Karst hydrogeological investigations at Walkerton

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Prepared for
Concerned Walkerton Citizens

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Preface

In the week of February 26th 2001 at the Walkerton Inquiry Dr. Robert Gillham presented the results of hydrogeological investigations in the vicinity of Walkerton's municipal wells. At the conclusion of the testimony of Dr. Gillham, Dr. Huck, and Dr Payment (the panel of experts on physical cause) there were a number of acknowledged unanswered questions about how the contamination of the Walkerton water supply occurred. In particular, there were questions on the role that karstification might have played in the contamination of the wells.

Concerned Walkerton Citizens retained Dr. Stephen Worthington and Wilf Ruland to undertake a modest course of hydrogeological field work and to present the results in a report. Dr. Christopher Smart of the University of Western Ontario and Dr. Derek Ford of McMaster University loaned equipment for use in the field. The field work was carried out by Steve Worthington, Chris Smart, Brad Simpson (University of Western Ontario) and Dr E. Calvin Alexander (University of Minnesota).

Some of the proposed field work included the use of small quantities of non-toxic tracers to measure groundwater velocities within wells and between wells. We have yet to receive comments from the Ministry of the Environment on our proposed testing. We will prepare an addendum to this report after we have carried out this tracing.

In the meantime, this report has been prepared to provide the Inquiry with the results which have been obtained to date, together with a description of karst processes and why these are likely to have played a key role in the contamination of the Walkerton water supply in the spring of 2000.

Executive Summary

The municipal wells at Walkerton draw water from karstic dolostone and limestone bedrock aquifers, and such aquifers are recognised to be extremely susceptible to bacterial contamination. In many areas overburden above the bedrock will protect the underlying karstic bedrock from bacterial contamination. However, those places where the overburden is thin and either fractured or composed of highly permeable gravels are at risk of rapid transport of bacteria through the overburden and into the bedrock. Once they have reached the bedrock, bacteria can move quickly along networks of karst conduits towards springs. The vicinity of karst springs may often provide copious supplies of groundwater, but such sites should generally be avoided when drilling wells for municipal water supplies. Unfortunately, all of Walkerton's wells were drilled near karst springs.

The springs at Well 5 have a groundwater catchment of approximately 150 hectares (0.6 square miles), and the springs close to Wells 6 and 7 have a groundwater catchment of more than 500 hectares (2 square miles). There are a number of areas within these groundwater catchments with thin overburden, and this makes the wells more susceptible to contamination than wells with smaller groundwater catchments. The three elements of thin overburden, karstic bedrock, and location of wells close to the springs combine to make Wells 5, 6, and 7 susceptible to bacterial contamination by groundwater flow. It appears that overland flow of bacterially contaminated water to the vicinity of Well 5 followed by surface contamination of the well is unlikely to have occurred.

Daily analyses of bacteria in the municipal wells and in a domestic well have helped demonstrate a relationship between precipitation and bacterial contamination of wells. The wells in these karst aquifers are most liable to contamination within hours to days of heavy rain. The most severe contamination occurs following heavy rain on saturated ground, and occurs when there is more than 100 mm of rain within a two week period. The period from May 9th to May 12th 2000 was one such period, and Wells 5, 6 and 7 probably all suffered from bacterial contamination via groundwater flow within hours to days of this rain. An earlier heavy rainfall of 35 mm on April 19th 2000 could also have resulted in bacteria being carried through the aquifer to one or more wells. Well 5 was likely the most severely contaminated, Well 7 the least.

Given the large groundwater catchment areas and the vulnerability to contamination of the wells, there were likely multiple sources of microorganisms which reached the Walkerton municipal water supply via the wells during early May 2000.

Biographical sketches of the authors

Steve Worthington is a hydrogeologist who has been studying karst aquifers for more than thirty years. He has a B.A. in Geology and Geography from Sheffield University (England), and an M.Sc. in karst geomorphology and a Ph.D. in karst hydrogeology from McMaster University. His Ph.D. thesis was titled "Karst hydrogeology of the Canadian Rocky Mountains". He has studied karst aquifers in 25 countries. For the last seven years he has worked as a consultant on problems in carbonate aquifers, and has specialised in bridging the gap between the karst and porous medium approaches in understanding carbonate aquifers. He was retained by the Concerned Walkerton Citizens to assist with the issue of the possible significance of karst in the bacterial contamination of the municipal wells at Walkerton, and has led the field research described in this report.

Chris Smart has been studying karst aquifers for 30 years. He has a B.Sc. in Geography from Bristol University (England), an M.Sc. from the University of Alberta in karst geomorphology and a Ph.D. from McMaster University in karst hydrogeology. His Ph.D. was titled "Hydrology of a glacierised alpine karst". He is an Associate Professor in the Department of Geography at the University of Western Ontario. His research focusses on the hydrogeology of karst aquifers and the hydrogeology of glaciers, and he has a keen interest in developing new measurement techniques and instrumentation. He designed and led the field work on the conductivity profiling of the boreholes at Walkerton.

Wilf Ruland is a hydrogeologist who has operated his own consulting firm (Citizens' Environmental Consulting) since 1988. He has a B. Sc. degree in Geography and Geology from McMaster University, and a M.Sc. degree in Earth Sciences from the University of Waterloo. His M.Sc. thesis was titled "Fracture depths and active groundwater flow in a weathered clayey till in Lambton County, Ontario". He specializes in contaminant hydrogeology, and has done extensive work on studying the hydrogeology of fractured silt and clay soils. He has worked in a wide variety of hydrogeological environments across Ontario, including work on other projects in areas with karst bedrock. He specializes in work for citizens' groups, and was retained by the Concerned Walkerton Citizens to assist the group with hydrogeological issues being raised at the Walkerton Inquiry.

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Introduction

This report is based on a review of existing geological and hydrogeological information and on field work carried out in the spring of 2001. It is intended to supplement the hydrogeology presentations by Dr. Ken Howard on October 16th 2000 and by Dr. Robert Gillham on February 28th and March 1st 2001. The report has three major technical sections, and then a fourth section which discusses how the bacterial contamination of the water supply in Walkerton occurred:

Section 1 This section outlines the characteristics of flow in karst aquifers such as Walkerton and explains why they are susceptible to bacterial contamination.

Section 2 This section describes how water quality variation at Wells 5, 6, and 7 is correlated to precipitation and spring flow.

Section 3 This section determines the hydrogeology of the wells from chemical data and electrical conductivity profiling and assesses the areas from which there could be flow to Wells 5, 6, and 7 within 50 days.

Section 4 This section draws together the evidence from the previous sections to discuss how the bacterial contamination of the water supply in Walkerton occurred, and presents conclusions and recommendations.

Section 1 Characteristics of flow in karst aquifers such as at Walkerton and why they are susceptible to bacterial contamination

1A Karst aquifers in Ontario and their susceptibility to bacterial contamination

It has been suggested by the U.S. Environmental Protection Agency that only a small percentage of all ground water systems are susceptible to fecal contamination (USEPA, 2000, p. 30222; also Walkerton Inquiry, Exhibit 264). The EPA document then identifies karst, fractured bedrock and gravel aquifer types as being the most susceptible since they can transmit fecal contamination over long distances in short periods.

The bedrock aquifer at Well 5 at Walkerton is composed of dolostone. The bedrock aquifer at Wells 6 and 7 is composed of limestone. Both limestone and dolostone form karst aquifers, and thus are at the top of the EPA list of aquifer types susceptible to fecal contamination. Limestone and dolostone are often referred to collectively as carbonate rocks.

Figure 1 shows groundwater velocities for the major types of aquifer materials. Four points are worth noting:

a) There is a remarkably large range in the ability to transmit water. Figure 1 shows that there is a range of ten million million (thirteen orders of magnitude) between groundwater velocities in different aquifers.

b) Aquifers are differentiated into two types: rocks (e.g. limestone, dolomite, basalt, sandstone, shale) and unconsolidated deposits (e.g. gravel, sand, silt, clay).

c) Most geologic materials are not considered by the EPA to be susceptible to fecal contamination. The highlighted aquifer types are those considered by the EPA to be susceptible; the figure shows that they have the fastest groundwater velocities.

d) The asterisks in Figure 1 show aquifer test results from Walkerton (Golder Associates, 2000b, Exhibit 259); they clearly lie within the range of aquifers which are most susceptible to fecal contamination.

Figure 2 shows the distribution of carbonate bedrock in southern Ontario. There are three major areas without carbonates, one around Toronto and west to the base of the Niagara Escarpment, a second between London and Chatham, and a third constituting the Canadian Shield, which also covers most of northern Ontario. The three areas without carbonates have fractured rock aquifers which tend to be less productive than the carbonates and are therefore less likely to be exploited as municipal groundwater supplies.

Figure 2 does not show overburden deposits, which are largely of glacial or fluvioglacial origin. Overburden covers almost all of southern Ontario and can reach thicknesses of more than 100 m. In southern Ontario, coarse grained overburden (e.g. gravels and sand) may host important aquifers, and finer grained materials may protect underlying bedrock aquifers from ingress of contaminated surface waters. The overburden deposits in the Walkerton area vary in thickness and composition; they provide little protection to the underlying karst aquifers where they are thin, or composed of sands and gravels.

In summary, karstic carbonate aquifers have been recognised by the U.S. EPA to be susceptible to bacterial contamination. Much of southern Ontario, including the Walkerton area, has carbonate aquifers which are likely to be karstified to some extent and thus susceptible to bacterial contamination. The degree of this susceptibility has been tragically demonstrated in Walkerton, but has yet to be properly addressed.

1B Characteristics of groundwater flow in karst bedrock

The term "karst" refers to a landscape where there are distinctive features resulting from the solution of the underlying bedrock. These features may include sinkholes, bedrock showing solutional features, sinking streams, springs and caves. If such landforms are present then this is a clear demonstration that the underlying aquifer is karstic. This criterion is of very limited use in Canada, because glaciation has relatively recently eroded many karst features, and buried most others beneath overburden.

While much of southern Ontario is underlain by carbonates, which form karst aquifers, more than 95% of this bedrock is overlain by sediments. Consequently, preexisting sinkholes and caves have been filled in and can no longer be identified, and karst landscapes are rare. However, the absence of a karst landscape does not indicate the absence of a karst aquifer.

Karst aquifers are characterised by the presence of interconnected networks of solutionally-enlarged fractures, commonly called channels or conduits. Channels become significant for the permeability of an aquifer once their aperture exceeds about 1 mm. In karst aquifers where the flow from a large area (typically >10 hectares or 0.04 square miles) is focussed on one conduit for a long period then it may be come enlarged to a size where people can enter it, in which case it is called a cave.

Almost all karst aquifers have tributary flow, rather like a river on the surface has tributaries. Figure 3 shows the mapped cave streams in one cave. There are many tributaries, and these converge on one passage, which feeds a spring. Only a small proportion of the 32 km of passages in this cave are shown. The remainder are omitted since they no longer carry flow. The probability of a randomly-placed borehole drilled above this cave actually intersecting one of the cave passages is only one in ninety. This value is typical for karst (Worthington, 1999, Table 2; see Exhibit 261).

We use the cave in Figure 3 because this shows very well how tributary flow occurs in karst. Much karst research is carried out in caves since they offer an ideal opportunity for studying an aquifer from the inside. The principles learned from cave studies apply equally to smaller conduits, such as those visible in the downhole videos in some of the wells at Walkerton, or at surface outcrops of carbonates. From the perspective of groundwater protection, the presence of "caves" is not the issue; if continuous millimetre scale openings are present, then the potential for rapid, unfiltered transport of contaminants becomes possible.

The three conditions necessary for karstification to occur were described by Stringfield and LeGrand (1966):

i) Fractured dolostone or limestone bedrock.

In theory, karst can occur in any soluble rock, but in practice only limestone and dolostone have the requisite combination of moderate solubility and high mechanical strength to allow widespread karstification.

ii) Chemically aggressive ground water to recharge the system.

This occurs when and where precipitation is greater than evaporation, and consequently infiltration takes place. Chemical aggressiveness is due to the presence of carbon dioxide dissolved in the water. Rain water is weakly aggressive because it has a low concentration of carbon dioxide. When this rainwater passes through soil it picks up more carbon dioxide (from decomposition of organic matter) to form carbonic acid. When this acidic water comes into contact with carbonate rocks it starts to dissolve the rock. This process is called solution. The process is rapid at first but becomes progressively slower until the carbonic acid is used up. At this point in the bedrock at Walkerton the groundwater contains about 350 parts per million of dissolved limestone or dolostone. This dissolved rock is carried by rivers down to the Atlantic Ocean, where is will eventually be used again to make new rocks in warm locations such as the Bahamas.

iii) A way for groundwater to drain from the system.

The water must be able to drain from the aquifer at a lower elevation than the input point.

Most solution occurs soon after infiltrating water comes into contact with carbonates. Where bedrock is exposed at the surface then this results in a weathered zone of solutionally enlarged fractures. The upper part of the bedrock at Well 5 is an example of such a weathered zone.

Carbonates may also be karstified much earlier in their geological history, leaving solutionally altered zones within the bedrock known as paleokarst. Such layers are usually infilled with sediment, but may be rapidly reactivated by contemporary groundwater flow.

The solution rate slows substantially as saturation is approached so that 1-2% of the solution takes place deep within the bedrock (Figure 4). Most solution takes place where there is the most flow, and this inexorably leads to the formation of a conduit network wherever water flows through carbonates. There is abundant field evidence for this, but the mathematical proof was only recently developed (Dreybrodt, 1996; Dreybrodt et al., 1999). Thus all carbonate aquifers should be karstified to some degree.

The importance of the solution process is two-fold. First, it is the solution which creates most of the permeability in the rock and makes carbonates such productive aquifers (Figure 1). Second, the solution creates a network of conduits - a plumbing system - in the aquifer, which allows water and contaminants to move rapidly along the pipes of the plumbing (the conduits) without significant filtration.

Most solution takes place close to the water table, but conduits are common at depths of tens or even hundreds of metres below the water table in some circumstances (Worthington 2001a; see Appendix 1). Figure 5 shows the largest spring in France. Exploration by divers and by a submersible craft have found that the river which flows out of the cave comes up from a depth of more than 300 m. Tracer tests have shown that in high flow conditions surface water enters the aquifer 30 km away and reaches the spring in just six days. This example shows that in karst aquifers deep groundwater may have recently been surface water, and thus could be bacterially contaminated.

The deep solution which has created the high productivity zone at a depth of 75 m in Well 7 is not unexpected in terms of deep flow in karst; similar high-productivity zones occur at depths in excess of 100 m in some wells at Cambridge, Ontario. Its great depth below the water table is not a guarantee of antiquity of the water.

A significant problem in the assessment of karstic aquifers and their vulnerability to contamination is that the positions and sizes of the channels or conduits carrying most of the groundwater are usually not known. Occasionally, the positions and sizes of some of the larger conduits are known from cave maps. With continued exploration and mapping the inventory of mapped caves is increasing by about 8% per year, but still only a minute fraction of all caves have been explored. Intensive hydrogeological studies have occasionally deduced some of the plumbing of karst aquifers, as in Figure 6, but such studies are very labour-intensive and require the application of a range of techniques uncommon in hydrogeological studies.

Table 1 shows the fraction of the flux of water through the conduits in four contrasting carbonate aquifers. In every case an overwhelming fraction of the flux of water is through the conduits. This is not surprising since they are interconnected and have large apertures. However, the channels generally make up less than 0.5% of the aquifer by volume, and are hard to find through conventional hydrogeological drilling and pump testing investigations.

The problem of boreholes probably missing the major pathways in an aquifer is hardly discussed in standard hydrogeology text books, but was addressed succinctly at a Joint Board Hearing (CH-86-02) on an application for a new landfill in Halton Region. The Reasons for Decision and Decision (Joint Board, 1989) states :

> "If the latter model [of significantly fractured zones] is correct, it seems to the Board that the problem of delineating leachate paths at site F would be like trying to determine blood circulation patterns in a new species by inserting needles in various parts of the anatomy. If the investigator missed the main veins or arteries with the first few needles, he might conclude that the movement of blood within was very low. How different his opinion had he struck an artery on his first attempt" (Joint Board, 1989, p. 83).

The "arteries" in the carbonates at Walkerton terminate at springs next to Well 5 and between Wells 6 and 7. It is an ineffective approach to determining the major characteristics of circulation (either in a new species or in a carbonate aquifer) by depending on chance intersections of "arteries". Instead, both the heart surgeon and the karst hydrogeologist address their concerns about the speed and destination of the circulation using the same flow equation (Poiseuille's Law) and the same fluorescent dye (sodium fluorescein) for tracer testing. Tracer testing is the only accurate way to assess flow velocities and trajectories in carbonate bedrock; that is why it is so widely used in these rocks (Figure 7).

Figure 7 shows the velocity at which water travels through conduits in carbonates, based on results from 2877 tracer tests. The average velocity is 0.2 m/s or 1.7 km/day (just over one mile per day), and maximum velocities are considerably more. These data are from tracer tests in carbonates in 31 countries, and Table 2 shows that Ontario is no different from elsewhere in having rapid groundwater flow in karst.

Tracer tests have been considered to be the definitive test for assessing water and contaminant movement in carbonate rocks since the first long-distance test in 1877. That test showed that water disappearing into the bed of the Danube River in Germany crossed under the European continental divide to emerge 16 km away just two days later at a large spring which flowed into the River Rhine (Käss, 1998). Since that time there have been many thousands of tracer tests in carbonate rocks which have shown that surface water can travel through aquifers and arrive at karst springs within days.

The primary contamination hazard in karst aquifers occurs where surface water appears in boreholes and springs considered to be safe. There is thus both a hydrological and attitudinal aspect to the problem. The most common problem occurs where surface streams disappear down sinkholes, such as in Figure 8 (and see Appendix 2). In such cases surface water is able to rapidly flow into the subsurface and move quickly to springs or, conduits permitting, wells. Figure 8 shows how a pulse of poor quality water arrived at the spring about 14 hours after rain started. In this case fecal coliform peaked at 280 cfu/100 mL just thirty hours after the start of rain. Dr. Pierre Payment cited a similar situation at the municipal water supply of Le Havre, France, which draws its water from springs in limestone (Exhibit 254, tab 3).

A further compromise to water quality may arise when springs are located in river beds or wetlands and temporarily reverse in flow, introducing surface water into the aquifer (Smart, 1988). Thus a significant question for determining the cause of the bacterial contamination at Walkerton is: are there any points where contaminated surface water may enter the karst aquifer? Such sites may include sinking streams, reversing springs, draining ponds, bedrock exposures, areas of thin overburden, or wells.

If there are no sinking streams then water quality changes at springs after rain are less dramatic, but rapid groundwater flow still occurs and significant water quality changes may occur. In order to detect possible rapid changes in water quality and flow in karst aquifers following runoff events it is necessary to collect water samples and water level data more frequently than in other aquifer materials (Quinlan et al., 1993; also Figure 8).

1C Evidence of karstification of the bedrock aquifers at Walkerton

Karst features such as sinkholes, caves, and springs are the simplest indicators of karstification, but due to glaciation at Walkerton these features, if present, are buried beneath glacial sediments. The exception is the presence of springs, such as those found close to Wells 5, 6, and 7. Boreholes are not ideal for identifying karstification, but the following are some of the most useful tests (Worthington, 1999; Worthington and Ford, 2001; see Appendix 3):

a) tracer testing to measure groundwater trajectories and velocities

b) characterisation of groundwater and frequent water quality monitoring

c) frequent water level monitoring

d) mapping of the water table to identify troughs indicating conduits feeding springs

Some indications of karstification at Walkerton include the following:

1) **The high hydraulic conductivity**.
This is within the range for karst aquifers identified by Freeze and Cherry (1979; see Exhibit 261 and Walkerton transcripts, March 1st, 2001, pages 126-127).

2) **The presence of lost circulation zones in the Bois Blanc Formation**.
The September 2000 Golder report (Exhibit 259) states that "The Bois Blanc Formation [which forms the uppermost bedrock at Wells 6 and 7] is generally considered in the drilling industry to contain "lost circulation" or water producing zones, indicating that it contains highly permeable strata" (Golder Associates, 2000b, p. 30). Lost circulation is where the drilling fluid being circulated down and then back up a borehole during its drilling is lost into a highly permeable zone such as a karst conduit.

3) **The occurrence of springs**.

Karst aquifers are characterised by a network of tributary conduits which converge on a major conduit feeding one or more springs in close proximity. There are significant springs close to Well 5 and to Wells 6 and 7.

At Well 5 the springs are on both sides of the road leading to the well, and we gauged the flow from these springs at a point downstream from the springs (Figure 9). At Wells 6 and 7 there is a spring midway between the two wells, and we gauged the flow there close to the spring orifice (Figure 10). At our two gauging points we found that average discharges are approximately 10-20 L/s (130 - 260 gallons per minute), and this demonstrates convergent karstic flow from areas larger than 100 hectares (0.4 square miles), as will be explained later.

4) **The distribution of inflows to the boreholes.**

When water is being pumped from a well in an aquifer such as sand it is replaced by water inflowing uniformly from the circumference of the well and from throughout the length of the well bore. In that case the velocity of water moving up the well bore would steadily increase from bottom to top. On the other hand, in a fractured aquifer there are typically sudden increases in velocity at points where water is inflowing from fractures. In the carbonate bedrock at Walkerton there are two common types of fracture. Bedding planes are near-horizontal fractures which separate different beds (or layers) of rock. Joints are near-vertical fractures. In fractured rocks most water travels along the fractures, so it is not surprising that in carbonates it is along the fractures that the conduits form because most solution takes place where there is most flow.

Figures 11 and 12 show the inflows to Wells 5, 6, 7, and TW1-86. These data are based on flow meter measurements. Downhole videos show that the major inflows typically occur along bedding planes. In some cases there may be inflow from much of the circumference of the bedding plane. However, a "tell-tale" tied to the video camera light in the Well 6 video demonstrated that much of the inflow at the producing bedding planes came from one side of the well (Golder Associates, 2000a, Exhibit 258, pages 339-341). This suggests that there is a major solutional karstic enlargement of the bedding plane at these inflow points.

For Well 7 we calculated the inflows to the well using both the flow meter velocity data and the caliper borehole width data (Golder Associates, 2000a, Appendices D and E). Our results are shown in Table 3 and Figure 12. The well narrows below -67 m, and this is apparent in both the caliper and video logs. Our calculations show that only 29% of the flow from the well comes from the narrow bottom section rather than the 60% stated in Golder Associates (2000a, Appendix E, p. 349).

Photos 16, 17, and 18 in Golder Associates (2000a) show the intrusion of turbid water into Well 5 after water inflowing from the surface was stirred up. The turbid cloud of water enters from the right-hand side of the video image, indicating that the bedding plane has a wide opening at this point. This intrusion of turbid water is also shown in the attached video.

There is excellent video footage of the nature of openings on the bedding plane at a depth of 64 feet in TW1-86 (Golder Associates, 2000a, p.392). This photo shows a bedding plane which is enlarged to a conduit, with a height of about 15 mm over a width of about 30 mm. The last fifteen minutes of the first video tape taken on July 18th 2000 show that under natural flow conditions there is flow up the well bore and that this flow exits the well at this 15 mm high conduit at a depth of 64 feet. The second video taken that day shows that there is inflow to the well at this point when the well is pumping. This conduit is also shown in the attached video.

Golder Associates ran a suite of geophysical tests in several of the boreholes (2000a, Table 5), and Dan Brown of Golder Associates kindly made the data available to us. Figure 13 shows the gamma logs for Wells 5, 6, and 7. The high gamma counts in impure horizons within the bedrock allows the three wells to be correlated. For instance, there are three impure beds (i.e. layers) at a depth of 62 - 67 m in Well 6. These three beds are found at a depth of 65 - 70 m in Well 7, and probably correlate with three impure beds at a depth of 10 - 15 m in Well 5. Figure 13 also shows the major points where water flows into each well when it is pumping. Some of these inflows can be correlated between wells, such as the inflows at –19 to –20 m in Wells 6 and TW1-86, and at –50 m in Well 6 and at –53 m in TW1-86.

It is common in karst for certain bedding planes to be favoured for dissolution, and conduits are more likely to be encountered on such bedding planes. However, it is quite possible for a borehole to miss the conduits on a bedding plane. For instance, TW1-86 is 16 cm in diameter, and encountered a conduit a few centimetres wide at a depth of 19.6 m (64 feet) in TW1-86. If the location of the well had been moved 20 cm (8 inches) then this conduit could well have been missed.

The inflow to Well 5 is rather different to the inflows to the other wells because it comes from the weathered zone at the top of the bedrock, where many fractures have large apertures (Gillham, 2001, p. 9). In limestone and dolostone bedrock in Ontario the weathered zone is typically just a few metres in thickness at most, and at Wells 6 and 7 the well casing extends at least several metres below the base of the weathered zone.

To summarise the flow metering and video data: most of the inflow to the wells occurs at a few bedding planes in each well, and in many cases it is clear that most of the flow is from karstic conduits.

5) **The occurrence of voids or bit drops.**
Karst aquifers have conduits which in some circumstances may attain diameters of metres. Consequently, if there are substantial drops in the drill bit during drilling of a borehole then this is an indication that a conduit has been intersected, with the drill bit dropping into the void in the bedrock conduit. There have been a few studies quantifying this effect. As discussed earlier, even where there are known caves there would still be a low probability of a randomly-drilled borehole intersecting a cave. The probability of a borehole intersecting a known cave passage for ten extensive and well-mapped cave systems ranged from 0.37% to 7.5%, with a geometric mean of 1.6% (Worthington, 1999, p. 33). Thus most boreholes will not intersect the very large karst conduits which people can walk through, though they may well intersect the more numerous smaller conduits with apertures of centimetres or decimetres.

A method of assessing voids at Walkerton is to plot the size distribution as identified from downhole videos and then compare the distribution to an area with caves. Some hydrogeologists incorrectly assume that an absence of voids indicates an absence of karstification. Void heights for Wells 5, 6, 7, TW2 and TW1-86 were estimated from inspection of the video logs. Tables 4 and 5 and Figure 14 shows a comparison between voids encountered in boreholes at Walkerton and at Mammoth Cave, Kentucky (Worthington and Ford, 1997; Worthington et al., 2000). The figure shows that there are *more* voids of any given size at Walkerton than at Mammoth Cave. This does not imply that there are likely to be large caves in the bedrock at Walkerton, but rather it shows that if the criterion of voids encountered during drilling is used, then the aquifers at Walkerton are at least as karstified as the aquifer at Mammoth Cave (the most extensive cave system in the world).

6) **The chemistry data**.
Analyses of the water from the wells show that limestone and dolostone are being dissolved. For instance, analyses at Well 5 showed that the total dissolved solids average 382 mg/L, of which 354 mg/L is dissolved dolostone (Golder Associates, 2000b, Table 7). We measured an average discharge of 17 L/s from the springs at Well 5, so that 354 times 17, or 6018 mg/s, or 520 kg of dolostone are removed on average each day from the aquifer. Figure 4 shows that some 98% of this solution will take place in the overburden or in the weathered zone at the top of the bedrock, but this still leaves the remaining 2%, or 10 kg per day of dolostone that is being removed from within this bedrock. Most of the dissolution in the bedrock is taking place in the conduits because this is where most of the flow is concentrated. Consequently, the conduit network is

enlarging day by day. Over thousands or tens of thousands of years this continued preferential dissolution results in well-established conduit networks feeding springs such as we see close to the municipal wells in Walkerton.

Section 2 Variation in water quality in the aquifers at Wells 5, 6, and 7 and at the nearby springs

Karst aquifers are frequently characterised by large and rapid changes in water quality, and some examples were cited earlier. By measuring the variation in water quality in an aquifer from place to place and over time it is possible to build up a picture of how the aquifer behaves. For instance, if water quality is uniform over space and there are only small changes over time then it is quite likely that the water is moving slowly and uniformly through the aquifer. On the other hand, if significant differences over space or time are measured then this shows that the contrasting water samples have different histories. Perhaps they come from different parts of the aquifer and have been able to dissolve different minerals, or perhaps the water is moving at different velocities and some samples are diluted by recent rain water.

We reviewed the existing water quality data and collected some data ourselves to build a picture of aquifer behaviour and to help determine the nature of bacterial transport through the aquifers at Walkerton. In Section 2A we will correlate the bacteria and turbidity results from the daily samples collected from the municipal wells with prior precipitation. In section 2B we will describe the spatial variation in the major dissolved ions in the water. We will summarise the results of our water quality sampling at springs close to the municipal wells in section 2C and water quality sampling in three test wells in section 2D.

2A Temporal variation in bacterial contamination at Wells 5, 6 and 7and at a nearby domestic well

Water quality results for bacteria and turbidity are presented in Exhibits 231 and 232, and these were discussed during the testimony of Marc Ethier on January 19th 2001. Much of the focus at that time was on the safety of the water quality in the distribution system. Here we will focus on the quality of the raw water at Wells 5, 6, 7, and at a domestic well (Goss, 2001b). Exhibits 231 and 232 have analyses of four water quality parameters which we will discuss, total coliform, E. coli, background (bacteria), and turbidity. Reporting limits (of exceedences above safe levels) for these parameters are 1 CFU/100 mL, 1 CFU/100 mL, 200 CFU/100mL, and 1 NTU, respectively. There was a concern that bacterial contamination of the wells might be associated with rain, so sampling at Well 7 was carried out on September 14th and 15th 2000 during and after a heavy rainfall of 42 mm at Well 7 (Turnbull, 2000). The water quality at Well 7 during this short period during and soon after the heavy rain was excellent.

The first step in our analysis was to compile precipitation data. Figure 15 shows the data from the Saugeen Valley Conservation gauge located at Hanover for the period May 1st to April 20th 2001, and thereafter it shows our measurements from a continuous recording gauge at Well 7. To help understand the impact of consecutive heavy rains we have plotted the running weekly and two-weekly total rainfall in Figure 15.

Well 5

Figure 16 shows water quality results from Well 5. Daily analyses are only available for May 28th to June 14th 2000. From this short period a correlation between water quality and precipitation is not apparent. There are high E. coli and total coliforms on many of the days, but turbidity is strikingly low. In May and June 2001 we observed that the turbidity at the springs beside Well 5 is always low. Even after heavy rain there is no visible turbidity in the spring water.

Weekly sampling of the water system before May 2000 showed that the water was usually not contaminated. For instance, in 1999 42 of 49 sets of weekly samples had no positives for either total coliform or for E. coli in any of the samples. In light of this it is possible that the high coliform and E. coli shown in Figure 16 represents bacteria transported through the bedrock and to the well during and soon after the heavy rains in May. If flow in the immediate vicinity of the well is slow, it is possible that the bacteria were not flushed out by pumping since pumping at Well 5 ceased on May 23rd 2000.

Wells 6 and 7

Figure 17 shows total coliforms at Wells 6 and 7. It is clear that there are a series of spikes of bacterially-contaminated water. Interpretation of these spikes is not simple because the spikes are of such short duration that they are inadequately defined by daily sampling. This is a common problem with karst groundwater contamination.

Results from tracer testing in carbonate rocks can help us understand how the coliform in Wells 6 and 7 are related to prior rain events. Figure 18 shows results from two tracer tests along the same groundwater flow path but under different flow conditions. The distance between the tracer injection and recovery points is 410 m. Trace #3 appeared at the spring after about one hour, and most of the tracer appeared at the spring over the following hour. In contrast trace #6 arrived at the spring after 12 hours, and most of the tracer arrived at the spring over the following 12 hours. Thus the duration of the tracer appearance is directly proportional to the time since the tracer was injected.

The average velocity of tracer tests along conduits to springs is 0.2 m/s or 1700 m/day, as shown earlier (Figure 7). However, along any single conduit the velocity is typically two to five times lower under low-flow conditions, and two to five times higher under high-flow conditions. Thus after heavy rain groundwater velocities along the conduits leading to the springs beside Well 5 and between Wells 6 and 7 might be in the order of several kilometres per day.

The incidences of coliform contamination in Wells 6 and 7 (Figure 17) typically are of one to three days in duration, which suggests that the event causing the introduction of bacteria to the aquifer probably occurred one to three days earlier. Some of highest coliform readings at Wells 6 and 7 fit this pattern, and can be attributed to prior rain. Examples include:

i) 36 mm of rain on June 11th -13th followed by coliform readings of 20 cfu/100 mL in Well 6 on June 14th and 6 cfu/100 mL in Well 7 on June 15th;

ii) 14 mm of rain on August 26th, followed by coliform readings of 4 cfu/100 mL in Well 7 on August 27th and 111 cfu/100 mL in Well 6 on August 28th;

iii) 111 mm of rain between September 10th and September 20th, followed by coliform detects in Well 7 from September 21st - 25th.

However, other examples do not appear to fit this pattern, such as:

iv) June 18th 2000, when there was >80 cfu/100 mL in Well 6 on the same day as 2.25 mm of rain;

v) July 9 2000, when there was 6 cfu/100 mL in Well 7 on the same day as 0.5 mm of rain;

vi) July 31st 2000, when there was 38.5 mm of rain but there was no coliform in Wells 6 or 7 on that day or any of the next four days.

A number of problems arise in comparisons of rainfall and bacterial contamination. The relationship between bacteria and rain is based on coliform at Wells 6 and 7 and rainfall at Hanover, which is 14 km to the east of the wells. It is quite possible that there was indeed rain in the catchment feeding Wells 6 and 7 on or just before June 18th 2000 and July 9th 2000, and little rain on July 31st 2000. This possibility is supported by a comparison of precipitation at Hanover and at Chesley (Figure 19). The Hanover and Chesley rain gauges are 17 km apart, but there are often substantial differences between the two gauges. We infer from this that the precipitation at Walkerton for some individual events is likely to be substantially different from Hanover, and this hinders the analysis.

A further problem in interpreting the data is the short duration of the bacterial contamination events at Wells 6 and 7. This is illustrated by Figure 20, using total coliform data from Well 7 between August 25th and August 28th 2000. There were 14 mm rain in Hanover on August 26th, and the sample from Well 7 the next day gave a total coliform value of 4 cfu/100 mL. It is possible that this sample was collected just at the time the water quality was most impaired (Figure 20, top), but it is more likely that the actual peak was missed, and that it occurred some hours earlier (Figure 20, middle) or later (Figure 20, bottom). A similar but higher peak was seen at Well 6, where total coliform values on the four days after the August 26th 2000 rain were 0, 111, 4, and 0 cfu/100 mL, respectively. Much more frequent sampling than once a day would be needed to properly evaluate bacteria variation at Wells 6 and 7 following substantial rain events. Sampling for bacteria every three hours during the two pumping tests shows that there are indeed substantial changes in bacteria levels at both Wells 5 and 6 on a timescale of hours (Figure 21).

High bacteria concentrations are often associated with high turbidity, and turbidity at Well 7 was being continuously monitored by OCWA during August 2000. Results for August 26th to August 28th 2000 are shown in Figure 22. Turbidity is measured every second at Well 7, but only substantial changes are saved by the system. There were three spikes in this period, but these lasted only one to two minutes, and all occur immediately after the well started pumping; they can be attributed to bubbles in the flow. The data show no spikes lasting a few hours to a few days, as one might expect there to be since there was bacterial contamination of this well on two of the three days in this period. This is puzzling as daily manual samples sometimes indicate somewhat higher turbidity.

Figures 23 and 24 show the daily background bacteria and turbidity data, respectively, for these wells. These data generally tell the same story as the coliform data, with some but not all high values occurring within a few days of rain. However, the period June 30th to July 13th 2000 does stand out, especially at Well 6 where there is high turbidity on most days. The pump had been removed from the well on June 21st 2000, and possibly the high turbidity is associated with replacing the pump.

Dr. Payment (2001, p. 66) noted that high turbidity is likely to be an indicator of serious contamination, and Figure 8 demonstrates such contamination. However, the converse may not be true, since there is bacterial contamination on a number of occasions at Wells 5, 6, and 7 at the same time as low turbidity. Differential filtration by aquifer materials seems to be unlikely as a cause for the poor correlation between bacteria and turbidity in the Walkerton wells since both clay particles and bacteria have approximately the same size (1 micrometre), and clay particles are a major contributor to turbidity. The reason for the poor correlation may instead be due to availability and mobilisation, both of sediment particles causing turbidity and of bacteria. For instance, sediment may be more easily mobilised just after ploughing, during intense rain, and when and where there is little vegetation. Bacteria concentrations will likely be highest just after manure spreading or during periods when cattle are grazing in pastures. There will likely be very different coliform to turbidity ratios in each field and with each different rain event, so perhaps the poor correlation is simply because there is not one single and persistent source of turbidity and bacteria feeding the groundwater system from which each well draws its water.

Domestic well west of Well 5

Samples were collected daily from June to November 2000 for bacterial analysis from a domestic well about 300 m west of Well 5 (Goss, 2001b, Exhibit 375). The well is 24.7 m deep (Goss, 2001a, p. 10). All samples from June 22nd to November 26th 2000 were analysed for total coliform and for E. coli, and the results are shown in Figure 25, where rainfall is also plotted. There is a remarkably strong correlation between bacteria and rainfall, with the peak in total coliform or E. coli usually coming one or two days after rain. Some of the daily samples were tested for background colonies and most of the samples were tested for heterotrophic plate counts. We have not analysed the latter data since they are incomplete.

There were eight events during the period from June 22nd to November 26th 2000 when total coliform in the well reached 10 cfu/100 mL or more. On each occasion there had been more than 10 mm of rain on that day or within the previous three days. Details of all rain events in this period with more than 10 mm are given in Table 6.

The average lag between the day with the most rainfall and the day with the highest total coliform is 1.5 days for the ten events in the above table where there was a coliform peak which could be associated with prior rain. There were five events between June 22nd to November 26th 2000 when E. coli was found in samples from the well. These are all shown in Table 6. All five E. coli peaks occur one day after rain events of 14 mm or more. These data show in a dramatic fashion how bacterial contamination in this well occurs very soon after heavy rain.

Correlation between runoff and adverse samples in the Walkerton water supply in 1999

Based on the good correlation between heavy rain and adverse bacteriological results at Wells 6 and 7 from the summer 2000 daily sampling, we decided to study the routine weekly sampling from 1999 and early 2000 to see whether we could detect a correlation between heavy rain or snowmelt and adverse results.

Adverse bacteriological results from 1999 and early 2000 are tabulated in Ross (2000, Appendix O). In the period January 1999 to the end of April 2000 samples were collected on 64 occasions at approximately weekly intervals, with from four to twelve samples being collected on each occasion. There were adverse samples on 13 occasions (Table 7). We checked prior weather conditions, using the rainfall record from the Saugeen Valley Conservation Authority gauge in Hanover for May 1 1999 to December 31 1999 and temperature records for the whole period. The SVGA does not maintain a precipitation gauge in Hanover over the winter months. In Table 7 we have tabulated weather conditions for the 13 dates with adverse results. Some of these seem to be correlated with prior weather, but most do not.

The second way we studied the data was to pick the weather events which we considered might cause substantial runoff. We found eight such events over the 16 month period. Three of these eight major weather events had adverse bacteriological results associated with them, so again the correlation is not very good (Table 8).

We consider that the major reason for the better correlation in the summer of 2000 is that there was daily rather than weekly sampling in 2000, and so bacterial contamination events of short duration (hours to a few days) were more likely to be detected.

Conclusions

The data tend to support the following conclusions on the link between rainfall and bacterial contamination:

i) episodes of contamination at Well 6 and Well 7 are often correlated, and are often associated with heavy rain, with contamination peaking within a few days of the rain.

ii) At a domestic well there is a very strong association between heavy rain and bacterial contamination of the well, usually with a lag of one to two days.

iii) The daily data set from Well 5 in May and June 2000 only spans 18 days, and this is too short to establish a relationship between rainfall and bacterial contamination.

iv) Rainfall events greater than 10 - 15 mm tend to cause bacterial contamination in at least some wells within four days.

v) Weekly sampling of a water supply for bacteria is likely to miss some short duration contamination events.

2B Spatial variation in water quality

Analyses for dissolved constituents of groundwater from a large number of wells are presented in Golder Associates (2000 a, b). We have compiled the data onto Piper diagrams in Figures 26 and 27. Piper diagrams display the major ions (the ions which commonly account for more than 90% of dissolved minerals in the water) in a water sample. The anions (negatively charged dissolved chemical species) provide the clearest pattern and these are shown in Figure 28.

The water from Wells 5 and 6 are typical of dolostone waters except that they have substantial sodium and chloride which is almost certainly from common salt. About half the monitoring wells close to Well 5 have a similar composition, but the remaining half have much higher proportions of sulphate. The wide variation in chemistry shows that the bedrock close to Well 5 is not a simple homogeneous aquifer. This is particularly manifested in the high sulphate concentration in bedrock monitoring wells such as 4D, 9D, and 10D.

Well 7 water is a varying mixture between a limestone/dolostone water and a gypsum water, with low chloride. Both shallow and deep monitors at Monitoring Well 18 (MW18) have similar composition, but the remaining monitoring wells close to 6 and 7 have very high sodium and chloride. MW18 also showed anomalously large drawdown during the pumping test (Golder Associates, 2000b, p. 34-35). During pumping, water levels close to Wells 6 and 7 should be lower than those further away, but there are lower water levels at MW18 both in the overburden and in the uppermost bedrock (Golder Associates, 2000b, Figures 27 and 28, respectively). We interpret the drawdown and chemistry at MW18 as signifying that it is relatively well- connected to the bedrock aquifer tapped by Wells 6 and 7.

The high sulphate in Well 7 could well be from gypsum nodules within the Bass Island or Bois Blanc Formation since gypsum is commonly found associated with limestone and dolostone.

Alternatively, it could be from water from the underlying Salina Formation. This is supported by analyses from three zones in Well 1, which have very high sulphate (Golder Associates, 2000a, Table 8, p. 78). Well 1 presumably penetrates the Salina Formation; the red shale reported at a depth of 155 to 165 feet is most likely close to the top of the Salina Formation (Golder Associates, 2000a, Appendix A, p. 99).

The high sodium and chloride in Wells 5, 6, and in most of the monitoring wells is unexpected. The dolostone and limestone aquifers which these wells penetrate should have low sodium and chloride (a few mg/L at most), such as is found in Wells 1, 3, and 7. The underlying Salina Formation is named after the salt beds in it, but the salt beds are overlain by some tens of metres of low permeability strata which separate the salt beds from the Bass Island Formation (Liberty and Bolton, 1971). This is corroborated by analyses from Well 1, which show very low chloride concentrations in the uppermost beds (4-5 mg/L : Golder Associates, 2000a, Table 8, p. 78). An alternative source for the high sodium and chloride is from surface anthropogenic contamination such as from road salt. We consider this to be more likely. If this is the case, then the high sodium and chloride in Wells 5 and 6 indicate salt-contaminated surface waters in these wells, while the low chloride in Well 7 indicates an absence of such water. The origin and pathway of such surface water recharge is of concern as it may be associated with bacterial contamination.

Chemical characterisation of surface waters at the springs close to Wells 5, 6, and 7, in the creek close to Wells 6 and 7 and in Silver Creek south branch to the south-west of Well 5 would help test this hypothesis of surface water contamination. Sampling at high and low flow and at different seasons would capture the variability in surface water quality, which is likely to be substantial. The primary objective would be to permit more ready identification of the presence of surface water in groundwater samples.

2C Temporal variation in water quality at the springs

Well 5

We undertook a limited program of water quality and flow monitoring at the springs close to Wells 5, 6, and 7. This involved installing equipment which measured water level and electrical conductivity every 30 seconds and stored average values every ten minutes on a datalogger. The ability of water to conduct electricity is dependent on the concentration of dissolved solids in the water. Electrical conductivity is simple to measure and is proportional to the total dissolved solids in the water.

There are several spring orifices beside the road leading to Well 5. The springs feed two creeks which join at a point 54 m from the Well 5 building, and we measured discharge at that point (Figure 29). We measured electrical conductivity at the spring orifice at the spring closest to Well 5. This spring is 23 m from the building housing Well 5. We placed our dataloggers inside the Well 5 building for security reasons. The electrical signals to the dataloggers were fairly noisy, so to plot the results shown in Figure 30 we used running daily averages.

Figure 30 shows a general decline in discharge through the period, which is normal in southern Ontario in the spring. This follows high flows from snowmelt, and is also due to increasing evapotranspiration as temperatures increase and the growing season progresses. Superimposed on this trend there was a sharp increase in discharge in late May 2001. This occurs almost immediately after rain, and the three peaks are associated with three rain events. There was 30 mm in nine hours on May 22nd 2001, 27 mm in six hours on May 25th 2001, and 14 mm in five hours on May 28th 2001 at Well 7 (Figure 31). The increase in discharge shown in Figure 30 is primarily the result of groundwater flow rather than overland flow since the topographic catchment of the spring (~2 ha, see below) could only have produced a small fraction of the increase in discharge at the springs. Furthermore, observations at 11:30 pm on May 25th 2001, five hours after the rain ended, showed no evidence of significant overland flow to the springs in the preceding 12 hours.

The three major rain events in late May 2001 caused a rapid response at the springs near Well 5. There was both a substantial increase in discharge and changes in electrical conductivity (Figure 30). The initial response following the rain was an increase in electrical conductivity. This is commonly seen in karst springs, and is interpreted as the flushing out from fractures into the conduits of highly-mineralised water. Then, just following the peak discharge on May 25th 2001 there was a dilution of ~2%, which is interpreted as indicating the arrival of newly recharged water flowing along conduits.

Another major rain event occurred on June 21st and June 22nd 2001, and this also caused a large increase in discharge and a drop in electrical conductivity, with the dilution on this occasion being ~4%. A more substantial (25%) dilution recorded in Kentucky (Figure 8) indicates a greater contribution of relatively dilute, rapid surface runoff to spring discharge. The smaller dilution at the springs at Well 5 means that there is a smaller direct contribution of surface water to rapid spring flow at Well 5. It may also be partly due to lesser contrasts between surface water and groundwater at Walkerton. Nevertheless, the data do indicate that some surface water is flowing through the aquifer and arriving at the springs within twelve hours of rain.

Wells 6 and 7

We installed monitoring equipment at a major spring midway between Well 6 and Well 7 (Spring B in Figure 32). The water emerges from a pipe, and the landowner informed us that the pipe was about 10 m long, and that he had installed it to drain a wet area where the spring was actually located. The continuous monitoring equipment at this spring performed poorly, and there is little usable data. We also continuously monitored the water level in Well 7, and this equipment performed well. It should be noted that the pipe at this spring is not the pipe where the E. coli O157:H7 was found in June 2000. That pipe is on the east side of Well 6, and adjacent to a pond, which is also shown on Figure 32.

Figure 33 shows a comparison between the water level in Well 7 and the electrical conductivity at the spring, which is 150 m from Well 7. Variation of electrical conductivity at the spring is somewhat out of phase with pumping at Well 7, with electrical conductivity starting to decrease two to three hours after the pump goes on, and electrical conductivity starting to increase one to two hours after the pump goes off. This indicates that there are distinct water sources feeding the spring and that Well 7 is capturing more of highly mineralised sources than of lower mineralised sources. This provides another indication that an important characteristic of the aquifer is the movement of waters with different chemistries through discrete conduits with limited connections. More insight on these sources was provided by the electrical conductivity profiling, which is described next.

2D Temporal variation in water quality at the test wells

We carried out electrical conductivity profiling in the two test wells (TW1-82 and TW2-82) close to Well 6 and in the test well (TW1-86) close to Well 7. Such profiling can show whether there are different types of water entering a borehole, where they enter and their relative importance, and whether their flow or chemistry changes under pumping conditions. The simplest case is a homogeneous aquifer with no discrete inflows to a borehole, no differences in chemistry in different parts of the borehole and no changes with different pumping conditions. At the other extreme is a karst aquifer, with discrete inputs and substantial spatial and temporal changes.

The major results are described here, and a fuller account is given in Appendix 4. Test well 1-86 will be used as an example of the complex but discrete flow paths which occur in the aquifer since the most complete information is available for this well. Not only is the most complete set of electrical conductivity logs for this well, but there are also flow meter and video logs for this well (Golder Associates, 2000a). There are no flow meter or video logs for the open boreholes in TW1-82 or TW2-82.

The flow meter tests in TW1-86 were carried out while the well itself was being pumped and are summarised as follows:

> The flow distribution profile showed that there is no water coming into the well from the bottom at 76.4 metres. About 15 per cent of the flow comes from 73.5 to 74.0 metres, 25 per cent comes from 70.7 to 71.5 metres, 55 per cent comes from 52.4 to 53.5 metres and 5 per cent from 19.7 metres (Golder Associates, 2000a, p. 369).

Additional flow meter tests when Well 7 rather than TW1-86 was being pumped showed upward flow at –67.8 m, almost no flow at –44.8 m, and slight downward flow initially at –28.3 m, though this flow stopped after about ten minutes (Golder Associates, 2000a, Table 12). Thus the direction and magnitude of flow in TW1-86 varies with time and with which well is being pumped. The video logs add more insight to flow conditions, although these were obtained when there was no pumping taking place. Water is seen to flow up the well to 19.7 m and then exit at this point via a conduit on a bedding plane. The conduit is about 15 mm high and 50 mm or more in width (Golder Associates, 2000a, photo 34). There is also a side shot at 53.1 m (174 feet 2 inches) which shows water entering the borehole via a conduit on a bedding plane.

Our tests in TW1-86 in general support the earlier work, but add more details. Figure 34 shows a series of 22 profiles taken between June 10th and June 14th 2001. Profile 1 was taken just before a 72 hour pump test at Well 9 was started, and the remaining 21 profiles were taken at increasing intervals during the pump test. We found five horizons with inflow and/or outflow, four of which had been located during the testing in 2000 by Golder Associates. These are marked A to E in Figure 34. The differences in electrical conductivity through the length of the borehole and the continual change with time throughout the 72 hour pumping test reflect the differing chemistries of the five major sources and the evolution of these five sources over time. There appears to be an open conduit link between TW1-86 and Well 7 at 19.7 m. Recovery of TW1-86 after pumping ceased, and its response to renewed pumping of Well 7 indicate further complications in the delivery and storage of water in the aquifer, but to date these are only partially documented.

A summary of the flow patterns during pumping and non-pumping conditions are shown in Figure 35. A major concern for the safety of the water supply at Wells 7 and 9 is that there is *downward* flow in TW1-86 when these wells are pumping, and that this provides a pathway for near surface water to reach Well 7. Extending the casing in Well 7 even to a depth of 50 m would not prevent the ingress of shallow water that is potentially bacterially contaminated.

TW1-82 and TW2-82 are located adjacent to Well 6. Pumping in Wells 7 and 9 generated a very rapid inflow of high electrical conductivity water at -18 m in TW1-82 and at -15 m in TW2-82. This water was not transported up or down the borehole, but appeared to be passing through. The water had electrical conductivity similar to local wetland surface water. We suspect that pumping at Well 7 or 9 induced surface water recharge. Furthermore, the rapid, simultaneous appearance of this water in both test wells indicates a very high permeability zone or a conduit integrating the entire suite of wells. This result is important because it suggests that surface water recharge in the vicinity of Well 6 is enhanced or induced by pumping Well 7 or 9. Furthermore, the rapidity of the response indicates potentially rapid transport of any surface water contaminants towards the supply wells. When the testing was done, the test wells did not appear to permit significant vertical migration in the aquifer, but this may not always be the case.

To summarise the electrical conductivity profiling, our results support the findings of Golder Associates (2000a) that almost all the water entering the tested wells comes from a few distinct horizons. Our results also show that these distinct inflows come from distinct sources, and that the proportion of these flowing into the well changes over time as the water level in the pumping well drops, and the sources of water become depleted. There are indications that surface water recharge is induced by pumping and that the water can travel very rapidly and with little dilution. Spring B is one such location where surface water recharges the aquifer (Figure 10). Distinct conduits can transmit water and bacteria rapidly over large distances in short periods. Furthermore, the test wells themselves may act as vertical conduits which could move bacteria downward through the aquifer much more rapidly than might normally occur.

Section 3 Assessment of the areas from which there could be flow to Wells 5, 6, and 7 within 50 days

We have used the arbitrary time of 50 days in the title above since 50 days is commonly used in regulations in Europe, and is a period after which most bacteria will have died off in groundwater (see Appendix 6, p. 407). It is clear that bacteria can survive in the environment far longer than 50 days, as Dr. Payment testified. However, there is a progressive die-off of bacteria over time. Dr. Payment's data show that there is 99% die-off typically in the first week to four months. The data show that the die-off is approximately exponential. This means that a 99% die-off in one week is equivalent to a 48% die-off each day. In the case of a 99% die-off over four months then this corresponds to a 4% die-off each day.

In the following pages we will suggest that surface derived bacteria can travel via the groundwater to wells in Walkerton within days. Thus there is the potential for bacterially-contaminated water to be pumped from wells before there has been significant die-off of bacteria.

3A Assessment of the area from which there could be flow to Well 5 in less than 50 days

There are a series of springs within 60 m of Well 5 (Figure 29). The presence of springs shows that groundwater flow converges to this area. If the discharge of the karst springs is measured then the area from which water flows through the bedrock to the springs can be estimated. This area is known as the groundwater catchment area. Surface creeks also have catchment area, and these can usually be defined by tracing the divide (the highest land) between adjacent catchments. Groundwater and surface water divides may coincide, but often do not, especially in karst aquifers.

During the pumping test at Well 5 in August 2000 it was found that the water level went down at the springs both to the north and to the south of the access road to Well 5 (Golder Associates, 2000b, Table 3). A subsequent tracer test showed that surface water being drawn into the aquifer during the pumping test took only about one hour to reach Well 5 (Golder Associates, 2000c; Exhibit 221, Appendix P). Thus there is an efficient direct connection between the springs and Well 5, and spring water quality is very relevant to the water quality in Well 5. The equipped capacity of Well 5 was 20.5 L/s (Ross and Associates, 2000, p.2). If Well 5 had been pumping during the spring of 2001 it seems likely that most of the water pumped from the well would have been water that otherwise would have emerged from the springs. Conversely, the spring flows at times when Well 5 would have been pumping would have been much reduced, and possibly zero at times when spring discharge was less than 20.5 L/s.

Figure 36 shows a geological cross-section through Well 5 and the nearby springs. The potential catchment area for the springs extends about 2 km to the south-west. It includes an area where the south branch of Silver Creek is flowing on the surface, but does not extend as far as Greenock Creek, as will be explained later. The location of the springs is unusual. Most springs are found in valleys, and often at the lowest outcrop point of a permeable unit. No low-permeability units have been identified in the well logs which would force the water to the surface here, and these springs are close to the top of a hill (Figure 36). The geological report for the area noted that the strata are much more steeply dipping to the east of the Saugeen River valley (Figure 36), and suggests that there may be faulting associated with the change in stratal dip (Liberty and Bolton, 1971, p. 82). Possibly there is faulting just to the east of the springs at Well 5, or impermeable overburden confines the aquifer and this forces the groundwater to the surface close to Well 5 where the overburden is thin and permeable.

We expect that these karst springs have conduits leading to them and we expect the conduit velocities to be similar to the velocities typically found in karst conduits, which average 1700 m/day (Figure 7). Thus in 50 days the travelled distance would hypothetically be 85 km. This distance far exceeds the likely catchment for these springs. Consequently, groundwater in the bedrock throughout the whole of the catchment area of the springs is likely to be within the 50-day travel radius of the springs.

The first step in determining spring catchment area for the Well 5 springs is to determine spring discharge. We gauged the flow on twelve occasions between April 24th and July 3rd 2001, and used the data to convert the continuous water level data to discharge. This gave an average discharge of 16.0 L/s (210 gallons per minute) (Figure 30).

The second step in determining the catchment area for the springs is to calculate the average runoff for the region during the period in the spring of 2001 when we measured discharge at the springs. We gauged discharge at 23 locations within several kilometres of the municipal wells (Figure 37 and Table 9) and estimated the topographic catchment areas for these points. We made measurements at a large number of locations to determine whether there were stretches of creek with losses (to groundwater) or with anomalously high gains (from springs). Table 9 shows that the springs near Wells 5, 6, and 7 have flows which are anomalously high relative to the size of their topographic catchment areas, indicative of flow from further afield.

Apart from the springs near Wells 5, 6 and 7 we also found anomalously high flows along Greenock Creek, and on closer investigation we found two karst springs at creek level. We had earlier hypothesised that Greenock Creek could be losing water at bedrock exposures and this water could then flow north to the springs near Wells 6 and 7 (Worthington, 2001b; Exhibit 261). Our measurements do not support the hypothesis expressed in Exhibit 261; this stretch of Greenock Creek is a gaining rather than a losing creek under the high-flow conditions when we have made measurements (April to June 2001). Under low aquifer head and high surface water conditions (e.g. during a late summer thunderstorm), these springs may allow creek water to enter the aquifer. Residents along Greenock Creek have described periodic contamination of their water.

We determined the average runoff from the area by taking the four largest creeks. The creek for which the springs near Well 7 form the headwaters has no formal name, but it is sometimes locally called (the) Golf Course Creek, and we use that name in this report. The 1:50,000 topographic map uses the name Allens Creek to refer to a tributary of an unnamed larger creek, and we use the name here to refer to the larger creek. We calculated the average runoff for the four creeks to be 19.3 L/s per square kilometre (Figure 38 and Table 10).

B.M. Ross and Associates (2000) made an estimate of 1.67 hectares (0.0064 square miles) for the topographic catchment area with surface runoff to Well 5 (Exhibit 221, Appendix L). If we add the area around the springs at Well 5 then the total surface catchment area is 2.0 hectares (0.0077 square miles: Figure 29). Given an average runoff in the area of 19.3 L/s/km^2 (Table 10) then this catchment area of 2.0 hectares contributes 0.39 L/s to the springs at Well 5; the remaining 98% of spring flow comes from outside this direct runoff area.

B.M. Ross and Associates (2000) estimate that the size of the area draining to a hollow immediately to the west is 11.93 hectares (0.046 square miles, North and South Catchments in Figure 39). Water level measurements made in the aquifer underlying this area by Golder Associates (2000b, Figures 13-16) indicate that flow is to the east, and much or all of this area may feed the springs. We can make similar calculations as before, and the total flow after adding this area is now 2.68 L/s, or 17% of spring discharge (Table 11). The remaining 83% of spring flow comes from groundwater flow further upgradient.

When it rains or when there is snow melt there are a number of pathways the water may follow. The water may flow downhill on the surface (overland flow), it may flow downhill parallel to the surface within the soil and uppermost bedrock (interflow), or it may descend to the water table and form part of groundwater flow (Howard, 2000, Slide 9A). A comparison of surface elevations along the south branch of Silver Creek and water levels in MOE records (Golder

Associates, 2000b, Figure 12) suggests that groundwater levels are generally above creek level, as shown in Figure 40. This implies that there is limited potential for leakage from the creek into the underlying aquifer.

Discharge measurements along the south branch of Silver Creek (stations 16 to 20 in Table 9) show that the average runoff is about half the average for the larger local catchments (numbers 1 to 4 in Table 9), indicating that roughly half of the runoff is by overland flow, interflow, and groundwater flow recharging Silver Creek South Branch. The remaining half must descend to the water table and become groundwater flow which then does not pass these gauging stations. Some of the latter groundwater flow forms the bulk of the flow to the springs at Well 5. This half of the areal average of 19.3 L/s/km^2 must therefore drain an area of about 138 hectares (0.53 square miles) to supplement the flow of the other components to the springs at Well 5 (Table 11).

In Figure 40 we present plan and profile views of the three areas which contribute runoff to the springs at Well 5. Within this area five different overburden deposits have been mapped (Ministry of Northern Development and Mines, 1986):

i) Elma Till: stony, sandy silt to silt till
ii) ice contact stratified drift: sand, gravel, silt and till
iii) glaciofluvial outwash gravel and gravelly sand
iv) glaciofluvial outwash sand; minor gravel
v) organic deposits: muck and peat.

In the neighbourhood of Well 5 the thickness of these deposits varies considerably over short distances (Figure 41), and we presume that overburden thickness also varies in the remainder of the catchment area for the springs at Well 5. Figure 42 shows two interpretations of the bedrock topography in the area, and there is a third in Figure 8 of Golder Associates (2000b). These three maps show considerable differences in interpolation between points where bedrock thickness is known (usually at wells). Overburden thickness regulates aquifer vulnerability to bacterial contamination, and so imprecise knowledge of overburden thickness in many places will result in imprecise knowledge of travel time through the overburden.

The considerable range in composition and thickness of the overburden implies that there must be a concomitant range in travel time through the overburden. For instance, at Golder's monitoring Well 12 the lower part of the 2.9 m of overburden is described as "mottled brown and grey sandy silt" (Golder Associates, 2000b, Appendix A, record of borehole 12). The mottling is probably due to chemical reactions associated with flow down fractures, and Dr.

Gillham suggested that if there are open fractures at that location then travel time down through the overburden via the fractures could be as short as “minutes to hours” (Transcripts, March 1 2001, p. 128-130). Nevertheless, at the same location some of the water would be travelling slowly down through the pores in the overburden, and this water could take on the order of a year or so to travel down through the overburden, as described by Dr Gillham (2001, Exhibit 256, p. 25; Transcripts, February 28 2001, p.135).

We presume that there are most likely to be a number of places in the catchment area for the springs at Well 5 where the travel time through the overburden may be days or less. These include areas of glaciofluvial gravels and areas with thin till that is fractured. Conversely, there are areas where the overburden is thicker than 10 m, and in these areas we consider it much less likely that there would be fractures and rapid flow through the overburden.

To summarise our findings on pathways for bacterial contaminations to reach Well 5:

i) The topographic catchment area for the springs beside Well 5 is about 150 hectares (0.6 square miles).
ii) Much of the water normally flowing to the springs would be captured by Well 5 when it was pumping, with relatively more during dry periods and relatively less during wet periods.
iii) There are substantial areas in the groundwater catchment area where overburden deposits are thin or are composed of gravel. In these areas water could flow though the overburden in days or less.
iv) Once bacterially contaminated groundwater is in the bedrock aquifer it could travel to the springs or nearby Well 5 in days or less.

3B Assessment of the area from which there could be flow to Wells 6 or 7 in less than 50 days

Characteristics of springs close to Wells 6 and 7

Wells 6 and 7 are situated beside a wetland, and there are two notable springs in this area, shown as Spring A and Spring B on Figure 32. These springs are close to Wells 6 and 7, and to estimate the contributing zone to the wells we estimated the catchment area for the springs. We assume that Wells 6 and 7 were capturing flow which otherwise would have emerged from one of the springs. We consider this likely to be the case, and is supported by the drying up of Spring A after Well 6 started pumping in 1983 (Powers, 1983).

When Well 6 was first drilled there were complaints from Don Gregg, the landowner of Spring A, that the spring and the pond which it fed had dried up, and the pond was subsequently filled in (Powers, 1983; Golder Associates, 2000b, p.7 and p. 41;). In late April 2001 the flow from this spring was about 2 L/s, and by June 2001 there was negligible flow crossing under Durham Road from this catchment of 78 hectares (0.30 square miles, Stantec, 2000). This catchment includes not only Spring A but also an extensive wetland area.

A second spring (Spring B) lies midway between Wells 6 and 7. We gauged the flow at this spring on ten occasions between April 16th and June 5th 2001. There was a steady decline in flow over the period, from 22 L/s to 5.8 L/s, with a mean of 12.7 L/s.

Golder Associates (2000b, Table 10) recorded the drawdown at Spring B during a 12 hour pumping test at Well 6. The drawdown at a sandpoint at the spring was 6 cm, and presumably the discharge from the spring was much reduced. This drawdown is ten times greater than the 0.6 cm recorded at the pond 118 m from Well 6, even though the sandpoint at the spring is much further from Well 6 (208 m). Pumping then started at Well 7, and after a further 36 hours the drawdown at Spring B was 45.5 cm, which again is far greater than the 10.4 cm recorded at the pond 118 m from Well 6, even though the sandpoint at the spring is further from either well (208 m from Well 6 and 146 m from Well 7).

A 72 hour pumping test was carried out at Well 9 from June 10th to June 14th 2001. During the test Spring B discharge decreased from 5.8 L/s at the start of the test to 1.5 L/s after 47 hours to 0.73 L/s after 71 hours. These pumping tests and the variation in electrical conductivity at Spring B (Figure 33) show that the spring is well-connected to the aquifer from which Wells 6, 7, and 9 draw their water.

These springs provide high-permeability connections between the aquifer and the surface. It is possible for surface water to be drawn into the aquifer via the spring orifices at times when groundwater levels are lower than surface water levels, e.g. during summer rainstorms when there is abundant surface runoff, a depleted aquifer, and drawdown resulting from pumping.

Calculation of the catchment area

To calculate the catchment area we first calculate spring discharge. We assume that the total flow which would have emerged from the springs is the total we measured downstream from the springs and Well 7 plus the total discharge pumped into the Walkerton municipal supply. It is probable that not all of the discharge pumped from Well 7 would otherwise have emerged at nearby springs. For instance, some the flow could continue downgradient to the north-east and directly recharge the Saugeen River. However, the substantial drops in spring flow when Wells 6, 7 and 9 are pumping suggests to us that most of the flow now being pumped from Well 7 would probably otherwise have emerged at nearby springs.

We measured the flow downstream from Well 7 at the point where the creek crosses the former rail line. From six measurements between April 30th and June 5th 2001 the range in flow was 22 to 49 L/s, with a mean of 36 L/s. This discharge includes not only natural flow but also the overflow from Well 7 when it is not pumping and the discharge from filter backflushing in the Zenon treatment plant. The total pumped from Well 7 into the municipal supply averages about 2500 m^3/day, or 29 L/s. The total surface and groundwater flow in the spring of 2001 was thus about 65 L/s.

From Table 10 we calculated that the average runoff in the Walkerton area in the spring of 2001 was 19.3 L/s per square kilometre. The topographic catchment of the area around Wells 6 and 7 was measured by Stantec (2000) to be 1.17 square kilometres, so a discharge of about 22 L/s would be expected from this catchment area. Thus the discharge of 65 L/s is far more than would be expected from such a small area (Figure 38).

We can calculate the approximate catchment area for the springs close to Wells 6 and 7 by the same methodology we applied at Well 5, assuming the remainder of the flow comes from other surface catchments where half the runoff flows locally to creeks and half is available as groundwater flow which may cross surface divides. Results are shown in Table 12, and indicate that the total catchment may be more than 500 hectares (2 square miles).

A geological cross-section of the area is shown in Figure 43. Well 7 penetrates all the Bois Blanc Formation and most of the Bass Island Formation. There is a deep buried valley under the Saugeen River valley and this cuts through both the Bois Blanc and Bass Island Formations. It is likely that there is some deep groundwater flow from the area of Wells 6 and 7 to the Saugeen Valley, but this flux may be minor and is not considered further.

Flow to the springs close to Wells 6 and 7 probably comes from the area to the south, and a very tentative catchment area is shown in Figure 44. This area is shown as extending along the strike of the strata since it is limited to the south-west by Greenock Creek, which also was a discharge area in Spring 2001 (Figure 38).

3C Source protection and the role of computer modelling in assessing capture zones and travel times to the municipal wells at Walkerton

Computer models have been used increasingly in the last 30 years to help understand groundwater flow. Almost all modelling has been done using models which assume that an aquifer behaves as a porous medium, with flow moving through the pores of the aquifer, and the aquifer being homogeneous over substantial areas. This assumption is fairly realistic for the many overburden aquifers in Ontario. For bedrock aquifers this approach may give reasonable estimates of water levels and response to pumping, but can give very inaccurate estimates of travel times.

In recent years there have been substantial advances in computer modelling of fracture systems, and such models can be very useful in showing what might happen given a postulated set of fractures. However, there is no practical way that all the actual apertures and connections of the fracture network can be measured, even in a small area such as within 50 m of Well 5 or Well 7. Thus any fracture network model based on hypothesized fractures can only ever be a hypothesis. Efforts to produce computer models of karst or fractured rock aquifers can actually be counterproductive since lay people may not realize that the modelled result of such a computer model is actually only one of many possibilities. The following is one such example.

Figure 45 (and see Appendix 5) illustrates how inaccurate porous medium models can be when applied to carbonate bedrock. It shows travel time estimates for flow to a spring in Utah, using a computer model similar to that used by Golder Associates (2000b) at Walkerton. Most of the catchment zone for Dewitt Spring in Utah was calculated to have a travel time to the spring of more than 15 years. Then three tracer tests were carried out from the furthest reaches of the catchment, and all took less than 31 days to arrive at the spring.

Tracer testing at Walkerton is needed to test the postulated travel times. The area lying inside the 50 day time-of-travel zone to Wells 5, 6, and 7 may constitute the whole catchment zone for these wells, as approximately delineated in Figure 44.

Within the catchment zones shown in Figure 44 there are substantial areas where the overburden is more than 10 m in thickness. Figures 40 and 43 give an indication of this variability in overburden thickness, as does Figure 9 of Golder Associates (2000b). However, Figure 42 shows that these sections and plan are based on interpolations between known points and thus are generalisations. Where the overburden is thicker than 10 m there is a low probability that there will be fractures, root casts or animal tunnels which provide pathways for bacterial contaminants to move rapidly into the aquifer. Where the overburden is thin (<5m thick) or composed of glaciofluvial outwash gravels, the underlying bedrock aquifer will be vulnerable to bacteriological contamination.

The wetland around Wells 6 and 7 is sustained by regional groundwater discharge. However, there is evidence that the surface water in the wetland may be induced to recharge the aquifer in response to pumping. The induced recharge appears to be rapid and karstic in character. Contaminants may be expected from time to time in such waters. The exact mechanism of recharge is unknown, and may involve gravels units. However, water-level springs are the most likely sites for rapid induced recharge.

The US EPA (2000) recognises in its proposed Groundwater Rule that karst aquifers constitute one of three aquifer types susceptible to bacterial contamination (Figure 1). Similarly, regulations in some countries of the European Community have recognised karst as an aquifer type more susceptible than others to contamination (European Commission, 1995; see Appendix 6). In both jurisdictions overburden thickness and type have been used to help define aquifer vulnerability.

Section 4 Discussion, conclusions and recommendations

4A Discussion - What happened to Walkerton's Wells in April/May 2000?

The key question of "What happened to Walkerton's wells in April/May 2000?" is on many people's minds, and the answers provided to date in the evidence to the Inquiry have not been as clear as they might have been. Our goal in this discussion is to provide the clearest possible answer to this key question, based on available information.

It is our view that the water being produced by at least two of Walkerton's three main water supply wells (Wells 5 and 6) was highly susceptible to bacterial contamination via the groundwater flow system, and that such contamination was likely occurring on a regular basis for years. The wells were contaminated on a regular basis because they were drilled in unfortunate positions in a karst aquifer.

The unfortunate choice of well locations can in part be attributed to:

i) a lack of any guidelines on appropriate locations for wells;

ii) poor screening of the well locations and inadequate interpretation of initial water quality results (and their implications), before the wells were approved by the MOE;

iii) a general lack of knowledge (province-wide) about karst systems, and the potential problems to look out for when completing a well in such a system.

As discussed in the previous sections of this review, the bedrock groundwater flow system in the Walkerton area is karstic. Flow in the karstified bedrock is rapid, and under certain conditions bacteria can be transported very rapidly (hundreds to thousands of metres per day).

In such karstic flow systems groundwater from across a wide area is captured in an interconnected network of karst channels or conduits, with flow converging on a few major springs. The springs mark the place where groundwater flow from a wide area is converging, as a result of karst processes which have been ongoing for many thousands of years.

From the perspective of the hydrogeologist, the vicinity of karst springs is an attractive site to drill a well because of the high and consistent yield of water. However, it will generally be a risky place in the groundwater flow system because all of the contamination from across the flow system converges (carried by the groundwater) at the springs.

In some karst areas, the water quality in springs is very good. In the Walkerton area it is not. Why the difference? There are several possible contributing factors:

1) Given the widespread livestock farming operations in the Walkerton area, pathogens may be widespread and have a high likelihood of being entrained by surface runoff and rapid recharge.

2) The overburden deposits which overlie the bedrock are relatively thin and in places quite permeable. As a result, there are "windows" in the overburden (areas where it is very thin and/or very permeable) through which bacteria can reach the underlying bedrock in a matter of a few hours or days.

3) The contamination which reaches the bedrock is inadequately diluted by clean groundwater prior to extraction

4) Springs lying at low elevations in wetlands provide potential points of entry for surface water.

5) The abundance of open wells permits ready vertical exchange of water, and additional points of entry of contaminated waters into the aquifer. This is especially true of wells located near livestock compounds.

This combination of abundant contaminant sources and windows through the overburden is what makes the bacterial contamination of the karst springs in the Walkerton area possible.

The potential for contamination of Well 5

The overburden in the groundwater catchment area for the springs near Well 5 is particularly thin (less than 3 m in places), and there are areas of highly permeable gravels which could also provide pathways for rapid flow through the overburden. Thus there are several possible windows through which bacteria and other contaminants can reach the bedrock.

The bedrock in the vicinity of Well 5 is karstic dolostone. Furthermore, Well 5 is shallow and well-connected to the conduit network feeding the springs, with the water taking less than an hour to travel via a conduit from the springs to the well.

A domestic bedrock well 25 m deep and situated to the west of Well 5 often becomes contaminated by bacteria within two days of moderate or heavy rain, and this demonstrates the speed with which contaminants can pass through the overburden, into karst conduits, and into a well. There are no data available on the speed with which bacterial contamination reaches Well 5 or the nearby springs following a heavy rain, but it is probable that it occurs within hours to days.

What Happened at Well 5 in April and May 2000?

During spring in southern Ontario, there is widespread animal manure, moist soil and limited development of crops, promoting overland flow of bacterially contaminated water. On April 20th and 21st 2000 36 mm of rain fell (Goss, 2001a, p.56). This is a large rain event that may well have resulted in bacteria being transported through the aquifer to Well 5 and which may have led to some of the initial illnesses in people using the Walkerton water supply (reported by Dr. Payment). On May 1st there was a rain of 5.5 mm, and if this were a high-intensity short-duration rain then it is possible that this too could have resulted in bacterial contamination of Well 5.

Starting on May 8th there were over 60 mm of rain in four days. This rain would have saturated the ground and increased the flow rate at the springs near Well 5, probably to 15-20 L/s. These four days of substantial rain could again have resulted in bacterial contamination of Well 5. On May 12th 2000 there was an estimated 70 mm of rain in Walkerton (Goss, 2001a, p.56), and most of this occurred after 6pm. The intense rain on the already saturated ground would have mobilized bacteria from any manure exposed to the rain, and carried the bacteria down through the thin overburden and along karst conduits to the springs and also to Well 5 (which was pumping, according to SCADA records (Ross, 2000, p. 25). This could certainly have occurred within days, and quite possibly within hours of when the heavy rain occurred.

Others have advanced the hypothesis that on May 12th 2000 there was overland flow of manure-contaminated water to area of the springs beside Well 5, and that this contaminated water then flowed down the springs and into Well 5. Unfortunately, there were no observations made at the time to support or disprove this hypothesis.

However, during our field work this year we observed what happened after heavy rain in May 2001. In response to the rain, there was a rapid increase in the flow rate of the springs and the discharge of the springs soon exceeded the former pumping capacity of Well 5 (Figure 30). We expect that at times when the springs were flowing at rates exceeding the pumping rate of Well 5, then flow would have been upward (out of the springs) and not downward to the well.

Based on our measurements this year, before the May 12th 2000 rain event the spring discharge was probably about 20 L/s. Spring discharge would have quickly increased during the heavy rain on May 12th 2000 and soon surpassed the pumping capacity of Well 5. Consequently, bacterially-contaminated overland flow could only have been drawn into Well 5 for a very limited time (if at all). As indicated by Dr. Goss at the Inquiry, water would have had to be ponding on the adjacent farm for quite some time before it was even possible for manure-contaminated water to reach a height at which overland flow was possible.

In our view, this combination of factors (Well 5 only being vulnerable to surface inflows from the springs early in the rain storm [if at all], and manure-contaminated water needing to pond for quite some time on the adjacent farm before overland flow was even possible) make it unlikely that Well 5 was contaminated by local overland flow.

The situation during the Golder pumping test at the end of August 2000 was very different, since under late-summer low flow conditions the discharge from the springs would likely have been much less than the pumping capacity of Well 5 (and thus water was draining from the ground surface to the well via the spring orifices when the well was pumping).

Potential for contamination of Wells 6 and 7 in April and May 2000

The situation at Wells 6 and 7 is fairly similar to the situation at Well 5, though Well 6 is less susceptible to contamination than Well 5, and Well 7 is least susceptible.

The capture zone for the wells includes substantial areas where the overburden is less than 10 m thick, and close to the wells it only 3 m thick in places (Golder Associates, 2000b, Figure 9 and record of boreholes 14 and 15). The bedrock is limestone, which is generally considered to be even more karstic than dolostone (which is the bedrock at Well 5).

Daily sampling for bacteria in the summer of 2000 provide a picture of how often and how severely Wells 6 and 7 are impacted by bacterial contamination. The longest data set is for Well 7, and the most severe episode of bacterial contamination was in the period September 21st to 25th 2000, with total coliform exceeding 20 cfu/100 mL on two days (Figure 17). The highest daily rainfall in the preceding period was 33 mm, which is not exceptional, but there were 86 mm over seven days, and 117 mm over fourteen days. In terms of the cumulative rain over either one week or over two weeks this was the most significant rain since May 9th to May 12th 2000, which was of a similar magnitude. It is thus possible that total coliform concentrations at Well 7 in May 2000 reached similar levels (>20 cfu/100 mL). E. coli concentrations in Well 7 in September 2000 were zero, so they may also have been zero in May 2000.

Well 6 was not being pumped during the heavy rain in September 2000. It was sampled on a daily basis for bacteria from June to August 2000, and usually had much higher bacteria counts than Well 7, though E. coli was consistently zero. However, if we extrapolate from the existing data it is likely that Well 6 had very high total coliform concentrations following the May 9 to 12th 2000 rains, and it is possible that there would have been E. coli in the water as well. Well 6 was pumping from May 10th to May 13th 2000, and the SCADA system did not properly record pumpage from May 14th to May 18th 2000 (Ross, 2000, p. 25). Thus there is uncertainty to the length of the time window when potentially contaminated water might have been pumped into the municipal supply from Well 6.

It should be noted that the DNA fingerprint of E-coli O157:H7 found in a water pipe connecting two spring-fed ponds near Well 6 was the same as that implicated as one of the causes of illness in the Walkerton Tragedy (GAP EnviroMicrobial Services, 2000, p.17-18). At least one of the ponds is hydraulically connected to Well 6, and lost 10 cm of water (calculated by Dr. Gillham to be 3 % of the water pumped) during the pumping test at Wells 6 and 7.

The indications of pumping-induced recharge from the wetland in TW1-82 and TW2-82 and the water chemistry of the area suggest that at least a component of the contamination may be derived from the local wetland as a direct result of groundwater pumping. In July 2001 flow into the aquifer was observed at Spring B (Figure 10), and there is potential at this location for bacterial contamination to enter the aquifer and travel quickly to Well 7. However, this reversal of flow at Spring B only occurs when the natural discharge is less than a few litres per second. In 2001 reversals of flow due to pumping only started in late June or at the beginning of July. It is most unlikely that the natural discharge at Spring B would have been low enough at any time during May 2000 for pumping at Well 7 to induce a reversal of flow. The effect of pumping at Well 6 on spring flow is unknown since the well was not pumping during 2001 when we made our measurements.

There are many other possible sources for the bacterial contamination of Wells 6 and 7 as well. According to our estimates they are likely to draw water from an area of at least 500 hectares (2 square miles) and there could be any number of places with thin overburden where bacteria could reach the bedrock and then quickly travel to the wells. Areas which are especially likely to provide windows for contaminants to pass through the overburden and into the bedrock include the nearby karst springs.

4B Conclusions

General conclusions

1) Karst aquifers are highly susceptible to bacterial contamination. In several countries in Europe there are special provisions for wellhead protection in karst aquifers, and the US EPA recognizes karst aquifers as one of only three aquifer types which are highly susceptible to bacterial contamination.

2) Much of southern Ontario in underlain by carbonate aquifers. These are likely to be karstified to varying degrees, though there has been no systematic assessment. Thus the susceptibility of these aquifers to bacterial contamination is poorly known.

3) Karst aquifers are characterized by networks of conduits. These conduits comprise a small fraction of the volume of a karst aquifer, and so the major ones are likely to be missed by wells. The conduits form tributary networks which deliver water rapidly to springs, with an average velocity of 1700 m/day. The conduits can thus transport contaminants large distances over short periods without significant amelioration in water quality, except perhaps by dilution.

4) The groundwater catchment for springs is roughly proportional to their discharge. Thus high-discharge springs drain large areas, and have a proportionately higher risk than small springs of being contaminated. On the other hand, the larger discharge at such springs may dilute the contamination to tolerable concentrations.

5) Groundwater velocities in carbonate aquifers which are calculated by computer models are liable to be too low if the models do not incorporate karstic conduit networks. It is essential to determine groundwater velocities in the field, rather than to rely on computer models.

Conclusions on the hydrogeology of the aquifers in the Walkerton area

6) Groundwater investigations at the municipal wells and at nearby wells in Walkerton have shown that most of the inflow to the wells occurs at a few discrete horizons, and downhole videos have in some cases shown that the inflow on these discrete horizons is from karst conduits which are a few centimetres in size.

7) Some bedrock wells (e.g Well 7) are in excess of 70 m deep. The aquifer is karstified even at this depth, and the deep production zones at Well 7 are consequently not immune from contamination. There is sufficient vertical permeability, not least in open wells, to permit surface water and shallow groundwater to penetrate rapidly to depth.

8) There are few karst features on the surface at Walkerton, except for springs, and so the surface would not be described as a karst landscape. However, hydrogeological testing at Walkerton has shown that the karst aquifers at Walkerton have characteristics similar to well-known karst aquifers such as at Mammoth Cave in Kentucky. Therefore karst aquifers are not necessarily associated with karst landscapes.

9) The Tragedy and subsequent investigations have shown that the karst aquifers at Well 5, and to a lesser extent at Wells 6 and 7, are susceptible to bacterial contamination. High turbidity is often a good indicator of high bacteria counts in other carbonate aquifers, but there is a poor association in the municipal wells at Walkerton, with high bacteria counts often being found in samples with low turbidity. This may be due to varying availability of bacteria and sediment over time, and may also be due to multiple sources.

10) The most severe contamination of the wells probably usually occurs within a few days of heavy rain, though this could be better proven with some further testing.

11) The location of supply wells in karst groundwater discharge wetlands (especially where springs lie at water level) permits pumping-induced recharge of surface water, especially during late summer rain storms.

Conclusions on flow to Well 5

12) The catchment area for the springs beside Well 5 is about 150 hectares (0.6 square miles). Well 5 also drew water from the same area. Much of the water normally flowing to the springs was probably captured by Well 5 when it was pumping, with relatively more during dry periods and relatively less during wet periods.

13) There is the potential for water in the south branch of Silver Creek to sink into the creek bed and flow to the springs at Well 5. However, this does not appear to be a major component of flow.

14) There are substantial areas in the groundwater catchment area for Well 5 where overburden deposits are thin or are composed of gravel. In these areas water could flow though the overburden in days or less. Once bacterially contaminated groundwater is in the bedrock aquifer it could travel to the springs or nearby Well 5 in days or less.

Conclusions on flow to Wells 6 and 7

15) The groundwater catchment for the area around Wells 6 and 7 is estimated to be at least 500 hectares (2 square miles).

16) Well 6 had greater bacterial contamination than Well 7. It is quite likely that this contamination entered the bedrock aquifer closer to Well 6 than to Well 7. The point(s) of entry are unknown, but could be one or more of nearby ponds, springs, or thin overburden. Pumping of Wells 7 and 9 appear to enhance wetland recharge and induce rapid transfer of the water through the shallow subsurface.

17) Deep open boreholes provide pathways for shallow water to descend to production zones in Well 7 and in the new Well 9. Such deep boreholes include Well 6 the three tests wells near Wells 6 and 7, and numerous private wells in the region.

4C Recommendations

1) Ontario should develop a classification system for aquifers, based on their susceptibility to contamination, and should develop maps showing the vulnerability of groundwater supplies.

2) The precautionary principle should be used in assessing carbonate aquifers. It should be assumed that rapid flow along conduits may be present and suitable precautions should be taken. It must be recognized that there is inevitably considerable uncertainty in many hydrogeologic parameters in karstified carbonate aquifers, especially those mantled by overburden.

3) Ontario should develop guidelines for monitoring municipal supply wells in karst and other fractured rock settings. It should be assumed that there may not only be seasonal changes in water quality and quantity, but also changes during and after heavy rain or snowmelt.

4) The test wells and Well 6 should either be plugged or converted to monitoring wells with different zones isolated to prevent ingress of possibly contaminated water to Wells 7 and 9. Springs should be inspected and isolated to prevent reverse flow. Well 7 should not be allowed to discharge to waste when not being pumped as the resulting depletion of the aquifer can only enhance the induced recharge of wetland water.

5) The understanding of karstic flow in the bedrock aquifers at Walkerton should be applied to the assessment of Well 9 and to the development of any further water supply wells for Walkerton.

6) Many of the conclusions made here are based of necessity on incomplete data. Appropriate hydrochemical characterisation and tracer testing are required to adequately evaluate these inferences. Tracer testing is the standard method for determining groundwater velocities in karst aquifers. The onus is on the Ministry of the Environment to review and provide permission for tracer testing in the Walkerton area, as such testing will provide firm and direct field evidence to further substantiate many of the observations and conclusions presented in this report.

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Table 1 **Principal flow and storage components in four carbonate aquifers (after Worthington, Ford and Beddows, 1999; see Exhibit 261)**

Area	Fraction of groundwater stored in the matrix %	Fraction of groundwater flow in karst channels %
Smithville, Ontario	99.7	97
Mammoth Cave, Kentucky	96.4	99.7
Chalk, England	99.9	94
Nohoch Nah Chich, Yucatan, Mexico	96.6	99.7

Table 2 **High-flow tracer velocities in conduits in carbonates in Ontario**

Location	Groundwater velocity in conduits
Greensville, Hamilton	4.6 km/day
Stoney Creek, Hamilton	5.7 km/day
Smithville, Niagara	20 km/day
Nogies Creek, Peterborough	11 km/day
Westmeath, Renfrew	21 km/day
Marble Lake, Frontenac	7.5 km/day

Table 3 **Calculations of discharge and inflows to Well 7 (data from Golder Associates, 2000a)**

Depth m	Depth ft	Velocity cm/s	Well diameter mm	Discharge L/s	% flow
14.0	46	48	381	54.7	100
14.3	47	47	381	53.6	98
16.8	55	37	420	51.3	94
17.1	56	37	420	51.3	94
18.9	62	40	400	50.3	92
23.6	77.5	43	400	54.0	99
23.8	78	43	400	54.0	99
30.8	101	42	400	52.8	96
37.5	123	47	381	53.6	98
37.8	124	47	381	53.6	98
45.7	150	42	381	47.9	88
46.0	151	40	381	45.6	83
51.4	168.5	31	400	39.0	71
51.5	169	30	400	37.7	69
51.8	170	29	400	36.4	67
61.0	200	7	660	23.9	44
68.1	223.5	51	200	16.0	29
68.3	224	51	200	16.0	29
69.6	228.5	45	200	14.1	26
69.8	229	48	200	15.1	28
70.1	230	48	200	15.1	28
72.4	237.5	49	200	15.4	28
72.5	238	50	200	15.7	29
72.5	238	49	200	15.4	28
72.7	238.5	48	200	15.1	28
72.8	239	47	200	14.8	27
72.8	239	47	200	14.8	27
73.2	240	42	200	13.2	24
74.4	244	0	200	0	0

Table 4 Heights of voids in five wells at Walkerton

Well	Depth (feet)	Void height (cm)
5	41	22
TW2	20	5
6	113	8
6	116	5
6	122	5
7	108	8
7	153	15
7	240	30
TW1-86	151	5
TW1-86	173	7
TW1-86	177	12
TW1-86	219	5
TW1-86	234	10
TW1-86	240	8

Table 5 Statistics for voids at Walkerton and at Mammoth Cave

	Walkerton	Mammoth Cave
Number of boreholes	5	6
Total length of open hole (m)	203	332
Average length of open hole (m)	41	55
Largest void (m)	0.3	0.13

Table 6 **Major rain events and the associated bacterial contamination at a domestic well near Well 5**

Date of maximum rain	Maximum daily rain mm	Total rain in rain event* mm	Total coliform (maximum) cfu/100 mL	E. coli (maximum) cfu/100 mL	Lag from rain peak to coliform peak (days)
June 25 2000	18	24.75	80	6	2
July 14 2000	30.75	50.5	52	16	1
July 31 2000	38.5	45	12	0	1
August 22 2000	8.25	10.5	13	0	1
August 26 2000	14	14.5	74	32	1
September 10 2000	26.26	26.26	2	0	1
September 14 2000	33.25	59.25	48	30	2
September 20 2000	24.75	31.5	10	2	4
October 6 2000	8.25	12	0	0	-
November 10 2000	25.75	35.5	2	0	0
November 16 2000	10	21.75	8	0	2

* a rain event is defined here as a period of one or more consecutive days with rain on each day

Table 7 Bacterial contamination of the Walkerton water supply in 1999 and early 2000

Date of sampling	Prior weather conditions
February 1 1999	just above 0º C
February 8 1999	just above 0º C
February 15 1999	maximum temperatures of 13 - 14º C on February 11-12 1999 possibly causing snowmelt
March 8 1999	around 0º C
July 19 1999	temperatures over 30º C, possibly local thunderstorms
August 3 1999	6 mm rain in previous week
October 18 1999	25 mm rain on October 12-16th at Hanover
January 31 2000	temperatures mostly below zero
March 1 2000	possibly snowmelt from warm weather and rain - 16.7º C on February 26th in Hanover; no local rain records but 13.4 mm recorded in Toronto on February 22-25
March 20 2000	maximum 13.4º C that day - possible snowmelt
April 3 2000	maximum temperature 12 - 16º C on March 31st to April 3rd
April 11 2000	
April 17 2000	

incidents from Ross and Associates (2000, Appendix O)

Table 8 Weather events possibly causing substantial runoff and bacteriological contamination of some wells

Date of event	Sampling dates
maximum temperatures of 13 - 14^{o} C on February 11-12 1999 possibly causing snowmelt	February 15 1999 (adverse results from raw and treated water at Well 5 and from distribution system)
maximum temperatures of 12 - 23^{o} C on March 27 to April 3 1999 possibly causing snowmelt	March 29 1999 (no adverse) April 7 1999 (no adverse)
110 mm rain on May 17 to June 3rd 1999	May 17, 25, 31 1999 (no adverse) June 7 1999 (no adverse)
48 mm rain on June 12-14 1999	June 14 1999 (no adverse) July 5 (no adverse)
60 mm rain on June 24 to July 1 1999	July 5 1999 (no adverse)
30 mm rain on July 24th 1999	July 26 1999 (no adverse)
maximum temperature of 25 ^{o} C on March 8 2000 possibly causing snowmelt	March 20 2000 (adverse results from raw water at Well 5)
maximum temperatures of 12 - 14^{o} C on March 31 to April 3 2000 possibly causing snowmelt	April 3 2000 (adverse results from raw and treated water at Well 5 and from distribution system)

Note: the sample dates and results are from Ross (2001, Appendix O).

Table 9 Discharge measurements at creeks in the vicinity of the municipal wells

ID	Site	Grid ref. (1)	Area km^2 (2)	Dis-charge on April 28/30 L/s	Specific runoff April 28/30 $L/s/km^2$	Dis-charge on May 31 L/s	Specific runoff May 31 $L/s/km^2$	Dis-charge on June 13 L/s	Specific runoff June 13 $L/s/km^2$
1	Golf Course Creek at Saugeen R.	872874	8.64	151	17	139	16	98	11
2	Silver Ck at Ridout St	873855	11.3	168	15	202	18	103	9.1
3	Greenock Creek at Formosa Road	822830	7.28	406	56	162	22	121	17
4	Allens Creek at Con. 2 north of Durham Road	788872	11.7	372	32	158	14	170	15
5	Springs near well 5	872849	0	19.1	955	19.6	980	13.2	660
6	Spring between wells 6 and 7	838863	0	16.4	820				
7	Golf Course Creek at old rail line	837866	1.17	49	42	37	32		
8	Golf Course Creek at Durham Road	842862	0.55	3.8	7				
9	Tributary to Golf Course Creek at Elora Rd	837865	0.11	4.3	39				
10	N fork Allens Ck at Greenock Brant townline	815867	3.7	78	21				
11	Tributary to Allens Ck at Greenock Brant townline	814874	1.8	17	9				
12	N tributary to Golf Course Creek at Elora Rd	834877	0.3	0.6	2			1.1	3.7
13	Golf Course Creek at Sideroad 5	856867	7.08	81	11				
14	Silver Creek at Sideroad 5	858854	4.01	40	10	26	6		
15	Silver Ck above tributary	864857	4.34			42	10		
16	Silver Ck south branch	864857	5.88			76	13		
17	Silver creek south branch at Highway 9	867845	5.21			52	10	20	3.8
18	Silver creek south branch at townline	864834	3.78			47	12	18	4.9
19	Silver creek south branch at sideroad	864826	2.25	29	13	25	11	18	8
20	Silver creek south branch at Con. 14	860821	1.5	10	7				
21	Otter Ck tributary at old rail line	883814	3.38	59	17				
22	Tributary to Greenock Creek at Carrick-Brant West	841829	1.05	57	54				
23	Greenock Creek at Elora Road	842834	3.38	108	32				

Notes: 1 The grid reference applies to Natural Resources Canada 1:50,000 topographic map 41 A/3
2 The catchment areas were determined from map 41 A/3, 1:10,000 Ontario Base maps and more detailed surveys close to wells 5, 6, and 7 (Exhibit 221, Report on cause, appendices L and M)

Table 10 Average runoff calculations for the areas around Wells 5, 6, and 7

ID	Site	Grid ref.	Area km^2	Dis-charge on April 28/30 L/s	Specific runoff April 28/30 L/s/km^2	Dis-charge on May 31 L/s	Specific runoff May 31 L/s/km^2	Dis-charge on June 13 L/s	Specific runoff June 13 L/s/km^2	Average specific runoff L/s/km^2
1	Golf Course Creek at Saugeen R.	872874	8.64	151	17	139	16	98	11	
2	Silver Ck at Ridout St	873855	11.3	168	15	202	18	103	9.1	
3	Greenock Creek at Formosa Road	822830	7.28	406	56	162	22	121	17	
4	Allens Creek at Con. 2 NDR	788872	11.68	372	32	158	14	170	15	
	TOTAL FOR ABOVE CREEKS		38.9	1097		661		492		
	AVERAGE FOR ABOVE CREEKS				28.2		17		12.6	19.3
5	Springs near well 5	872849	0.02	19.1	955	19.6	980	13.2	660	
6	Spring between wells 6 and 7	838863	0.02	16.4	820					

Table 11 Components used to calculate the catchment area for the springs at well 5

Area	Area (hectares)	Predicted runoff (L/s)	Fraction of total
Direct runoff to well 5	1.67	0.32	2
Spring area	0.3	0.06	0.4
The hollow (north and south catchments of B.M. Ross)	11.93	2.3	14.4
Contributing area in Silver Creek (S branch) catchment	138	13.32	83.2
TOTAL CATCHMENT	152	16	100

Table 12 Components used to calculate the catchment area for the springs at Wells 6 and 7

Area	Area (hectares)	Predicted runoff (L/s)	Fraction of total
Direct runoff	117	22	34
Contributing area outside topographic catchment	446	43	66
TOTAL CATCHMENT	563	65	100