Ground and Water: Theory to Practice
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ASSESSMENT OF GROUNDWATER VELOCITIES TO THE MUNICIPAL WELLS AT WALKERTON

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ABSTRACT
Bacterial contamination of well water in a carbonate aquifer in Walkerton, Ontario resulted in the deaths of seven people and in 2300 illnesses. Subsequent hydrogeological investigations done for the town of Walkerton assumed that the aquifer behaved as an equivalent porous medium and that groundwater flow rates were relatively slow. However, field investigations including tracer tests have shown that the aquifer is karstic, and is characterized by rapid groundwater flow (320 to 480 m/day) through solutionally-enlarged fractures in the aquifer. Other evidence supporting our view of the karstic nature of the bedrock includes the high hydraulic conductivity and the presence of discrete production zones in wells from solutionally enlarged fractures. As a result, the potential source area for contamination is expanded by three orders of magnitude, and includes many farms, streams and drains excluded from the field investigation of cause. The example of Walkerton demonstrates the importance of taking a precautionary approach when investigating carbonate aquifers.

RÉSUMÉ
La contamination bactériologique de l'eau des forages dans une aquifère carbonate à Walkerton, Ontario a amené a sept mortalités et 2300 malades. Les investigations hydrogéologiques pour la ville de Walkerton s'arroge l'aquifère était une milieu poreux avec vitesse de l'eau relativement lent. La recherche au terrain, comprenant des traçages montrait que l'aquifère est karstique avec taux de l'eau rapide (320 a 480 m par jour) au travers des fractures agrandis par la dissolution. Evidence supplémentaire compris conductivité hydraulique élevé, et la présence des zones de production discret associe avec les niveau dissous dans les forages. Par conséquence, la surface de la région d'origine de la contamination est agrandit par trois ordres de magnitudes. Beaucoup d'autres fermes, ruisseau et fosses sont possible pour l'origine de la contamination. L'exemple de Walkerton démontre l'importance de prendre une approche de précaution dans le cas des aquifères carbonates.

1. INTRODUCTION

Seven people died and about 2300 people became ill as a result of contamination of the municipal water supply at Walkerton in May 2000 by bacteria. The principal pathogens were *Escherichia coli O157:H7* and *Campylobacter jejuni*. Subsequent epidemiological investigations indicated that most of the contamination of the water supply had occurred within hours or days at most after heavy rain. Hydrogeological investigations since then have sought to establish potential source areas, pathways, and travel times for this bacterial contamination of the water supply.

2. CHRONOLOGY

On May 18th 2000 two children with bloody diarrhoea and abdominal pain were admitted to the hospital in Walkerton, and over the succeeding days large numbers of people became ill (Figure 1). On May 21 the health unit issued a boil water advisory. The following day the Ontario Ministry of the Environment initiated an investigation of the Walkerton water supply. This included both groundwater investigations and analysis of surface water, groundwater, and stool samples for pathogenic bacteria from wild and farm animals and from humans.

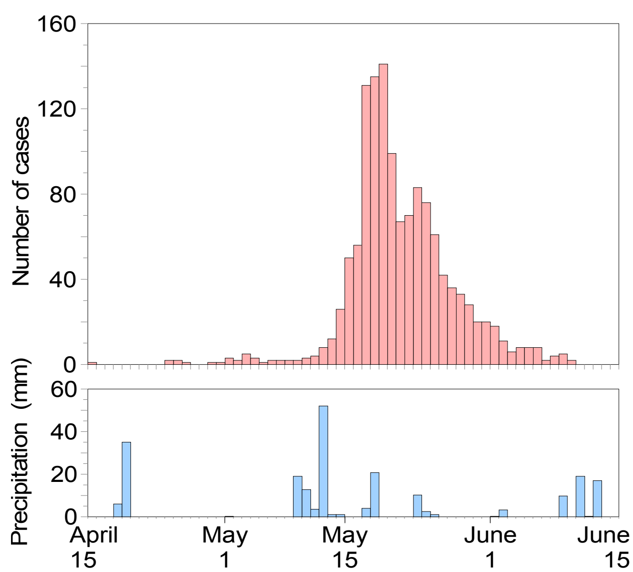

Figure 1 Comparison of illness onset dates and precipitation (after Bruce-Grey-Owen Sound Health Unit, 2000)

In the summer and fall of 2000 a hydrogeological investigation was carried out for the town of Walkerton. This included the drilling of 38 boreholes, surface and downhole geophysics, pump tests, and the testing of numerous samples for both bacteriological and chemical parameters. A numerical model of groundwater flow (using MODFLOW) indicated that the 30-day time of travel capture zones extended 290 m from Well 5, 150 m from Well 6, and 200 m from Well 7. These results suggested that if a groundwater pathway were implicated in the contamination then the source must have been very close to one of the wells.

Well 5 was closed because of bacterial contamination and because a groundwater spring 30 m from Well 5 reversed during pumping. An informal tracer test and borehole video indicated that surface water reached the well in less than one hour, entering by a solutionally enlarged fracture. In addition, Well 6 was also decommissioned due to frequent episodic bacterial contamination.

A public inquiry into the tragedy held hearings between October 2000 and October 2001. The Walkerton Inquiry retained Dr. Robert Gillham to interpret and present the hydrogeological findings to the inquiry, and this took place in February 2001. Dr. Gillham suggested that the limestone and dolostone bedrock aquifer at Walkerton is karstic, and that water could move through the bedrock at hundreds of metres per day (Walkerton Inquiry transcripts, February 28 2001, p. 157). Far more extensive, irregular-shaped capture zones might be expected as a result.

Following this testimony the authors of this paper were commissioned by the Concerned Walkerton Citizens to further investigate the aquifer and in particular to resolve the conflicting ideas on groundwater velocities in the vicinity of the three wells by means of tracer testing. We also correlated bacterial contamination of the wells with antecedent rain, conducted water quality profiling of three test wells adjacent to Wells 6 and 7, and assessed the capture zones for the three municipal wells. Interim results were presented to the Walkerton Inquiry in July 2001, though delays in obtaining permission from the MOE had prevented any tracer testing from being done. Initial tracer testing was eventually carried in October and November 2001 in cooperation with the Town's consultants, and more tracer testing is planned for 2002.

3. GROUNDWATER INVESTIGATIONS PRESENTED TO THE PUBLIC HEARINGS OF THE WALKERTON INQUIRY

3.1 Conceptual models for flow through the bedrock

A large increase in the number of human illnesses at Walkerton commenced within days of heavy rain, so it is reasonable to assume that the source area for the pathogenic bacteria must have been within a very few days time of travel from the wells. The hydrogeologists involved with the groundwater investigations at Walkerton considered two very different conceptual models of flow in the aquifer. The two different conceptual models result in widely differing estimates of groundwater velocities, and thus widely differing estimates of potential source areas for the pathogenic bacteria at Walkerton.

The hypothesis of the Town's consultants hypothesis assumed that any large-aperture openings in the bedrock would have a very limited spatial extent and would not intersect other large-aperture voids. Where one open fracture peters out the groundwater would flow through the matrix of the rock, and consequently the aquifer would behave as a porous medium aquifer This model is often referred to as an equivalent porous medium (EPM) model.

Our hypothesis was that the aquifer is karstic. This implies that solution of the bedrock has resulted in an *interconnected* network of enlarged fractures. Fracture enlargement would take place on bedding planes and joints, and would be localised along channels in these fractures. The resulting elliptical or circular openings would have apertures much larger than are associated with tectonic fractures, which typically have apertures less than 0.1 mm. The flow channels assumed in this model are supported by lab investigations of kinetic processes in the solution of limestone and dolostone (Berner and Morse, 1974; Plummer and Wigley, 1976; Herman and White, 1984) and by numerical modelling (Dreybrodt, 1996; Hanna and Rajaram, 1998), as well as by numerous tracer tests and studies of karst (White, 1988; Ford and Williams, 1989). A large majority of these channels have apertures in the range 0.1 mm - 1 cm, and are likely to have laminar flow. Where apertures are larger than 1 cm there may be turbulent flow (White, 1988; Howard and Groves, 1995); a very small fraction of channels may be enlarged to the size of caves. Boreholes are unlikely to encounter caves, but are likely to link into smaller solutional channels (Worthington 1999).

It is important to use the correct conceptual model in assessing carbonate aquifers, but surprisingly there is only a small literature on test methods to differentiate karstic from non-karstic carbonate aquifers. Pankow et al. (1986) and Price (1994) offer methods for differentiating EPM and fracture flow aquifers, and Freeze and Cherry (1979), Hickey (1984), Worthington and Ford (1995), Domenico and Schwartz (1998) and Worthington (1999) offer methods for differentiating karstic from either fracture flow or EPM aquifers.

Glacial erosion and deposition have removed or obscured surficial karst landscape around Walkerton, but this does not preclude the presence of a karst aquifer. Reconnaissance mapping showed solution channels in outcrops, discrete, variable flow and reversing springs and streams recharging the aquifer, all indications of karst hydrogeology. Three data sets collected before the end of the hearings of the Walkerton Inquiry are applicable to determining the appropriate model: pumping tests, the locations of inflow to the wells, and the shape of the openings through which water flows into the well. However, the most relevant way of determining groundwater velocities is to measure them directly with tracer tests. Despite the critical results from tracing at Well 5, and an analogous spring between Wells 6 and 7, additional tests were not permitted until after the public hearings had ended.

3.2 Pumping tests

Both Freeze and Cherry (1979, p. 29) and Domenico and Schwartz (1998, p. 39) suggest that karstic limestones have hydraulic conductivity (*K*) values greater than 10^{-6} m/s, whereas non-karstic limestones have $K < 10^{-5}$ m/s. A 36 hour pump test at Well 5 yielded a calculated *K* of 1.5×10^{-3} m/s, and a 48 hour pump test of both Wells 6 and 7 pumping yielded a calculated *K* of 1.2×10^{-4} m/s (Golder Associates, 2000b). These values indicate that the aquifers at both Well 5 and at Wells 6 and 7 are karstic.

3.3 Location of inflows to the wells

The location and discharge of inflows to Wells 5, 6, and BH 1-86 (a test well 8 m from Well 7) were determined by flow metering (Golder Associates, 2000a). We have superimposed these data on correlated natural gamma profiles (Figure 2). Almost all the flow enters Well 5 in the weathered or epikarst zone, which is typically found in the top of carbonate aquifers. The remaining two wells are cased to below the weathered zone, but in each case at least half the inflow occurs at a single bedding plane (Figure 2).

If the aquifer were a uniform porous medium then seepage into the well bore would occur throughout each open hole. If the aquifer behaved as an EPM then many small inflows would be expected along fractures. Neither case occurs at any of the three wells. At Well 5 essentially all the pumped flow of 24 L/s entered through the 1 m thick epikarst zone. At Well 6 half the flow of 21 L/s entered at a single bedding plane at a depth of 20 m. At the Well 7 test well 55% of the flow under non-pumping artesian flow conditions entered from a single bedding plane at a depth of 53 m. Such highly localized flow is typical of karst aquifers.

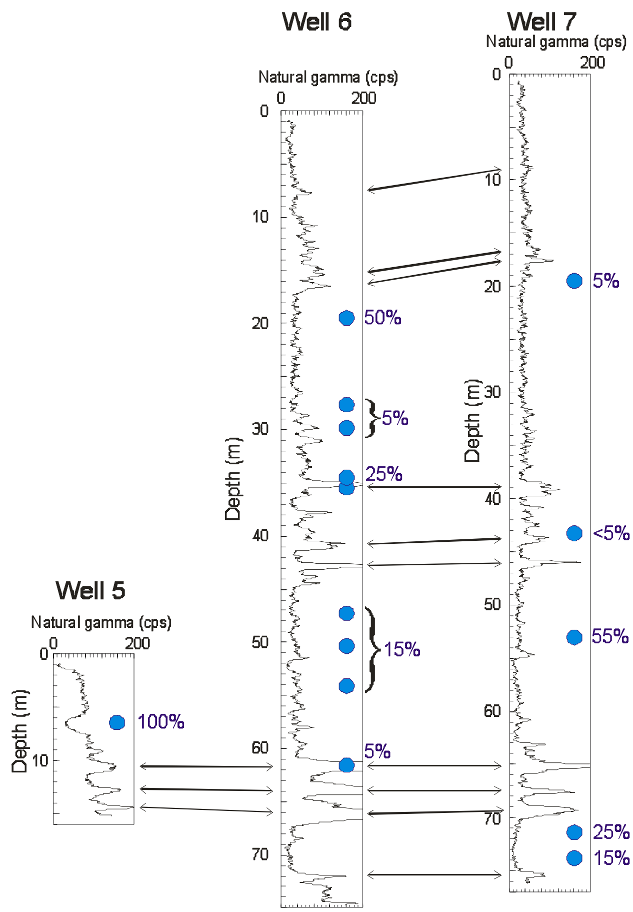

Figure 2 Stratigraphic correlation of Wells 5, 6, and 7 using gamma logs, showing the major locations of inflow to the wells (after Worthington et al., 2000a)

3.4 Shape of the openings through which water flows into the wells

If the aquifer at Walkerton were a simple fractured aquifer with open fractures being the result of tectonic forces, then fractures apertures would be fairly constant and fracture apertures would be much less than 1mm.

Downhole videos were taken in Wells 5 and 6 with only vertical views down the well, but horizontal views were taken of the major production zones in Well 7 and the Well 7 test well (BH1-86). The horizontal shot of the major production zone in BH1-86 shows that the flow comes from a bedding plane which has been enlarged by solution to an elliptical conduit approximately 30 mm high and 150 mm wide (Golder Associates, 2000a, Photo 35). In the video water can be seen exiting the well at a depth of 20 m via a second conduit. This latter conduit has developed on the bedding plane, and is about 15 mm high and 50 mm wide (Golder Associates, 2000a, Photo 34). Little solutional enlargement has taken place on the remainder of the bedding plane.

These horizontal shots clearly show that dissolutional enlargement along bedding planes has resulted in the formation of conduits with apertures in the tens of millimetres, and that most of the flow into and out of the borehole takes place via these conduits. Such flow is characteristic of karst.

3.5 Discussion of findings presented to the Inquiry

The evidence described above indicates that the aquifer is karstic. Flow through conduits in karst aquifers is very rapid, with velocities in the hundreds to thousands of metres per day. The theory of flow in karst suggests that the conduits seen in the downhole videos should be part of conduit networks that extend throughout the aquifer (e.g. Ford and Williams, 1989)

If there were comprehensive horizontal video records of the boreholes at Walkerton then it would be possible to calculate what fraction of the aquifer is occupied by conduits. Such records do not exist, but in their absence a rough estimate can be made for BH 1-86. The 16 cm diameter borehole has an open hole depth of 61 m, which means that the borehole intersects an aquifer cross-section of 9.76 m^2. The sum of the cross-sectional areas of the two conduits described above is 0.0038 m^2, or 0.039% of the aquifer cross-section intersected by the borehole. Flow meter measurements shows there are five flow zones (Well 7 in Figure 2). Assuming the three remaining flow zones have conduits with similar apertures to the two with measurements, then the conduits occupy roughly 0.1% of the aquifer. This approximation is similar to the geometric mean of 0.037% for conduit porosity calculated for four contrasting karstic carbonate aquifers using aquifer tests and spring discharges (Worthington, 1999).

The Town of Walkerton's consultants assumed that the conduits are discontinuous and that the aquifer behaves as an EPM, allowing MODFLOW to be used to characterize flow in the aquifer. Thus the possibility of bacterial contamination arising from reversal of Spring B between Wells 6 and 7 (Figure 3) was rejected because a one month travel time was computed. However, if the well and spring are connected by conduits then the travel time would be much less. A comparison of EPM and karstic travel times based on comparable conditions (Table 1) showed a one day travel time under karstic conditions.

Table 1. Calculated travel times in the Walkerton bedrock aquifer under different assumptions (after Worthington et al., 2001a)

Parameter (units)	Karst model	EPM model
Distance from spring to Well 7 (m)	150	150
Transmissivity (m/day)	350	350
Thickness of active flow zone (m)	60	35
Hydraulic conductivity (m/day)	5.8	10
Porosity (%)	5	5
Hydraulic gradient	0.025	0.025
Effective porosity (%)	0.1	5
Travel time (days)	1.1	30

4. GROUNDWATER INVESTIGATIONS AFTER THE PUBLIC HEARINGS ENDED

The presentation of conflicting testimony on groundwater velocities in the bedrock caused uncertainty in identifying possible source areas for the bacterial contamination of the wells, and it was not until 17 months after the contamination of the wells that long-distance tracer testing finally commenced at our request. By this time Well 5 and other deep monitoring wells had been plugged, Well 6 had been converted to a nest of four monitors, the casing in Wells 7and TW 1-86 had been extended, and a new 75 m deep water supply well, Well 9, had been drilled. Furthermore, the period of flow reversal at spring B had ceased.

On October 29th 2001 simultaneous injections were made of two fluorescent dyes, uranine (sodium fluorescein) in the deep monitor in Well 6 and eosine in Well 9. Well 7 was pumped continuously for the first 72 hours of the test. Water not needed for the public water supply was run to waste at a site several kilometres from the pumping well. The tracers were injected at similar depths in Wells 6 and 9 to the main producing zone near the bottom of Well 7, so that flow would follow a simple horizontal flow path along bedding planes.

Results are shown in Figure 3. The tracer from Well 9 (100 m away) arrived after five hours and peaked after nine hours. The tracer from Well 6 (350 m away) arrived after 26 hours and peaked after 60 hours. Velocities for the two tests are about 80 times faster than the MODFLOW simulation of Golder (2000b), but are similar to the predictions made three months earlier by Worthington et al. (2001a) under the assumption that the aquifer is karstic.

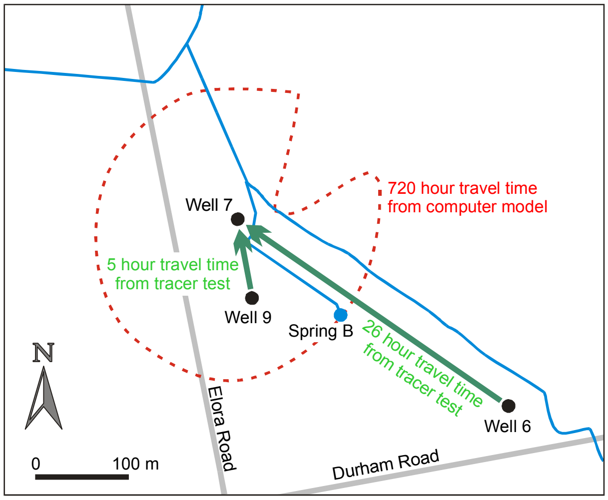

Figure 3 Trajectories and travel times for the tracer tests started on October 29th 2001, showing velocities >300 m/day, compared to a 30 day capture zone predicted using MODFLOW (Worthington et al., 2001b).

5. DISCUSSION

Our review of the available data combined with direct evidence from tracer testing has confirmed the karstic nature of the aquifer at Walkerton. The groundwater velocities observed in the tracer test (480 m/day between Well 9 and Well 7 and 320 m/day from Well 6 to Well 7) are typical of karst. The tracer test results are inconsistent with the equivalent porous medium model and the MODFLOW simulation (based on that model) of the Town of Walkerton's consultants.

The rapid groundwater velocities observed in the tracer testing show that the potential source area for the pathogenic bacteria responsible for the Walkerton Tragedy would have extended far beyond the one farm (immediately adjacent to Well 5) which is implicated as the likely source of most of the bacteria (O'Connor, 2002a, p. 142). Overburden in the Walkerton area is often thin and fractured and probably ineffective in protecting the underlying carbonate aquifer from surface contamination, and thus other more distant bacteria sources cannot be ruled out. Furthermore, rapid transmission of surface water into the water supply presents the possibility of contamination by compounds not necessarily ameliorated by filtration and chlorination.

The example of Walkerton vividly demonstrates the necessity of taking a precautionary approach in hydrogeological investigations of carbonate aquifers. In our view, such an approach should be based on the assumptions that karstic conduits may be present in a carbonate aquifer. The authors are familiar with too many other cases in Ontario and in several U.S. states where a "best-case" optimistic approach has been taken, that assumes the absence of karst permeability, but where subsequent investigations using tracer testing have shown groundwater velocities far faster than calculations from pump tests or MODFLOW had indicated.

6. CONCLUSION

The carbonate aquifers in the Walkerton area are karstic; that is, they contain solutionally enlarged conduits which can transmit groundwater (and contaminants) at rates of hundreds of metres per day. Evidence indicating the karstic nature of the Walkerton aquifers includes:

! surface features such as discrete springs and solution channels in outcrops

! hydraulic conductivities of 10^{-4} to 10^{-3} m/s obtained from pumping tests on the Town's wells are characteristic of karst aquifers

! much of the groundwater flowing into the wells enters via a few discrete horizons, which is typical of karst aquifers

! the views of major production zones in horizontal downhole videos clearly show karstic conduits (solutionally-enlarged elliptical conduits measuring 30 mm x 150 mm and 15 mm x 50 mm) which formed on otherwise typical bedding planes

! the groundwater velocities measured during a tracer test ranged from 320 to 480 m/day, which are typical velocities in karst aquifers.

The experience of Walkerton underlines the importance of taking a precautionary approach when carrying out hydrogeological investigations in carbonate aquifers. Justice O'Connor endorsed using a precautionary approach where investigating systems that may affect public health (O'Connor, 2002b, p. 150). In assessing carbonate aquifers, such an approach would be based on the assumption that karst features may be present and would include tracer testing as an important part of the hydrogeological investigations.

7. ACKNOWLEDGMENTS

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