PATHOGENS IN BEDROCK AQUIFERS

A DETAILED STUDY OF THE PRESENCE AND TRANSPORT OF PATHOGENS IN URBANIZED SETTINGS WITH PRIVATE BEDROCK WELLS

KENT NOVAKOWSKI, QUEEN'S UNIVERSITY

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Canadian Water Network

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WHY DID WE DO THIS RESEARCH?

Domestic wells are used to provide drinking water supplies to a significant number of Canadians across the country. Approximately 30% of Canadians consume groundwater; the majority from their own wells. Many domestic wells are drilled near on-site wastewater systems (septic systems), which may pose a source of possible contamination depending on the geological setting. In areas where the wells are drilled into thick and protected sand and gravel aquifers, the risk of well contamination is low. In cases where the aquifer is fractured bedrock with minimal soil cover, the risk of contamination may be higher due to the rapid migration of surface infiltration and groundwater.

Approximately 70% of the regional aquifers that provide domestic supply in Canada are fractured rock. Some of these settings have a protective cover such as glacial till or clay, but there are also broad regions across the country where very little protection above the bedrock exists. There have been few studies that explore the occurrence of bacterially-related contamination in well water in these settings.

Under current regulations across most of the country, wells constructed in bedrock settings are required to have at least six metres of casing and a required setback distance from on-site waste systems. The purpose of the setback is to provide sufficient travel distance between the waste system and the well for bacterial compounds to be removed by natural attenuation in a sandy environment. If a sandy environment is not present, it is the responsibility of the well owner to vigilantly check the well for bacterial contamination on a regular basis. In most jurisdictions, sample analysis is provided free of charge by the local public health unit.

Microbial pathogens are a wide group of disease-causing organisms that include bacteria, parasites, fungi and viruses. In approximately half of the groundwater borne disease outbreaks in the United States, the responsible agent is a virus. Because of the difficulty and prohibitive cost to sample for viruses on a regular basis, very little is known about the presence of viruses in domestic well water, particularly in wells drilled into fractured rock aquifers. In some studies, the occurrence of fecal coliform bacteria has been used as an indicator of the presence of viruses, but the effectiveness of this method has not been reliably evaluated for vulnerable settings such as fractured rock.

In addition, little is known about the transport processes that control the natural attenuation and delivery of the organisms to the receiving wells. Bacteria are small entities (about the size of the diameter of a human hair) and viruses are even smaller. Their behavior during transport is thought to be complex and governed by gravity, electrostatic forces, and in the case of bacteria, their ability to be mobile.

The objectives of this three-year study (2007-2010) were:

1. To collect evidence regarding the potential distribution of pathogens —particularly viruses — in sensitive groundwater settings such as bedrock aquifers, and
2. To develop a better understanding of the transport of the pathogens in the fractures that provide the pathways between source and well receptor. The results were used to develop recommendations for regulators and domestic well water consumers on the risks and potential avenues of management for this issue.

HOW WAS THE RESEARCH CONDUCTED?

1. PATHOGEN OCCURRENCE IN BEDROCK AQUIFERS

A survey of pathogens in groundwater was conducted in three rural locations across Canada: Torbay, Newfoundland; Portland, Ontario; and Gabriola and Hornby Island, British Columbia. Sites were identified in collaboration with provincial representatives and local public interest groups and were selected based on the presence of fractured bedrock aquifers with little or no soil cover and on-site waste systems located on the same or adjacent property. Groundwater was obtained from aquifers at each location, which were of sedimentary or crystalline rock. Dedicated monitoring wells or domestic wells were used for the sampling (Figure 1). A survey of septic system locations was also conducted at each location to evaluate travel distance and population density relationships.

Figure 1. An example of a water well

Samples were analyzed for the presence of various human enteric viruses using methods based on the DNA of the organism. The process required to obtain these samples is extremely complex and requires the filtration of a large volume of sample water, usually 1000L. As viruses are infective (i.e. will infect a human) at very low concentrations, large volume samples are required to ensure that enough water is collected to properly represent the likely number of viruses in the well. Unfiltered water samples were also collected from the same sources and analyzed for the presence of common chemical parameters and fecal indicator bacteria. A total of 61 sample sets were collected at various times from 30 wells over a 10-month period, from July 2008 to May 2009. An image of the sampling apparatus is provided in Figure 2. It should be noted that the method of analysis only identifies the presence of the virus and not the potential infectivity (i.e. not whether it is alive or dead).

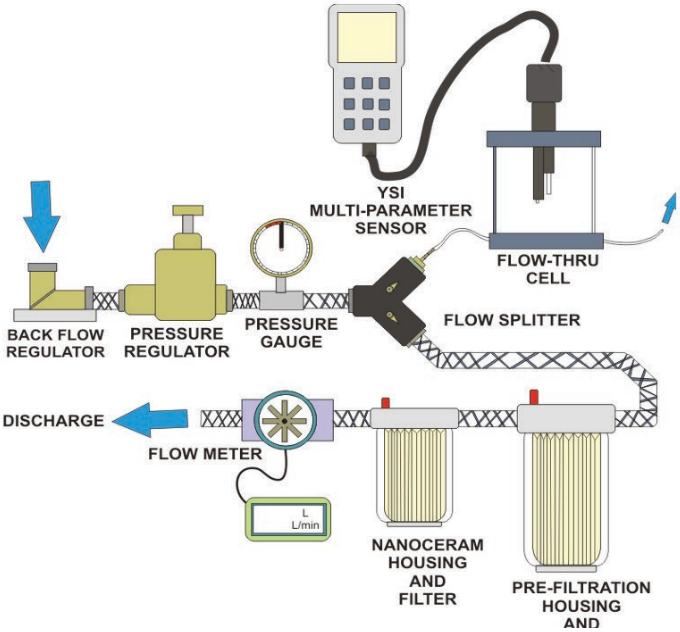

Figure 2. Sampling apparatus

2. PATHOGEN TRANSPORT IN ROCK FRACTURES

Field and laboratory experiments investigating pathogen transport in real and simulated rock fractures were also conducted in discrete fracture features under controlled conditions. In both cases, bacteriophages were used as surrogates for viruses. Bacteriophages are non-pathogenic organisms (harmless) of similar size to viruses, typically in the tens of nanometre (nm) range. Microspheres of three different diameters (20 nm, 200 nm, and 500 nm) were used in the laboratory experiments to simulate the transport of pathogens with a range of sizes.

The field experiment was conducted by simulating a source of viruses at the ground surface – for example, what might be released via the effluent from an on-site waste treatment system sitting directly on bedrock. The experiment was performed on a 10x10 m outcrop of the bedrock aquifer, into which two boreholes had been drilled to a depth of 20 m, separated at surface by 6 m (Figure 3). One well was completed as a multi-level monitoring well (TW-3) and the other left as an open well (TW-20), simulating a domestic well condition without the required 6 m of protective casing. To

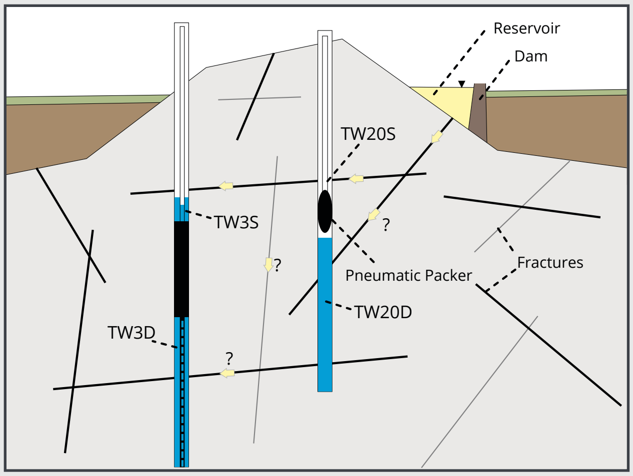

Figure 3. Conceptual cross-section of the rock outcrop used for the tracer experiment

simulate the release of viruses, a reservoir of approximately 1500 L was established by pumping from the open well onto the edge of the outcrop. Once the flow system was established over several hours, a bacteriophage with a non-toxic fluorescent tracer was added to the reservoir, and arrival of the mixture was observed by sampling the discharge from TW-20 and by sampling the multi-level intervals in TW-3 and the isolated zone at the top of the TW-20. Measurement was also conducted in the field for pH, temperature, conductivity, and dissolved oxygen.

Laboratory experiments were conducted using blocks of rock 0.28×0.21×0.07 m in dimension. The intact block was fractured to produce a discrete fracture feature along the length. Two fractures were generated, and inlet, outlet and measuring ports were added to each end, allowing for the characterisation of fracture properties via sampling and hydraulic and tracer experiments. Experiments using a variety of pH conditions, ionic strengths and geochemical constituents were then performed using various combinations of the bacteriophage, microspheres and an inert tracer, bromide.

WHAT WERE THE RESULTS?

1. PATHOGEN OCCURRENCE IN BEDROCK AQUIFERS

SITE	# OF SAMPLES COLLECTED	# OF POSITIVE SAMPLES	% OF POSITIVE WELLS (WHERE POSITIVE = VIRUS PRESENCE)
Torbay, NL	14	7	66.7
Portland, ON	24	11	77.7
The Gulf Islands, BC	23	5	38.5

Table 1. Virus occurrence in three sampling locations across Canada

The results of the field sampling shows 37.7% of samples and 58.1% of wells tested positive for viruses (see Table 1). Rota and adenovirus were the most widely detected viruses, which are believed to cause gastrointestinal illness in children. The number of positive samples seems remarkably high in the Newfoundland and Ontario sites, but less so at the British Columbia site. This may occur because on-site waste systems are more widely distributed in British Columbia than in the other two locations, and on-site waste system sources are linked to the presence of these viruses. In fact, when the density of homes (i.e., number of homes in a 2500 m^2 area) is plotted versus the number of positive virus samples, a linearly increasing relation is observed, suggesting that there may be a relationship between the numbers of these systems in the vicinity of the wells and virus occurrence.

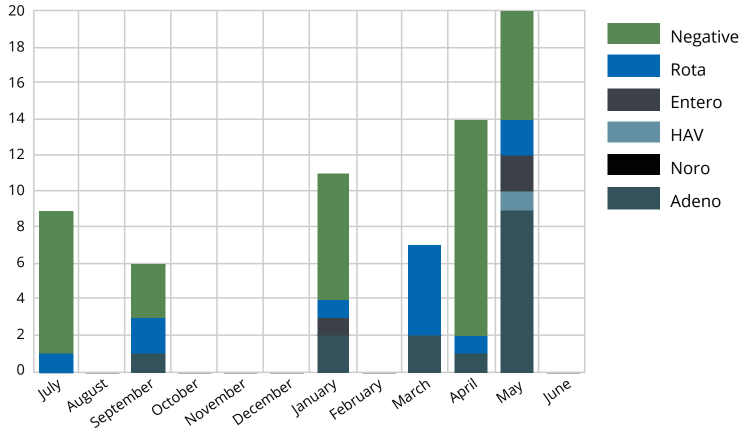

Figure 4. Occurrence of positive virus samples throughout the year

As illustrated in Figure 4, the majority of positive samples were observed during the winter and spring months, which coincides with the virus-based outbreaks that are typically observed during these months. The results suggest that the transport time from on-site waste systems sources to the domestic wells is very short.

Samples were also analysed for total and fecal coliform bacteria. As these bacteria are often used to predict the presence of other pathogens such as viruses, a statistical analysis was conducted of the correlation between the occurrence of these bacteria and the viruses detected. Results indicate that the occurrence of both total and fecal coliforms is poorly correlated with the occurrence of viruses in both samples and wells. For the wells in Newfoundland, no indicator bacteria were found in any of the samples, yet there were virus positives in several. Since the source, transport and survival of bacterial organisms is known to differ greatly from that for viruses, the observed results may suggest that the lack of bacterial indicators in a sample is not an indicator of the absence in human viruses in groundwater. However, since bacterial samples were collected relatively infrequently over the course of the study, it is possible that more frequent collection in wells that showed virus positives may have also shown bacterial positives. More research is needed to fully understand this relationship.

2. PATHOGEN TRANSPORT IN ROCK FRACTURES

Rapid transport was observed during the field tracer experiment. Figure 5 shows the peak arrival of the bacteriophage tracer in just a few hours after application. This clearly indicates that the primary pathway was the vertical fractures, as shown in the conceptual diagram (Figure 3). The comparison between the arrival curves for the fluorescent tracer and the bacteriophage shows that the bacteriophage arrived well before the appearance of the fluorescent tracer. This is believed to be the result of pore-exclusion effects and preferential flow pathways in the fracture planes. As each fracture has a distribution of opening sizes, including areas where the fracture walls are in contact, the particle tracer (i.e. the bacteriophage) will follow only the largest openings, while the solute tracer (i.e. the fluorescent dye) will track through much more of the total pore space.

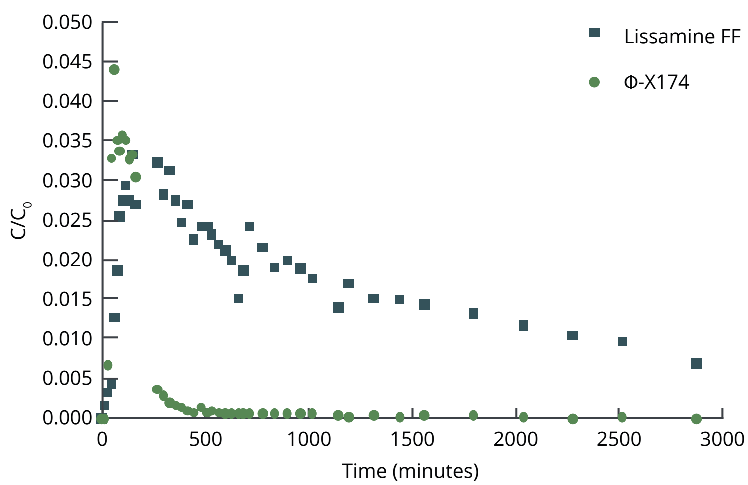

Figure 5. Results of the field tracer experiment showing the arrival of the bacteriophage (Φ-X174) ahead of the fluorescent tracer (Lissamine FF).

This was also observed in the laboratory experiments conducted using multiple sizes of microspheres, which showed that the largest particles travelled faster than smaller particles, which in turn exceeded the rate of solute tracers. Pore exclusion was enhanced with the larger-sized (i.e. bacteria-sized) particles. The experiments also showed significant effects of the chemistry of the groundwater and the mineralogy of the rock – the higher the concentration of ionic compounds in the groundwater, the less mobile the bacteriophage became. Similar effects were observed using the microspheres, where smaller sized particles were more retained at higher concentration of ionic species. In both cases the increase in retention was attributed to electrochemistry of the mineralogic surfaces on the fracture walls.

WHAT ARE THE IMPLICATIONS FOR STAKEHOLDERS AND DECISION MAKERS?

The widespread presence of pathogens in bedrock aquifers has long been suspected; this study points to the ubiquitous occurrence of viruses in this source of drinking water. The source must be on-site waste treatment systems, as the viruses found in this study originate in the human gut. Although treatment systems are known to work well when constructed with underlying protective layers such as clay, older treatment systems sitting directly on bedrock likely represent a risk.

In every jurisdiction in Canada, there are regulations for the setback of on-site waste systems on private lots. Similarly, there are regulations for the setback of domestic wells away from the on-site waste systems and other possible sources of contamination. In many jurisdictions, wells drilled in bedrock aquifers require a 6m casing, although older wells may not have that degree of protection. As travel time for viruses and bacteria may be very short in bedrock systems, the setbacks suggested in current regulations may not be meaningful, and penetration of the pathogens to depths greater than the casing is entirely possible.

There is no simple regulatory fix, outside of having a professional scientist or engineer locate each well and on-site waste system as properties are developed. In the case of a subdivision located on a bedrock aquifer, this may be impossible, as many complex interrelationships would develop between neighboring systems. Requirements for drilled wells with deeper casing may help, but that would require a more detailed hydrogeological investigation of each subdivision than is currently legislated. This is clearly an area that requires some discussion amongst policy makers and technical experts.

For homeowners who rely on a domestic well that uses water from a bedrock aquifer, and have an on-site waste system on their property or nearby, vigilance and proper well maintenance is key. Testing wells frequently is a wise idea, which can be done for free through public health units across the country. Although the testing is for bacteria, and we have shown that the presence of bacteria may not be a good indicator that viruses are present, if any bacteria are detected at any time, it is a reasonable assumption that viruses are also occasionally present and the well water should be chlorinated or treated regularly.

Local governments and public health agencies should continue to educate well-owners on their responsibilities.

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