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Environnement Canada

Hydraulic Head and Groundwater Velocity Variations in Flat Lying Fractured Sedimentary Rock

By:
Pat Lapcevic & Kent Novakowski

NWRI Contribution # 00-93

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MANAGEMENT PERSPECTIVE

Since 1995, the Groundwater group at NWRI has been involved in an extensive field and laboratory hydrogeological research program at the Smithville PCB site in Smithville, ON. Part of this work included the installation of Westbay multi-level monitoring instrumentation in 11 boreholes. Hydraulic heads at over 100 monitoring points have been measured on a weekly basis between 1996-March 2000. Currently the monitoring program is continuing with measurements on a monthly basis. This paper discusses some of the results of this monitoring program. In particular the variation of hydraulic gradient and groundwater velocity both temporally and spatially is explored. This research will further our understanding of the hydrogeology of heterogeneous rock systems and improve our ability to predict and prevent the environmental effects of toxic substances in groundwater and help to conserve and restore priority ecosystems in the Great Lakes Basin.

The monitoring program is currently being carried out on a monthly basis. Further analysis of the data will also be completed. It is expected that a more comprehensive report will be completed in mid 2001.

VARIATIONS DE LA PRESSION HYDRAULIQUE ET DE LA VITESSE DES EAUX SOUTERRAINES DANS DES ROCHES SÉDIMENTAIRES HORIZONTALES FRACTURÉES

Pat Lapcevic et Kent Novakowski

SOMMAIRE À L'INTENTION DE LA DIRECTION

Depuis 1995, le groupe des eaux souterraines de l'INRE a participé à un vaste programme de recherches hydrogéologiques sur place et en laboratoire au dépôt de PCB de Smithville (Ontario). Certains de ces travaux portaient notamment sur l'installation d'instruments de surveillance à diverses profondeurs dans 11 trous de sondage à Westbay. De 1996 à mars 2000, on a mesuré chaque semaine les pressions hydrauliques à plus de 100 points de surveillance. Actuellement, le programme de surveillance se poursuit avec des mesure mensuelles. Cet article examine certains des résultats de ce programme de surveillance, et notamment la variation dans le temps et dans l'espace du gradient hydraulique et de la vitesse des eaux souterraines. Cette étude doit nous permettre de mieux comprendre l'hydrogéologie des systèmes rocheux hétérogènes et d'améliorer notre aptitude à prévoir et à prévenir les effets environnementaux des substances toxiques dans les eaux souterraines, et de contribuer ainsi à la conservation et à la remise en état des écosystèmes prioritaire du bassin des Grands Lacs.

On poursuit actuellement le programme de surveillance avec des mesures mensuelles. On doit également terminer d'autres analyses des données. On prévoit la publication d'un rapport plus exhaustif vers le milieu de 2001.

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1. INTRODUCTION

Measuring groundwater velocity, either directly through the results of tracer experiments or indirectly through Darcy calculations, is essential to understanding contaminant transport in complex groundwater environments such as heterogeneous bedrock sequences. Additionally, reliable field estimates of groundwater velocity are also necessary to calibrate numerical models of flow and provide confidence in the use for these models for the prediction and protection of valuable groundwater resources.

Flat-lying sedimentary rocks underlie large portions of North America. Groundwater usually flows in this type of rock through an interconnected network of fractures. In the Lockport dolostone in southern Ontario and western New York State, fracturing generally consists of large extensive bedding plane fractures connected by vertical joints of varying length. Regional groundwater flow is generally thought to be dominated by these laterally extensive fractures often extending several kilometres (Novakowski and Lapcevic, 1988; Yager et al., 1996).

This study focuses on determining horizontal hydraulic gradients in the Lockport Dolostone at a site in Southern Ontario. Weekly measurements of hydraulic head in 85 monitoring points were used to examine both the temporal and spatial distribution of hydraulic head in flat-lying sedimentary rock at two spatial scales (regionally and at the site scale).

2. FIELD SETTING

The study area is located near the town of Smithville, several kilometres south of the edge of the Niagara escarpment in Southern Ontario (Figure 1). The Lockport dolostone underlies this region and ranges in thickness between 26 and 40 m and dips in southwesterly direction at an incline ranging from 0° to 2°. It is overlain by 2 to 25 m of overburden and underlain by the Rochester Shale. The topography of the region is mostly flat-lying with a total relief of about 20 m in an area about 100 square kilometres (Novakowski et al., 1999). The southern boundary of the study area is Twenty-Mile Creek, which drains eastward in the area. The northern boundary for this study is a bedrock ridge oriented in the northwest-southeast direction and having a relief of 8.5 m lying approximately 4.5 km to the north of the town boundary.

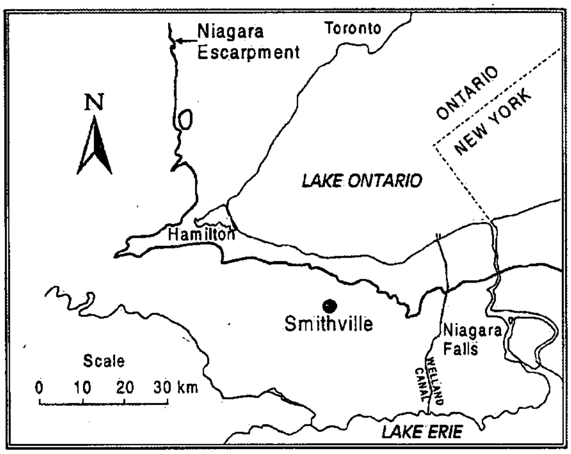

Figure 1. Location of study area.

The CWML site is located about a kilometre north of the town of Smithville (Figure 2). The site and surrounding area has been extensively studied since the late 1980s when PCB and other organic wastes, remnant of a transfer station were discovered on site and subsequently confirmed in the groundwater of the underlying overburden and bedrock. Between 1995 and 1998, 20 boreholes which intersect the entire Lockport formation were constructed both in the site area and in the surrounding region. Field and laboratory measurements from these boreholes were used to develop a conceptual model for flow and aqueous contaminant transport in the bedrock to provide a basis for the selection of a permanent remedial alternative for the site.

Geologically, the Lockport dolostone is subdivided into several units ranging in thickness between 3 and 20 m. (Figure 3). Horizontal (bedding plane) fractures dominate the fracturing in all units. Vertical fractures are most prevalent in the upper units (Eramosa Member) and decrease in frequency and spacing in the lower units. Overall, a wide distribution of transmissivity (<10^{-10} to 10^{-2} m^2/s) was measured in the system. While there is no trend to decreasing permeability with depth, a low permeability unit ranging in thickness from 1-5 m and located in the Lower Vinemount unit appears to be continuous in the region. The groundwater flow system in this region is dominated by the presence of laterally extensive horizontal fractures.

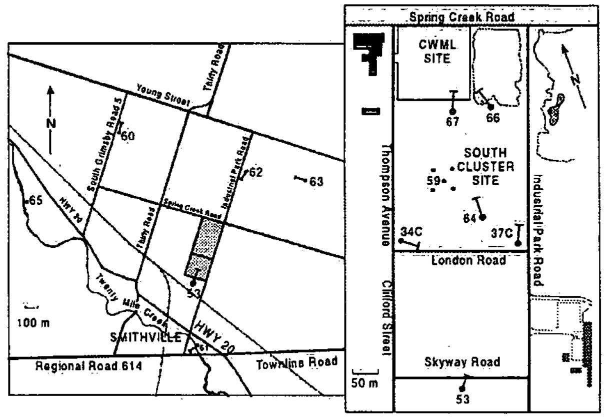

Figure 2. Map showing location of CWML site and boreholes used in this study.

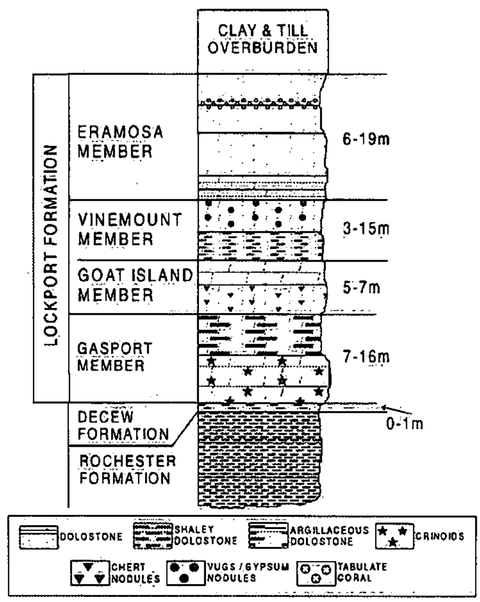

Figure 3. Geological column showing lithology of Lockport dolostone. Member names are terms used locally and differ slightly from 'official' terminology.

3. MONITORING POINTS

The three dimensional distribution of hydraulic head was determined using 85 monitoring zones permanently installed in eleven boreholes. Open rock boreholes were permanently instrumented with the Westbay® System. This system consists of water-filled packers connected by casing elements and specially designed pumping and measurement/sampling ports (Black, 1987). Water pressure within each isolated zone is measured using a submersible probe, which is lowered into the casing and connected to an electronic data acquisition device on surface. The probe has a small arm, which is used to locate each measurement port inside the casing. Once positioned on the port, a mechanical foot is activated and presses the probe against the inner casing wall. This causes an O-ring on the opposite side of the probe to seal around a button valve, exposing the pressure transducer in the probe to water pressure outside the casing. Hydraulic head, h, (masl) is calculated from the pressure measurements in each Westbay® zone using:

[1] $$h=BH_{elev}-((p_i-p_{out})*0.7038)$$

where BH_{elev} is the elevation of the casing top (masl), p_i is the pressure inside the casing (ie. prior to activating the shoe) (psi), p_{out} is the pressure in the monitoring interval (psi) and 0.7038 is a constant converting the pressure measured to metres of water. Equation [1] is stated assuming that a pressure measurement is obtained with the casing completely filled with water. This is important particularly with inclined boreholes. Additionally, it should be noted that hydraulic head calculations were not corrected for differences in salinity between the formation water and that used within the casing. This may have influenced a few of the zones and will be investigated further.

The location of the 11 boreholes completed with the Westbay® instrumentation is shown in Figure 2. Six to ten monitoring intervals, each 2 to 20 m in length, are isolated in each borehole. In all cases the choice of monitoring intervals was based on the results of field hydraulic testing which determined the vertical distribution of permeability in each borehole (Figure 4).

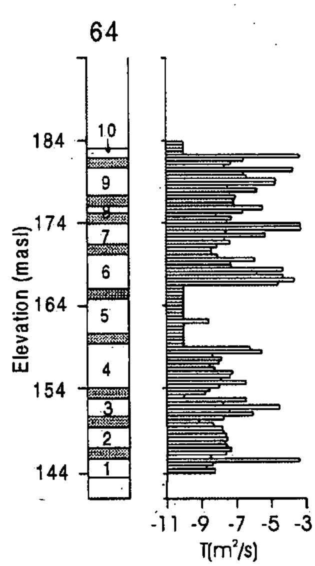

Figure 4. Transmissivity profile compared to monitoring intervals for borehole 64.

Transmissivity was measured continuously in each borehole using constant-head injection tests with test intervals ranging from 0.5-m 2.0-m (Novakowski et al., 1999).

Four of the regional boreholes were instrumented in August 1996 while two additional boreholes were instrumented in July 1997. Finally, five site boreholes were instrumented in May 1999. The distribution of measurement zones in the five site boreholes is shown in Figure 5.

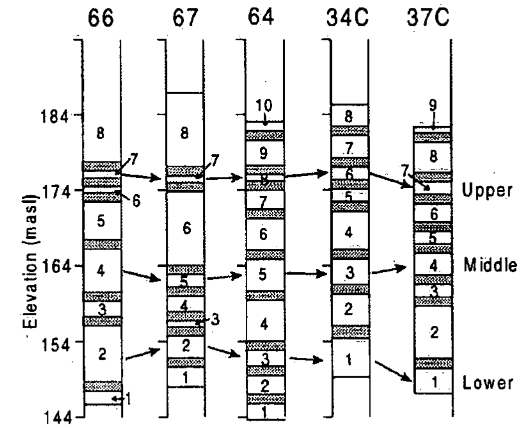

Figure 5. Cross-section of monitoring intervals in 5 site boreholes.

Measurements of hydraulic head have been obtained on a weekly basis since the completion of each Westbay®-instrumented borehole. Thus, the length of record in each borehole ranges from 1 to 4 years.

4. RESULTS & DISCUSSION

4.1 Regional Groundwater Flow

Understanding groundwater flow regionally is dependent on determining which zones are hydraulically connected spatially. Hydraulic connections do not necessarily follow geological unit boundaries. Regionally, in what appears to be the most connected zone, groundwater generally flows in a south-south-easterly direction in the southern portion of the study area and in a more easterly direction in the northern portion (Novakowski et al., 1999). In the upper Eramosa Unit, which is the shallow bedrock at the site, groundwater flow directions are more uniform and oriented in a more southerly direction (Figure 6). It has been postulated that regionally the groundwater flow can be represented as two distinct systems in which horizontal flow dominates and little vertical connection between the zones (Zanini et al., 2000). Regional groundwater flow in this system in the context of recharge and discharge is discussed in detail in Novakowski et al. (2000).

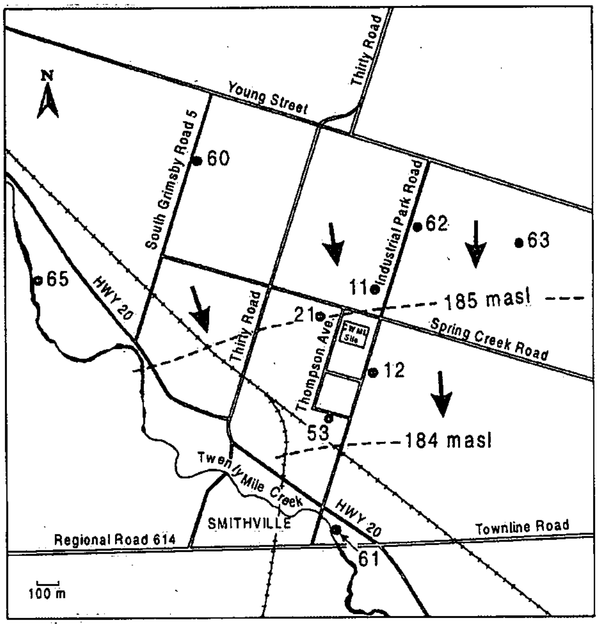

Figure 6. Groundwater flow directions in the Upper Eramosa unit.

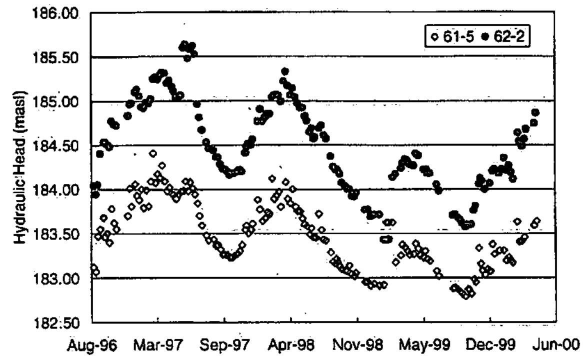

Figure 7. Hydrographs for two zones illustrating temporal variations in hydraulic head in study area.

4.2 Temporal Variations in Hydraulic Head

The temporal variations in hydraulic head are illustrated in Figure 7 for two zones believed to be connected and located several kilometres apart. Monitoring zone 62-2 is located at the north end of the study area while 61-5 is located at the south end of the study area near Twenty Mile creek. In both zones seasonal variations in hydraulic head are noted with high levels in March-April and minimum levels in October-January. While minimum levels usually occur in October, the 1998 decline in levels extended to January 1999. Additionally, the maximum levels noted in the spring of 1999 and 2000 are about 0.8 m lower than the previous two years (Figure 7). These last two observations reflect low precipitation levels and explain the generally low groundwater levels in the region. Similar temporal trends are noted in the other zones. Additionally, there are no distinct differences in the magnitude of these changes with depth. This is not surprising due to the low storativity of the rock and geologically mapping has suggested that some of the deeper units outcrop closer to the escarpment face (Novakowski et al., 1999)

4.3 Vertical variations

Typical vertical profiles of hydraulic head in the 5 site boreholes are shown in Figure 8. In the upper flow zone, hydraulic head decreases with depth in hydraulic head to about 165-170 masl. Below this level there is a general uniformity in the hydraulic head measurements. For example in borehole 34C there is about 0.2 m head difference in the upper units and less than 0.02 m difference in the lower units. The detailed permeability measurements in these boreholes determined eight orders of magnitude variation in transmissivity in the rock, few vertical fractures and numerous low-permeability intervals (Novakowski et al., 1999). This suggests that the fairly uniform hydraulic heads measured are indicative of a strongly-stratified horizontal flow system with virtually no vertical driving forces (i.e. sinks), present. Vertically, the different zones respond similarly to temporal changes with no difference with depth. In other words the change relative to a mean hydraulic head in each zone is the same.

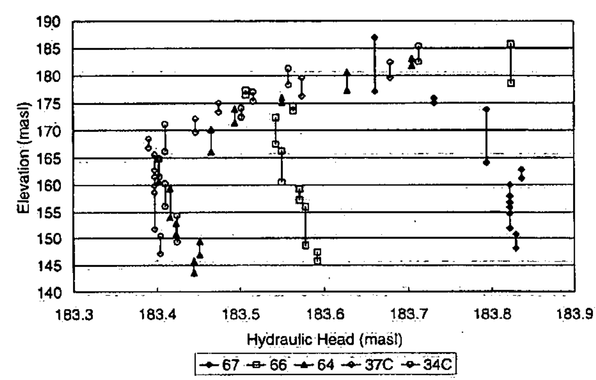

Figure 8. Vertical hydraulic head variations in five site boreholes.

4.4 Hydraulic gradients and groundwater velocities

Horizontal hydraulic gradients in three connected zones within the five site boreholes were determined by finding the equation of a plane through hydraulic head measurements. These three zones are referred to as upper, middle and lower zones (Figure 5). Magnitude and direction of the hydraulic gradient were calculated for all measurement dates in the three zones. Over the year hydraulic gradients in the lower and middle zones vary by approximately half an order of magnitude ranging from 5×10^{-4} to 9×10^{-4}. Lower gradients were determined in the upper zone with a range from 1×10^{-4} to 4×10^{-4}. (Figure 9)

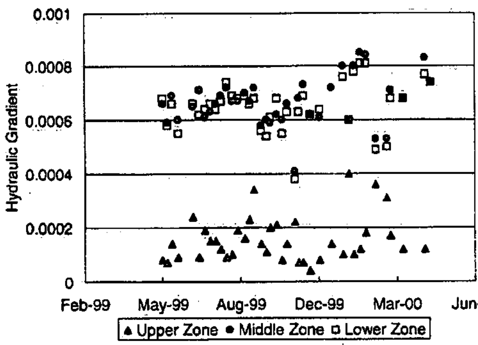

Figure 9. Hydraulic gradients in three connected zones at the site scale.

The middle and lower zones are located below the low permeability-confining unit ubiquitous in the area. This low permeability unit is considered to separate two separate flow regimes in the region (Zanini et al., 2000). Based on geological contact information the gradient of the bedrock in the region is about 5×10^{-3}.

The spread in groundwater flow direction within these zones as determined from the gradient calculations is shown in Figure 10. In the lower features the spread in gradient direction over the year is roughly 15° with flow to the south (Figure 10(a) & 10(b)). In the middle feature the flow direction is slightly to the southwest and in the lower feature the bulk of the measurements indicate a flow direction slightly to the southeast. In the upper feature we see flow is predominantly in the 100-110° direction and there is a larger spread in flow directions including several measurements indicating groundwater flow 'upgradient' (Figure 10(c)). Considering that the hydraulic gradient is often about 1×10^{-4} it is likely that much of the variation is due to measurement error. Nevertheless this analysis illustrates the difficulty in obtaining measures of groundwater direction in fractured rock of very low hydraulic gradient. Note that the boreholes used in this analysis are several hundred metres apart and in situated an area at the scale of many contaminated sites. The variation in groundwater flow directions may be significant in determining contaminant plume directions and requires further investigation.

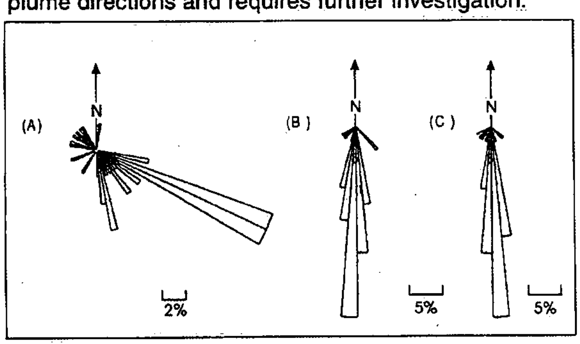

Figure 10. Hydraulic gradients in three connected zones: (a) upper, (b) middle and (c) lower.

Groundwater velocities within the connected zones were calculated using the mean horizontal hydraulic gradients calculated above and a range of hydraulic apertures (Table 1). The hydraulic apertures were based on typical results from the hydraulic testing program conducted in these boreholes. While not considering the spatial variation in permeability within each zone these calculations do illustrate that a wide range of expected groundwater velocities are possible with this magnitude of horizontal hydraulic gradient.

Table 1. Groundwater velocities in the three studied zones at the site scale.

Zone	Mean Hydraulic Gradient	Hydraulic Aperture $2b_H$ (μm)	Velocity (m/day)
		500	2
Upper	2E-04	1000	8
		2500	50
		500	9
Middle	7E-04	1000	34
		2500	213
		500	8
Lower	7E-04	1000	34
		2500	211

Point dilution experiments can be used to obtain measurements of groundwater velocity in discrete fractures (Novakowski et al., 1999). A point dilution experiment is conducted by injecting a conservative tracer into a sealed off portion of the borehole isolating a single fracture. The decay of tracer in the well bore due to natural groundwater flow can then be related to the groundwater velocity. Several point dilution experiments have been conducted in boreholes at the Smithville site. In particular, Table 2 shows the results of experiments carried out in borehole 37C (prior to Westbay installation) and in borehole 59 (not currently instrumented) (Figure 2). Both of these features are located in the upper flow zone. Hydraulic apertures were measured using a constant-head injection test immediately after the completion of the point dilution experiment. Hydraulic gradients were calculated from the measured velocities and hydraulic apertures using the cubic and Darcy laws.
The gradients in the two features in 59 are similar to that calculated from the hydraulic head measurements while the measurement calculated in 37C is an order of magnitude higher than the hydraulic head measurements. This difference may suggest that the groundwater velocities determined from inferred horizontal connections may not be adequately capturing the spatial variations in the groundwater flow field in discretely fractured media. Further investigation of using both direct and indirect field measurements to determine groundwater velocities in fractured media at the site scale is ongoing.

Table 2. Results of point dilution experiments.

Test ID	Borehole	Elevation (masl)	$2b_H$ (μm)	v (m/day)	dh/dx
PD96-3.5	37C	178.5	425	33	4.E-03
PD99-03	59	177.0	604	2	1.E-04
PD99-04B	59	176.4	638	4	2.E-04

5. CONCLUSIONS

The weekly measurement program carried out over four years showed that the hydraulic head at all levels varied by over 1.5 m with seasonal maximum and minimum values consistent with regional climatic conditions. At the site scale horizontal hydraulic gradients vary both in magnitude and direction over the course of the year. Additionally measurements made in the different groundwater flow systems vary by over half an order of magnitude. Determining groundwater velocities, using hydraulic head measurements at different scales in fractured rock deposits is difficult. At the regional scale the connectivity of the flow paths may not be easy to discern or necessarily follow the geological unit boundaries. In addition to determining connectivity of fractures zones both in the horizontal and vertical dimensions, at the site scale differences in hydraulic head in the order of centimetres leads to hydraulic gradients and groundwater velocity measurements which are prone to measurement error. Consequently, if complex groundwater systems are to be understood other direct methods of measuring groundwater velocity need to be used to corroborate both the inferred hydraulic connections and the groundwater velocities. These may include point-dilution and multi-well tracer experiments and inter-borehole hydraulic tests.

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7. REFERENCES

Black, W. H., H. R. Smith, and F. D. Patton, Multiple-level groundwater monitoring with the MP system, In: Proceedings NWWA-AGU Conf. Surface and Borehole Geophysical Methods and Groundwater Instrumentation, NWWA, Dublin, Ohio, 1987.

Novakowski, K. S., and P. A. Lapcevic, Regional hydrogeology of the Silurian and Ordovician sedimentary rock underlying Niagara Falls, Ontario, Canada, J. Hydrol., 104, 211-236, 1988.

Novakowski, K., P. Lapcevic, G. Bickerton, J. Voralek, L. Zanini and C. Talbot, 1999. The development of conceptual model for contaminant transport in the dolostone underlying Smithville, Ontario, National Water Research Institute, Burlington, Ontario, Canada, NWRI Contribution # 99-250, 245pp.

Novakowski, K. S., Lapcevic, P., Oxtobee, J., and Zanini, L., 2000. Groundwater flow in the Lockport Formation underlying the Smithville, Ontario Area, this volume.

Yager, R. M., 1996. Simulated three-dimensional groundwater flow in the Lockport Group, a fractured-dolomite aquifer near Niagara Falls, New York, U.S. Geological Survey Water Supply Paper, W 2487.

Zanini, L., Novakowski, K. S., Lapcevic, P., Bickerton, G. S., Voralek, J., and C. Talbot, 2000. Groundwater Flow in a Fractured Carbonate Aquifer Inferred from Combined Hydrogeological and Geochemical Measurements, Journal of Groundwater, Volume 38, pp 350-360.

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