there is a mixture of surface water and shallow groundwater in this sample. The sample collected on August 3 had an δ^{18}O value of -6.4 and a δ^{2}H value of -40 (Table 1). The result plots directly on the LMWL in the zone defined as surface water. This indicates the sample is made up primarily of surface water that has not undergone secondary evaporation. The observed δ^{18}O and δ^{2}H values are a result of a substantial rainfall (22 mm) that occurred 2 days before the sample was collected. Although the creek did not reconnect, the volume of water carried in the horizontal feature (recent runoff) dramatically increased.

The final sample collected on July 23, 2000 had an δ^{18}O value of -6.5 and a δ^{2}H value of -48 (Table 1). At the time this sample was collected, the creek was fully connected and large volumes of surface water (lost to the subsurface upstream) were discharged at the resurface point. The result plots below the LMWL, in the area defined as surface water. This indicates the sample is made up of surface water that has undergone some secondary evaporation.

D1 was determined to be a resurface point where a mixture of groundwater and creek water lost to the subsurface through a laterally extensive, horizontal fracture rejoins the creek. In general, during periods of high flow in the creek, the isotopic signature plots in the surface water zone, and during periods of low flow, δ^{18}O and δ^{2}H results move towards the defined groundwater zone.

Locations D2 and D3 are associated with two groundwater fed springs that flow into Twenty Mile Creek. The δ^{18}O and δ^{2}H results for both locations consistently plot within the defined groundwater zone. D4 is located 7 m downstream from sample location #6 in Twenty Mile Creek. An area of elevated electrical conductivity and decreased temperature was identified within a small group of fractures during low-flow conditions in Twenty Mile Creek.

D5 is located at Station N4 in North Creek. The streambed at this location consists of sand and gravel, and local till. Water levels in mini-piezometers in excess of 0.2 m above stream level suggest a good connection to a vertical fracture at this location. A sample for isotope analysis was collected from a mini-piezometer on September 24, 1999. A second sample was collected from a seepage meter on August 3, 2000. The results for both samples are displayed in Table 1 (denoted D5).

D4 and D5 are attributed to open vertical fractures that intersect the base of Twenty Mile Creek and North Creek, respectively. The $\delta^{18}O$ and $\delta^{2}H$ results for both locations plot within the defined groundwater zone for the study area.

Isotopic results for water samples collected from all five locations are consistent with shallow groundwater and indicate the groundwater most likely originates in the Upper Eramosa Member (top 3–7 m of bedrock).

4.3. Groundwater and stream discharge measurements

Once the five locations were confirmed as groundwater discharge points, the volume of groundwater entering the creek was estimated using weirs, seepage meters, and mixing calculations. All point measurements of groundwater discharge were obtained during baseflow conditions.

Groundwater discharge entering Twenty Mile Creek at D1 was estimated to be 0.3 l/s using a natural weir. The discharge at D2 was negligible. During baseflow conditions (early July until September, 1999) groundwater at D2 sustained a pool at the discharge point, but did not provide enough flow to enter Twenty Mile Creek. The discharge at D3 was estimated to be 1.2 l/s using a sharp crested 'V' notch weir.

The creekbed at D4 lays directly on bedrock, therefore seepage meters could not be used to estimate the rate of groundwater discharge. As a result, the groundwater discharge at D4 was estimated using a simple two-component mixing model. For the model, it is assumed that conservation of mass can be used to estimate final mixed electrical conductivity, and complete mixing is obtained within the creek. The results of the model provide an estimate of the mixed electrical conductivity using the flow proportional difference in initial electrical conductivity of the surface water and groundwater. The equation has been adapted from Freeze and Cherry (1979). The model is described by the following equation:

$$Q_D = Q_C(EC_C - EC_{C+D})/(EC_{C+D} - EC_D) \qquad (4.1)$$

where EC_C is the ambient electrical conductivity of the creek (measured), EC_D is the ambient electrical conductivity of discharging groundwater (measured), EC_{C+D} is the electrical conductivity resulting from mixing (measured), Q_C is the ambient creek discharge rate (measured), and Q_D is the groundwater discharge rate. Using data collected on August 30, 1999, where $EC_C = 1.32$ mS/cm, $EC_D = 2.87$ mS/cm, $EC_{C+D} = 1.47$ mS/cm, and Q_C was estimated to be 0.002 m^3/s, the rate of groundwater discharge was estimated to be 2.1×10^{-4} m^3/s (0.21 l/s).

The groundwater discharge at D5 was estimated to be 0.2 l/s using seepage meters. The spatial distribution of the discharge zone was estimated using mini-piezometers, and a sum of the seepage results within the zone was used to estimate the total volumetric discharge.

Using these results, the total discharge of groundwater entering Twenty Mile Creek over the 8-km study reach, under baseflow conditions, including groundwater originating in North Creek was estimated to be 2×10^{-3} m^3/s.

For comparative purposes, the groundwater volume flowing within the Eramosa member for the study area can be approximated using an estimate of the regional hydraulic gradient, measured transmissivity from the Eramosa member, and the width of the study area (~6.5 km). Transmissivity values of 1×10^{-2} m^2/s were observed in boreholes 61 and 65 in the Eramosa member. These values of transmissivity represent the presence of one or more large-aperture fractures. The presence of fractures having a similar transmissivity, at the same depth was observed elsewhere in the study area (Novakowski et al., 1999), indicating a relative homogeneity to these features. Previous studies estimate the regional hydraulic gradient to be 1.0×10^{-3} (Novakowski et al., 1999). A value of 6.5×10^{-2} m^3/s is obtained for the volume of groundwater flowing within the Eramosa member within the study area. This result is greater than one order of magnitude larger than the estimated groundwater discharge into the creek, suggesting that greater than 95% of the groundwater in the Eramosa underflows the creek during baseflow conditions.

Stream gauging was completed in Twenty Mile Creek and North Creek from May 25 to June 18, 1999. Due to the inability to accurately account for all the surface water inputs (agricultural runoff and storm sewer outfalls identified on Fig. 6) within the study area, work completed on changes in discharge with respect to distance (as measured by stream gauging), to identify areas of gain and loss in Twenty Mile Creek have been inconclusive. In addition, because the estimate of groundwater discharge is a small fraction of the average stream flow, the error involved in measuring the stream flow discharge between locations likely exceeds this value.

4.4. Storm events

Inspection of the electrical conductivity and hydraulic head profiles measured during spring rainfall events for deep boreholes 53, 61, and 65 show no significant change over the period of the precipitation events.

Electrical conductivity results obtained on May 27, June 3, and June 10 span a period of increased flow within Twenty Mile Creek. During this time, there was a change in stream stage of approximately 30 cm. There was no significant change observed in the electrical conductivity profiles at the three wells during this period.

The stream stage and electrical conductivity measurements obtained using the Hydrolab Datasonde 3 located at sample location #1 from November 2 to 15 are shown on Fig. 13. Approximately 77 mm of rain fell within the study area between November 2 and 3, 1999. The stream stage increased from a depth of approximately 0.25 to 1.5 m over a 3-day period. Over the next 10 days, the creek returned to near baseflow conditions with only a slight response to small rainfall events observed on November 10 and 13, 1999. During the initial rise in water level, the electrical conductivity decreased from a value above 0.6 to approximately 0.3 mS/cm, and oscillated around this value until the peak in stream stage was reached. Following the peak in stream stage, the electrical

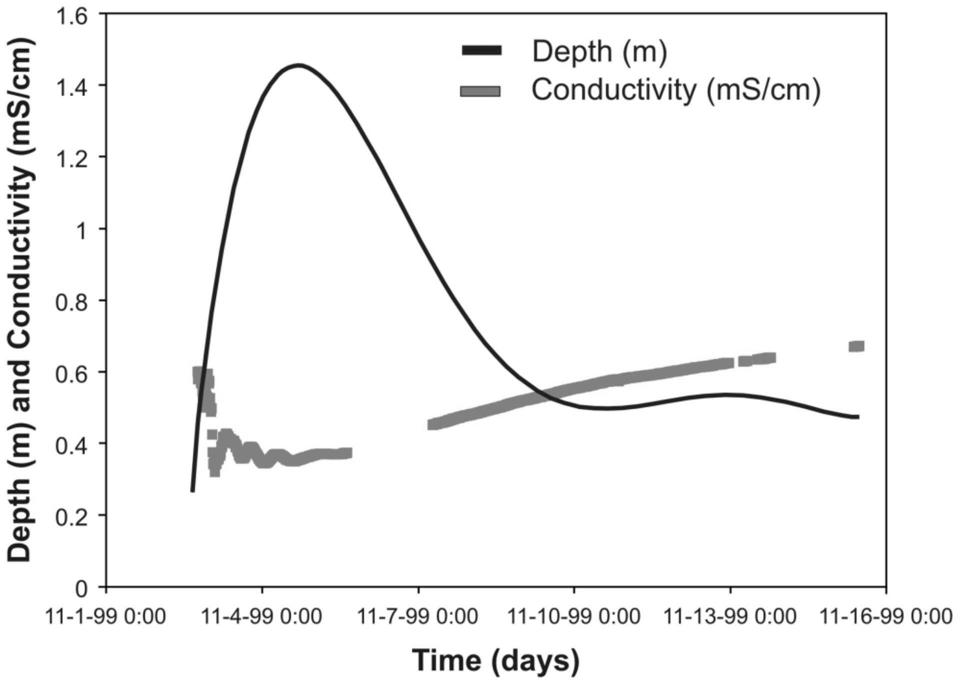

Fig. 13. Stream stage and electrical conductivity measurements obtained at sample location #1 between November 2 and 15, 1999.

conductivity began a steady rise back towards a value greater than 0.6 mS/cm.

Mixing between more saline water present in the creek prior to the storm and new water arriving from the rainfall is believed to result in the oscillations observed during the onset of the storm hydrograph. The low value of electrical conductivity observed in the creek at peak discharge strongly indicates very little new groundwater is introduced into the stream during storm events. If a large quantity of groundwater were released, the sharp drop in electrical conductivity would not have been observed, nor would we expect to see a rise in conductivity after the peak in discharge. However, based on the minimum value of electrical conductivity of 0.3 mS/cm observed in the creek (well above electrical conductivity values observed for rainwater in the study area) it is possible that some groundwater is introduced upstream from this location.

The stream stage and conductivity measurements obtained using the Hydrolab Datasonde 3 located at sample location N4 from November 2 to 15 are shown on Fig. 14. In this case, the Hydrolab was located immediately downstream from a known groundwater discharge point. As observed at the location in Twenty Mile Creek, the stream stage rises rapidly over a short period, followed by a recession curve lasting approximately 10 days. The behavior of the electrical conductivity is also similar, initially a rapid decline is observed, followed by a slow rise. However, large-scale oscillations are observed towards the end of the data set as the water levels return to low-flow conditions. These oscillations appear to be a result of the proximity to the groundwater discharge point, and indicate the groundwater contribution occurs at a steady but small rate. The observed pulses may be attributed to incomplete mixing of the discharging groundwater. Once again the electrical conductivity data indicate there is no significant pulse of groundwater contributed to the creek during the storm event.

4.5. Hydraulic head measurements

Water level measurements (expressed in meters above sea level) for OW3–5 and OW3–10, located immediately adjacent to Twenty Mile Creek are

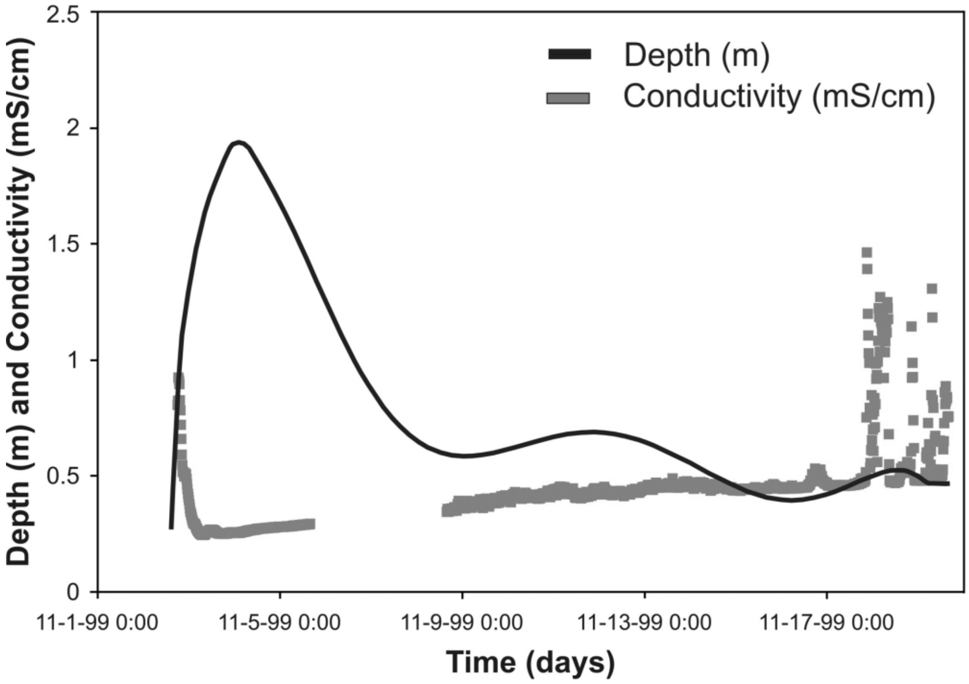

Fig. 14. Stream stage and electrical conductivity measurements obtained at sample location N4 between November 2 and 15, 1999.

shown in Fig. 15. During the course of the field season, the hydraulic head steadily declined until the onset of the fall rains. During this time, increases in hydraulic head of as much as 0.5 m were observed over the span of a few days. Over the course of the field season, the direction and magnitude of the vertical gradient remained unchanged. Given that the vertical gradient was consistently upward, and the hydraulic head measurements are constantly above the elevation of the creek level, the absence of groundwater discharge points in this area suggest there is poor vertical communication between the fracture network and the creek at this location. In addition, electrical conductivity measurements obtained within the creek during the significant jumps in hydraulic head indicated there was no associated increase in groundwater discharge at this location during storm events.

A peak in stream discharge corresponding to a major storm event in the upper watershed was observed on June 8 within Twenty Mile Creek. During this time, no rain fell within the study area, however, water levels in Twenty Mile Creek were higher than during any other period over the late-spring and summer portion of the 1999 field season. This provided an opportunity to observe the effects on hydraulic head in the OW3 wells due to an increase in stream stage in the absence of local recharge. Hydraulic head results within the wells showed no corresponding increase during this time (see Fig. 15).

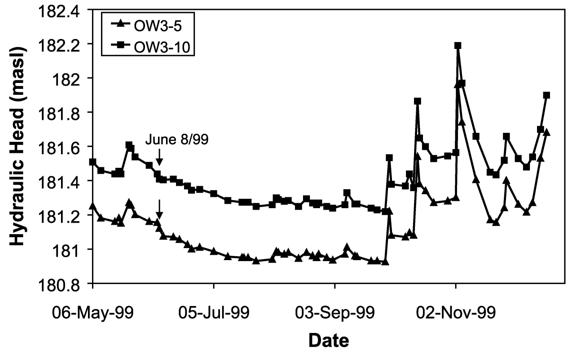

Fig. 15. Measurements of hydraulic head in shallow monitoring wells (OW3 wells) over the course of the 1999 field season (May 6–December 17, 1999).

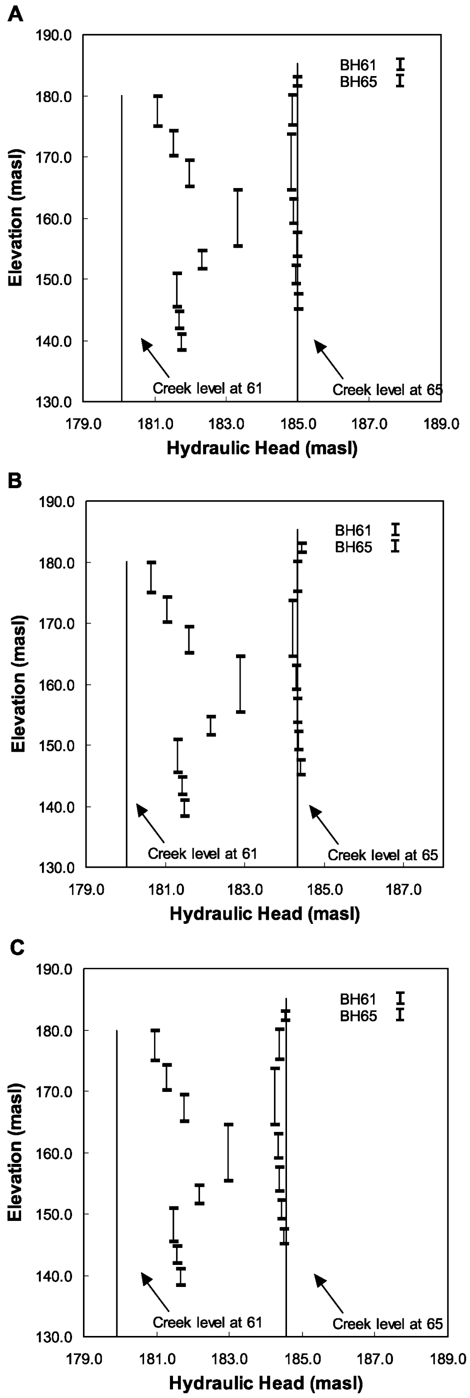

Fig. 16. The distribution of hydraulic head in boreholes 61 and 65 typical of (A) spring conditions (April 1, 1999), (B) summer conditions (August 16, 1999), and (C) fall conditions (October 25, 1999) compared to the measured water level in Twenty Mile Creek.

This indicates surface water is not being lost to the subsurface at this location as a result of increased stream stage.

Similar results regarding vertical fracture communication are observed in the area surrounding boreholes 61 and 65. Fig. 16(A)–(C) displays the distribution of hydraulic head in boreholes 61 and 65 during the spring, summer, and fall for 1999 relative to measured water levels in Twenty Mile Creek. If a vertical connection exists, groundwater discharge should be observed when hydraulic heads in the underlying aquifer exceed the hydrostatic head in the overlying surface water.

The profile of hydraulic head at borehole 61 consistently shows strong upward and downward hydraulic gradients originating from a zone of artesian hydraulic head present in the Vinemount member. In borehole 61, the hydraulic head in all intervals are in excess of the creek level throughout the year (see Fig. 16(A)–(C)). However, surveys of electrical conductivity in this area indicate groundwater is not discharging in the vicinity of the borehole, once again suggesting extremely poor vertical communication in the fracture network.

The profile of hydraulic head at borehole 65 is consistently uniform with depth, and hydraulic heads in all intervals are equal to, or below the measured creek level throughout the year (see Fig. 16(A)–(C)). As a result, groundwater discharge is not expected to occur in this area. Data collected from electrical conductivity and isotopic analysis confirm that groundwater is not discharging in the vicinity of borehole 65. The limited vertical connections in the Eramosa, in conjunction with the uniform distribution of hydraulic head with depth indicate groundwater is completely underflowing the creek at this location.

Since the hydraulic head results for each interval within boreholes 61 and 65, and the OW3 wells are equal to or above the measured water level in Twenty Mile Creek throughout the year, significant loss of surface water to the subsurface within the study area is not expected.

5. Conclusions

A study of groundwater/surface water interaction between Twenty Mile Creek and the local aquifer in Smithville, Ont. was completed during the 1999 and 2000 field seasons. The points of interaction were identified and quantified through the use of air-photo interpretation, detailed stream surveys, electrical conductivity and temperature surveys, isotopic analysis, mixing calculations and point measurements of hydraulic head and discharge obtained using mini-piezometers, seepage meters and weirs.

The results indicate that groundwater and surface water can be easily distinguished within the study area based on differences in electrical conductivity, temperature, and isotopic signatures. The interaction between Twenty Mile Creek and the local aquifer was found to be extremely limited with greater than 95% of the groundwater within the study area underflowing the creek completely during baseflow conditions. The invariance in the groundwater discharge during storm events, and the uniformity of the regional hydraulic head distribution with time indicates the groundwater discharge and underflow are also likely constant with time. The small quantity of groundwater that is observed to discharge into Twenty Mile Creek has an electrical conductivity and isotopic signature consistent with shallow groundwater and most likely originates in the Upper Eramosa Member (top 3–7 m of bedrock).

Although previous investigations have identified potentially open vertical fractures within the study area, it is apparent from data collected in this study that the fracture network has extremely poor vertical connections limiting groundwater exchange in the vicinity of the creek. In addition, the low velocity and discharge rate within the creek does not allow for incising into the bedrock. As a result, horizontal fractures do not play a significant roll in the exchange process within the study area.

Groundwater discharge in fractured bedrock stream environments primarily appears as discrete point sources associated with open fractures, as compared to more diffuse, or continuous seepage zones often observed in a porous media environment. Increases in groundwater discharge during storm events was not observed, and no loss from the stream to the fracture network was observed, even under conditions where stream stage increased in the absence of local recharge.

In this study area, measurements of stream discharge to determine areas of large-scale loss or gain proved to be inconclusive due to the relatively small volume of groundwater discharge occurring. It was also found that the use of stable isotope signatures to differentiate between groundwater and surface water was limited during winter months due to the similarity in $\delta^{18}O$ and $\delta^{2}H$ content. As a result, the applicability of this method is seasonally dependent. Other techniques, such as measurements of electrical conductivity, temperature, and hydraulic heads normally used in studies of groundwater discharge in porous media were found to adapt well for use in fractured bedrock environments.

Acknowledgments

This project was funded in part by the Natural Science and Engineering Research Council of Canada, the Smithville Phase IV Bedrock Remediation Project, and Queen's University. The authors wish to acknowledge A. Crowe and B. Kueper for helpful advice during the project. Thanks are also extended to P. Kryger and C. Talbot for field assistance.

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