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Environmental and artificial tracers in hydrogeology

title: **Rapid response in a gneissic bedrock fracture network to surface loading of nutrient- and pathogen-surrogate tracers in an agricultural watershed, Canada**

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Crystalline aquifers are often the primary drinking water source for well owners in rural North America; however these aquifers are susceptible to agricultural contamination, especially when overburden is thin. Pathogens and nutrients in manure can pose a significant health risk when transported to a well, while the inherent anisotropy of crystalline fractured rock aquifers makes it difficult to characterize transport mechanisms. Nitrates are very soluble and readily leached (Nolan, 1999; Nolan et al., 2002), and are thus transported with groundwater flow while bacteria, alternatively, are generally transported like a colloid (McCarthy, Zachara, 1989). The structure of a fractured rock aquifer provides the framework for groundwater flow and contaminant transport (Lapcevic et al., 1999). Most fractured rock aquifers rely on flow in fractures or secondary porosity to transport water and contaminants within the aquifer system (Domenico, Schwartz, 2002). Fractures are generally not planar, as the cubic law suggests, but exhibit extreme variability in surface roughness causing straining of materials the size of colloids, such as bacteria (Taylor et al., 2004). To explore these issues, a regional-scale monitoring study and surface-to-fracture tracer experiments adjacent to a rock outcrop were initiated in the Precambrian Shield of Ontario, Canada.

The study area is characterized by sparsely-fractured Precambrian syenite-migmatite overlain by 0–3m of sandstone. Rock outcrops are common in this terrain, but overburden thickness can be greater than 4m. Twenty-two bedrock wells were drilled between 2004 and 2008 to depths from 30–45m below ground surface (bgs) in a 40 km^2 area. Hydraulic testing to identify horizontal fracture features was completed on each well and most were instrumented with multilevel piezometers. Results from a regional monitoring program indicate that areas of minimal overburden must create direct transport pathways for pathogens, such as *E. coli*. Little overburden coupled with recharge events creates an optimal environment for the introduction of pathogens to fractured rock aquifers. Bacteria occur most often in shallow piezometer sections indicating direct connection to the surface. However, bacteria were also found in deep piezometers (~30m bgs) suggesting that vertical fractures encourage transport to deeper horizontal fractures.

Initial tracer experiments were completed using Lissamine FF to explore conservative transport. A final tracer experiment was completed in September 2009 by applying 10^{11} particles/mL of 0.3 μm and 10^{11} particles/mL of 1.75 μm microspheres and 0.3 g/L of Lissamine to a dammed area adjacent to a rock outcrop. A single packer was positioned at 4 m bgs creating a seal where water and tracer solution could be collected above the packer. The dammed area was filled by pumping 1200 L of water from TW8. Once the pool was filled, the flow rate was reduced to 7 L/min to create steady state conditions, where the pool remained full throughout the duration of the experiment. The deep section was pumped at a rate of 7 L/min using a submersible pump fed through the upper packer to create a downwards hydraulic gradient in the closest well (5m from the pond) and to retain a saturated flow loop with the pool. The upper section of the closest well and the shallow section of another nearby piezometer (15 m from the pond) were pumped continuously at a rate of approximately 0.6 L/min using peristaltic pumps. The tracer experiment was executed over a period of 72 hours. Bulk samples were collected from three intervals at 15-minute intervals for the first two hours and at 4-hour intervals toward the end of the experiment. The Lissamine samples were analyzed using a Turner Designs Au-10 field fluorometer. Microspheres were enumerated using epifluorescence microscopy and computer imaging software with counting capabilities.

Tracer experiments indicate that transport times can be very fast, with arrival times between 30 minutes to five hours after tracer application on the rock outcrop. Microspheres arrive earlier than the conservative flow, but straining is evident. The dominant flow likely occurs through a semi-vertical fracture from the pond area and trickles down into the closest well (5 m from the pond). Some of the tracer is flowing downwards to a larger fracture deeper in the deeper interval in the same well. Significant tracer reaches the nearby well (15 m from the pond) through shallow horizontal and vertical fractures. All results from the tracer experiments indicate that wells drilled on rock outcrops are extremely vulnerable to surface contamination from agricultural processes.

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