Performance comparison of large diameter residential drinking water wells

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ABSTRACT
Large diameter residential drinking water wells are at a higher risk of contamination from surface water impacts than drilled wells. The possibility of a higher incidence of contamination of large diameter wells is attributed to site selection and construction problems. The objective of this investigation is to assess several design changes that are thought to improve the structural integrity of large diameter wells and to determine whether one design is more prone to contamination than the others. This paper describes the construction of the large diameter wells and results from ongoing laboratory and field trials.

RÉSUMÉ
L'étanchéité des larges puits résidentiels est moindre que celui des puits forés donc ils sont plus susceptible d'être contaminer par les eaux de surface. Les chances de contamination des larges puits dépendent de sa location et des problèmes de fabrication. Les objectifs de cette étude sont d'évaluer plusieurs conceptions reconnues pour améliorer l'intégrité des larges puits résidentiels et de déterminer si une conception est plus vulnérable à la contamination que les autres. Cet article décrit les étapes de construction des larges puits résidentiels et présente les résultats d'essais de laboratoire et de terrain.

1 INTRODUCTION

In Ontario, about 30% of residential drinking water requirements are from groundwater sources, but the rural population depends almost entirely on the extraction of groundwater from private wells (Goss *et al.*, 1998). The most common types of private water wells are either drilled or, dug or bored (Gibb, 1973). Drilled wells are constructed using mechanical devices to advance the hole and remove cuttings. These wells are typically 10 to 15 cm in diameter and use steel or PVC casings (NGWA, 1998). Drilled wells are normally constructed in areas that are underlain by permeable deposits of sand and gravel or bedrock formations that are capable of yielding water to a well as fast as it is withdrawn (Gibb, 1973). Dug wells were historically dug by hand and cased with brick, stone or wood. Presently, dug wells are dug with excavation equipment and bored wells are advanced with boring equipment. In Ontario, these wells typically utilize prefabricated concrete tile or corrugated galvanized steel pipe ranging in diameter from 60 to 120 cm (Simpson, 2004). Large diameter drinking water wells are typically dug or bored wells usually constructed in areas where waterbearing materials are thin or relatively impermeable (Gibb, 1973). These types of aquifers cannot yield water as fast as it is withdrawn and require the large diameter of the well casing to act as a reservoir to store water.

The construction of wells in Ontario is governed by the Ontario Water Resources Act under Wells Regulation 903 (last amendment is O. Reg. 372/07). The regulation states that all wells constructed in Ontario must be completed by licensed individuals who have undergone training and testing. The regulation also provides the standards that must be met to become a licensed well contractor or technician. Proper well locations, construction practices, and altering of wells are also standardized in the regulation.

Published scientific work indicates that residential large diameter drinking water wells are at a higher risk of contamination from surface water impacts than drilled wells. The possibility of a higher incidence of contamination of large diameter wells is attributed to site selection and construction problems such as leaking joints in the well casing, ineffective annular sealant placed between the well casing and the formation, poorly fitted lids or covers, inadequate air filtration system, wells located down gradient of septic effluent sources, and depth limitations due to improper equipment used to advance the well which results in shallow wells often situated in topographical lows. In some situations flaws in the well design were deliberate measures intended to capture surface water at sites with low groundwater yield. Historically, residential drinking water well investigations have been performed on existing wells (Goss *et al.*, 1998; Exner and Spalding, 1985). These studies have been unable to control the influence of design variations because of the different well ages, uncertainties about the actual well construction (portions of the well "as constructed design" are buried and not readily confirmable), and variable maintenance efforts.

Well ventilation systems allow air to enter or exit the well as the water level rises or drops and prevents the well from becoming pressurized particularly with the larger volume of water exchange that occurs within a large diameter well. In the past large diameter drinking water wells were not fitted with any ventilation other than loosely fitting covers, or were fitted with ventilation pipes open to the atmosphere. Open vents will prevent the wells from becoming pressurized but airborne contaminants can enter the well through the open ventilation pipe. These contaminants should not have direct contact with the well water. Open ventilation pipes also provide a means for vermin or insects to enter the well, become trapped, and contaminate the water supply with their decaying corpses. New products on the market that utilize HEPA (high efficiency particulate air) filter technology provide filtration of the air as it enters or exits the well. HEPA filters use a mat of randomly arranged fibres that remove at least 99.97% of airborne particles 0.3 µm in diameter (TSI Inc., 2008). This level of filtration would prevent most airborne bacteria from entering the well.

Contamination of the well water may be caused by contaminated surface water that infiltrates into the well casing. Older bored or dug wells were constructed without joint sealant between the concrete tile sections and this combined with the lack of a proper annular sealant created a pathway for contaminated surface water to enter the well. Annular sealant is used to fill the void between the well casing and existing formation to a minimum depth of 2.5 m below ground surface. This creates a watertight seal between the casing and formation to prevent water from short circuiting into the well. The sealant used should have a lower permeability than the surrounding native soils (St. Germain and Robin, 2007). Appropriate joint sealant between concrete tile sections and a proper annular sealant should greatly reduce the risk of surface water entering the well. Goss *et al.* (1998) completed a study comparing well construction types with nitrate and bacterial contamination of rural drinking water wells in Ontario and observed that dug or bored wells had a much higher incidence of nitrate and bacterial contamination than drilled wells. The higher incidence of nitrate and bacterial contamination increased with well age and decreased with well depth. This suggests that newer wells with proper seals are less likely to become contaminated. They also observed that drilled wells that are completed in deeper aquifers are less likely to be impacted by surface water since the casings (steel or PVC) were less likely to transmit surface water. Steel and PVC well casings have fewer joints and these joints seal better than those used in large diameter wells. These general findings support the conclusions reached by Exner and Spalding (1985) who conducted a similar survey in southeast Nebraska.

The purpose of this field and laboratory study is to assess the performance of several design changes that are thought to improve the structural integrity of large diameter drinking water wells, and to determine whether one design is more prone to contamination from surface water sources than the other. To assess the design improvements four "simulated" large diameter drinking water wells were constructed at the Fleming College Lindsay campus. According to Wells Regulation 903 these wells can be classified as "test holes" since the wells were "(a) made to test or to obtain information in respect of ground water or an aquifer, and (b) not used or intended for use as a source of water for agriculture or human consumption."

Although these test holes are exempt from the Wells Regulation's minimum construction features for water supply wells were used in the construction. Three of the test holes were constructed according to the current Wells Regulation (O. Reg. 327/07) and one was constructed using actual test hole regulation standards, for comparison. Although these wells are all classified as "test holes", in this paper they are referred to as "test wells".

The field study component of this research involves the performance monitoring of four large diameter water wells including routine water quality monitoring, smoke and aqueous tracer tests, and geophysical methods. The laboratory component includes an evaluation of the ease of removal of biofilm from different casing materials, and an assessment of structural integrity of various annular sealant designs for vertical load bearing capacity and hydraulic conductivity.

2 FIELD STUDY SITE, MATERIALS AND METHODS

2.1 Field study site

The field study site is located west of the Scugog River in a field bordered by forest, and marshland at the Fleming College campus in Lindsay, Ontario, 90 km northeast of Toronto, Ontario and 35 km west of Peterborough, Ontario, Canada. Environment Canada reports climate norms from 1971 – 2000 for Lindsay as having an average annual temperature of 6.3 °C with an average annual maximum of 11.3 °C and an average annual minimum of 1.3 °C. The average annual precipitation is 881.6 mm with 718.8 mm as rain and 162.8 mm as snow.

Gillespie and Richards (1957) report that the quaternary geology in the vicinity of the study site is classified as a Solmesville clay loam which is described as "soils have gently to very gently sloping topography resulting in imperfect drainage conditions within the soil profiles. Although generally there is at least a foot of lacustrine clay over the stony till, slight elevations occur in many fields where the clay deposit is very thin and stones appear on the surface. The profile development is characteristic of the Grey-Brown Podzolic soils."

Four conventional monitoring wells (MW1, MW2, MW3, and MW4) were installed on this site as part of a previous investigation and provide background information on both stratigraphy and groundwater hydraulics. In general, a ~0.3 m thick layer of topsoil overlays 4.0 m of silty till with gravel that sits on weathered limestone bedrock. The well casing is white PVC with an inside diameter of 5 cm and the annular space is sealed with bentonite slurry to the top of the screened interval (PVC slot #0.10). The space surrounding the screened interval is filled with filter sand. Frequent water level measurements from the four monitoring wells indicate the flow direction is southeast toward the Scugog River. The water table is close to the ground surface at ~0.5 m below ground surface (bgs) suggesting that the higher conductivity weathered bedrock zone provides the hydraulic support observed in the till. MW2 is located upgradient of the test wells and should not have been impacted by test well construction practices or materials and is used as a background well for water quality purposes.

2.2 Large diameter drinking water well installations

2.2.1 General

Four large diameter drinking water test wells were installed at the field study site (Figure 1); three are an advanced design (ETH1, ETH2, and ETH3), and one a conventional design (CTH1) (see Table 1). Test wells were constructed and installed by licensed well technicians. The test wells were located and logged in accordance to Wells Reg. 903. The concrete casing sections used for ETH1, ETH2 and CTH1 were fully cured and commercially manufactured. The casing sections for ETH1 and ETH2 were properly aligned in the hole so that the joints were flush and the casing was centered. The concrete casing sections were joined with a mastic sealing material that remains pliable and waterproof and is approved for potable water use by NSF International. The casing sections for CTH1 were misaligned and no joint sealant was used. The corrugated galvanised casing used for ETH3 is 18 gauge galvanized steel.

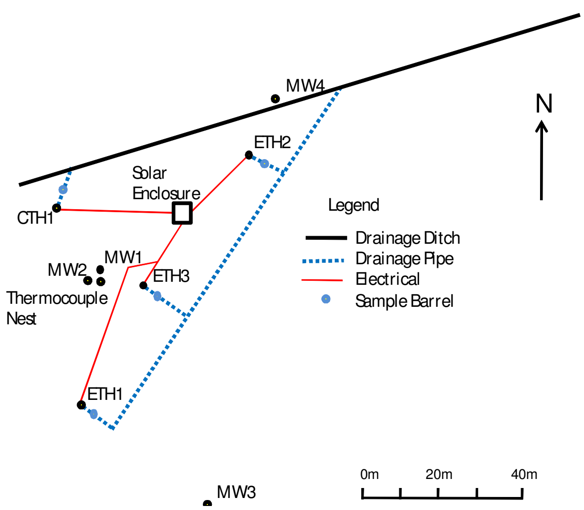

Figure 1. Site Map.

Table 1. Test well construction details.

	Casing Type	Mastic Sealant	Annular Sealant	Air Vent w/ Filtration
CTH1	Concrete	No	Drill cuttings	No
ETH1	Concrete	Yes	Bentonite slurry and sand (>20% bentonite solids)	Yes
ETH2	Concrete	Yes	Non-hydrated bentonite chips	Yes
ETH3	Galvanized steel	No	Bentonite granules and pea stone	Yes

The large diameter test wells were bored with a bucket auger rig. The bucket auger bore was 132 cm (52”) in diameter and the precast concrete casing sections were 91 cm (36”) ID and 76 cm (30”) high. The outside diameter of the precast concrete sections were 112 cm (44”) forming a 10 cm (4”) annular ring around the casing. The galvanized well casing was 82 cm (32”) in diameter forming a larger annular ring of 25 cm (10”).

The annular space was sealed to prevent any movement of water, natural gas, contaminants or other material between subsurface formations, or between a subsurface formation and the ground surface by means of the annular space. From the ground surface to a depth of at least 2.5 m, the annular space was filled with non-hydrated bentonite chips (ETH2), bentonite slurry and sand (ETH1), bentonite granules and pea stone (ETH3), or drill cuttings (CTH1). The test wells were then fitted with secure covers and ventilation (except for CTH1). Each test well was installed with a portion of the well casing above the ground surface (stickup). This stickup provides protection from surface water entering the well in the event that water ponds around the well casing and the entry of heavier airborne particles. The enhanced test wells have stickups that range in height from 0.55 m to 0.84 m, whereas the conventional well has a stickup of 0.47 m.

During construction of the test wells, observations of the stratigraphy were consistent with the existing monitoring wells. In general, observations made during test well installation indicate that an average 0.30 m of topsoil overlays an average 2.5 m of brown sandy clayey till. At all test wells the clayey till was underlain with highly weathered limestone bedrock

Once the lower rings of the well casings were securely in place a sandpack consisting of filter sand was placed in the annular space around each well. In the case of the galvanized casing the filter sand was placed once the entire casing was installed.

Test wells ETH1, ETH2, and ETH3 have air filters built into the air vents attached to the Poly-Lok lids. These air vents were constructed from 10 cm (4 inch) ABS pipe. The vent opening to the atmosphere points down to prevent precipitation from entering the test well and is covered with wire mesh (2 mm square) that inhibits the entry of vermin and most insects. The removable filter material is Polyveyor Air ~ Permeable Fabric (model 1950 – Low Permeability) and is sealed between two flanges. Polyveyor is nonwoven polyester material used for pneumatic conveying and is rot and mildew resistant and has average pore openings of 4 μm (Albarrie Canada Ltd., 2009). This pore size is capable of preventing particulate matter and most bacteria from entering into the well through the air vent. The air vents are permanently attached to the Poly-Lok lids and sealed with neoprene gaskets, constructed from 4 mm neoprene sheets, and an outdoor acrylic latex caulk with silicone.

2.2.2 Water extraction system

The pumps and pitless adapters were installed by licensed well technicians. Pitless adaptors were installed in the enhanced test wells and an improper connection was made at the conventional test well (CTH1). The pitless adaptors employed in these test wells are constructed of brass and have an inside diameter of 25.4 mm (1"). To install the pitless adaptors and water lines, the soil material next to the test wells was excavated to an average depth of 1 m and 1 m in width.

The holes for the pitless adaptors in concrete cased test wells, ETH1 and ETH2, were bored with a 51 mm (2") hammer core drill bit. These were drilled with a hammer drill above the static water level in the test wells at the time of installation. The pitless adaptors were then installed in the hole and tightened on the outside of the casing. Once the pitless adaptors were installed the annular sealant was replaced. A bentonite granule (Envirocore – Medium) was placed in the space around the ETH1 pitless adaptor and backfilled. Existing hydrated bentonite granules were placed around the ETH2 pitless adaptor and backfilled.

The test well with a galvanized casing (ETH3) utilized the same pitless adaptor as the concrete cased wells. Since the corrugations in the casing would not permit a proper seal between the gaskets of the pitless adaptor, the pitless adaptor was attached to a 30 cm long 25.4 mm threaded brass pipe. The brass pipe was then passed through a hole drilled in the casing and sealed with silicone on the outside and inside of the casing. Wet bentonite granules (Envirocore – Medium) were placed around the pipe on the outside of the casing. Concrete was placed on top of the bentonite and pipe. The concrete was used to counter balance the weight of the pump and piping.

The conventional test well (CTH1) did not utilize a sanitary drinking water connection; instead a 63.5 mm (2.5") hole was drilled using the same type of bit and drill as used for the ETH1 and ETH2 wells. The pipe and power cable for the pump were passed through the hole and existing material from the excavation was packed around the opening. The excavation was then backfilled.

A water delivery line (1.91 cm (¾") PVC pipe) sloping away from the test wells at 0.5 % extends from the pitless adaptor (ETH1, ETH2 and ETH3) or pipe (CTH1) to a sample collection facility. This sample collection facility is comprised of a 170 L plastic barrel with screw top lid and allows water samples to be collected as required and provided a convenient location to place a cumulative flow gauge (Omega FTB-4000, turbine meter). The water line from the pitless adaptor enters the barrel and water exits through a 100 mm solid tile drain pipe located below the water line. A check valve was installed on the outlet of the water line to ensure that water cannot flow back into the test well. Water in the barrel is allowed to discharge by gravity through the drainage line to a drainage ditch that runs along the northern boundary of the field site. To reduce erosion in the drainage ditch and help prevent freezing the outlet of the pipe in the drainage ditch was covered with stone. To minimize the risk of freezing during the winter, straw bales were used to cover all sampling facilities and the water line from CTH1 since it is the shallowest.

Solar powered submergible impeller pumps (24 V, 16 amps, Rule 3700) were selected for use in this test well project. These pumps are capable of pumping 20 L/minute at ~4.0 m of hydraulic head. The pumps were connected to the pitless adaptors using brass fittings and stainless steel hose clamps for ETH1, ETH2, and ETH3. For CTH1, galvanized fittings were used since they are not as safe for drinking water and may reflect a pump not installed correctly. The holes for the electrical conduit were drilled about 5 to 10 cm above the ground surface and the conduit was placed in the hole in the casing and secured with silicone. The pumps were wired and placed in the test well by licensed well technicians and connected to an automated control system with daily pumping beginning on November 25, 2008.

The power for these pumps is provided by 2-12 V deep cycle batteries in series providing 24 V of power. The batteries are charged by two 1.22 m x 0.61 m (48" x 24"), 24 Watt solar panels in series. The solar panels are set on the top of a steel pole in a central location relative to the test wells. The wires from each pump are buried 45 cm below ground in conduit and meet at the solar panel. The solar panel and all controls are contained in a fenced enclosure. The electrical equipment is secured in a large plastic box with desiccant packs to absorb any moisture. Due to the high amperage of the pumps only one pump can run at a time. An Allen-Bradley Pico programmable controller (model 1760-L12DWD) operates 30 Amp relays that turn the pumps on and off for set periods of time based on the flow rates and the desired amount of water to be removed.

2.2.3 Monitoring instrumentation

All of the test wells and two of the monitoring wells (MW2 and MW3) are instrumented with pressure transducers (Solinst Levelogger Junior in MW2, MW3, CTH1, ETH1, and ETH3, and a Solinst Levelogger Gold LTC in ETH2) to continuously monitor fluctuations in the water level in each well. The pressure transducer in ETH2 provides an accuracy of $\pm$ 0.3 cm and a resolution of 0.001 % of the full scale of the measurement, and the pressure transducer in the remaining wells provide an accuracy of $\pm$ 0.5 cm and a resolution of 0.028 % of the full scale of the measurement.

To provide soil profile temperature information, a thermocouple nest was installed between 30 cm and 135 cm bgs. Eight (8) thermocouples (Onset L-TMA-M006) with a range of -40°C to 100°C and an accuracy of $\pm$ 0.7°C were placed every 15 cm. Two 4-channel data loggers (HOBO U12-008) log and store the measurements. The thermocouples were affixed to a dowel using shrink wrap sheets and placed into an augured hole that was then backfilled with bentonite slurry.

Mini-piezometers nests were installed in the bentonite chip annular sealant of ETH2 to allow air pressure tests to be performed to investigate the hydration of the bentonite chips used as an annular sealant in this test well. Three nests of three piezometers each were placed around ETH2. Each nest has a shallow (0.3 m bgs), medium (1.5 m bgs), and deep (2.4 m bgs) piezometer. The mini-piezometers are constructed from 25.4 mm (1") diameter PVC pipe and are capped at the end in the ground. The top of the mini-piezometers have a removable screw cap.

The PVC was slotted with a hacksaw to create a screen similar to a monitoring well screen. The slots are 1 mm wide, spaced ~5 mm apart, and are on two sides of the pipe. The screened section extends 0.5 m from the bottom of the mini-piezometers, with the exception of the shallow which only extends 15 cm from the bottom.

2.2.4 Extraction and recovery tests

A series of extraction and recovery tests were conducted to determine the response of the water level in all the test wells due to pumping a single test well, and to establish the recovery behaviour of each test well. Water was extracted from one test well at a time and the response in the test wells and monitoring wells was monitored using the pressure transducers. The data collected provided well interaction information and recovery rates for each test well and were used to design the operation of the water extraction system.

2.2.5 Geophysical methods

To non-destructively assess the *in situ* integrity of the annular seal materials geophysical methods consisting of ground penetrating radar (GPR) surveys and ultrasonic pulse velocity tests were considered. To facilitate these geophysical measurements, geophysical access tubes (4" diameter PVC) were installed with the Frost campus geotechnical auger rig. A pair of geophysical access tubes was installed on each side of the annular sealant for each test well. One of the access tubes was placed in a vertical hole on the geologic formation side of the annular sealant and the other access tube was fixed to the nearest location on the interior casing wall for test wells CTH1, ETH1 and ETH2. The tubes are affixed to the interior wall of the casing with metal strapping and improved contact with the casing wall is achieved with neat cement sealant. The installed access tubes protrude from the cover and lid assemblies where it is sealed with neat cement. Since the performance of the GPR is reduced when the signal has to pass through steel, the interior access tube at test well ETH3 was installed on the outside of the corrugated galvanized steel casing. All access tubes extend from below the annular seal to the top of the well casing.

2.2.6 Disinfection

To disinfect the test wells, 1.25 mL of bleach was added for every litre of water stored in the test wells. Bleach was poured down the inside walls of the test well casing. Twelve (12) to twenty-four (24) hours after the bleach was added water samples were collected from the test wells and analyzed for free chlorine. The water sample from the test wells were collected from the discharge of each monitoring barrel and rinsed with sample water three times prior to sampling. The results from the free chlorine test were <50 mg/L for all test wells. Due to the low free chlorine levels the water was pumped from the test wells until the free chlorine residual was <1 mg/L. The disinfection procedures were repeated and twenty-three (23) hours after the wells were dosed they were tested for free chlorine levels. This resulted in three (3) of the four (4) wells being in the range of 50 mg/L to 200 mg/L as stipulated by Regulation 903. ETH3 had a free chlorine concentration of 38.5 mg/L, whereas the other test wells ranged between 51 and 67 mg/L.

2.3 Tracer tests

2.3.1 Smoke tracer tests

Smoke tracer tests were used to assess potential pathways between the atmosphere and the interior of the test well. Pathways were identified visually, and the escaping flow rate and flow volume provides qualitative information on the degree of atmospheric interaction. The tests were completed using both pressure (provided by a Dewalt 1.6 hp, 56.8 L air compressor) and smoke (from a chemical smoke generator (Superior No. 1A)) to determine if there were any potential pathways between the atmosphere and the interior of the test wells. Each test well was tested by attaching the air compressor and increasing the air pressure to 68.9 to 103.4 kPa (10 to 15 psi) and holding it there for three 5 minutes periods, the pressure was allowed to drop after 5 minutes and increased again. The smoke generator was initiated and allowed to fill the air space in the test wells. The smoke generator was suspended in the test wells above the static water level. The air compressor pressurized the test well and visual recordings and observations were made. The test well was then purged of smoke by removing the smoke generator and access lid.

2.3.2 Aqueous tracer tests

Aqueous tracer tests will be used to determine if casing material, annular sealant or construction methods provide pathways for surface water to enter the well. Due to excavation work completed in Oct 2008 around the test wells the first aqueous tracer test has been postponed until June 2009. The excavation to install the water line created a preferential pathway for the tracer solution to infiltrate and also removed the vegetative cover. The aqueous tracer test will be completed once suitable vegetation has grown and the excavated area has had a chance to settle.

To replicate a worst-case scenario a conservative tracer solution will be ponded around each test well until a specified volume infiltrates. The grass around the test well will be trimmed to ensure uniform infiltration potential and an infiltration gallery will be constructed around each test well. Approximately 1000 L of conservative tracer solution, Rhodamine WT (fluorescent tracer) and sodium bromide, will be prepared and placed in the infiltration gallery. The interior of the test well will be visually inspected, and the effluent will be monitored for indications of potential surface water impact (conservative tracer solution). The test well will then be pumped at a sustainable flow rate to maintain a decreased static head relative to the potentiometric surface. The test well will be visually monitored for signs of the conservative tracer for a period of twice the time it takes the tracer to completely infiltrate. Using a fluorometer and conductivity probe the effluent pumped from the test wells will be continuously monitored and recorded on a data logger for a period of 24 to 48 hours. The effluent from each test well will be periodically monitored daily for a period of 2 weeks.

2.4 Baseline water quality

Water samples were collected from the test wells on March 4, 2008 (interim baseline) and then following the first smoke test and disinfection on February 11, 2009 (baseline). A water sample was also collected from monitoring well MW2 on February 11, 2009 and assumed to be representative of upgradient background water quality. Samples were analysed for metals, cations and anions, and *E. coli*, and total coliform.

3 RESULTS AND DISCUSSION

3.1 Water level measurements

Water level measurements made at the test wells indicate that groundwater water flows southeast toward the Scugog River, which the historical data from the monitoring wells support. Depending on the season the water table elevation can fluctuate by as much as 0.8 m (Figure 2, data from level loggers). The water table is close to the ground surface, as was found during excavation work and with water level measurements. The majority of the water recharging the wells is from the much higher conductivity stony till as this is where water can enter the wells.

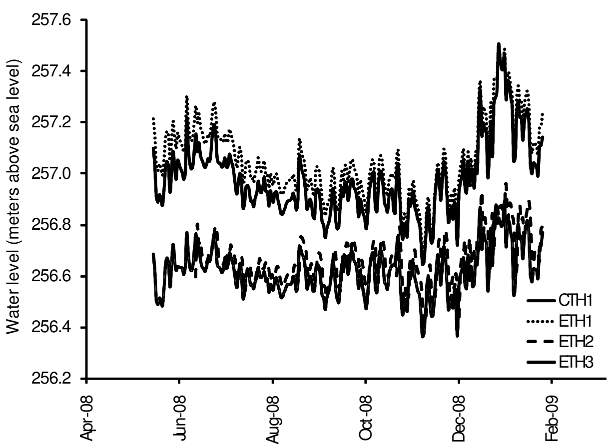

Figure 2. Test well water elevations.

3.2 Water extraction system

Based on data provided so far the pumps function properly but some problems occurred in the drainage system (Figure 3). Freezing problems in CTH1 prevented pumping during January and account for the lower amount of water pumped from the well. The lens on the flowmeter in ETH3 was obscured with condensation and could not be read in March, which accounts for the flat line and steep rise. The pumps were operational for 133 days at the time of the last reading and the desired amount of water to be removed from the test wells is 133,000 L. The pumping program is close for the enhanced wells which have no significant problems.

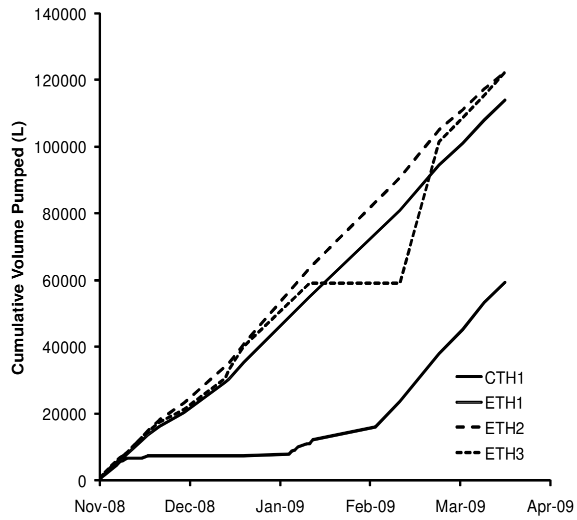

Figure 3. Cummulative volume of water extracted from test wells.

3.3 ETH2 annular sealant hydration test

Piezometers installed in the bentonite chip annular sealant of ETH2 were tested during the winter of 2008 (76 days after installation) and summer of 2008 (175 days after installation). During the winter 2008 test large volumes of air (9.5 m^3/min) were forced into the piezometers. When air was forced down the deep piezometers (2.4 m bgs) no air was detected exiting any of the other piezometers suggesting that the bentonite was saturated at this depth at all nests. This is consistent with the water table location at less than a meter below the ground surface. When air was forced into the medium depth piezometers (1.5 m bgs) air was detected exiting the other medium depth piezometers and the shallow depth piezometers (0.3 m bgs) for all nests. When air was forced into the shallow depth piezometers air was only detected exiting the other shallow piezometers. This suggests that the bentonite is not saturated at the medium depth. Due to the water table location above the medium depth piezometers it was expected that these would be saturated. At ground surface the bentonite seemed to be saturated but during the winter testing the annular sealant was frozen at the surface. When the test was conducted again in the summer of 2008 all of the piezometers were sealed as air could not be detected exiting out at any other locations. This indicates that the bentonite chips are fully hydrated. This conclusion was visually confirmed when the excavation work to install the pitless adaptors was completed and the seal was exposed 306 days after installation.

3.4 Smoke tracer test #1

Smoke tracer tests were conducted in December 2008 to determine if any pathways for airborne contaminants exist. After the smoke generator was placed inside the test well and before the air compressor was connected, smoke was seen escaping from the casing joints and the joint between the casing and the lid of all the wells. This indicated that raising the pressure inside the test wells was not responsible for the air leaks. Raising the pressure inside the test well did not increase the amount of visible smoke or location of leaks but did force the smoke out for a longer period of time, making it easier to observe the various pathways.

At all test wells smoke could be seen escaping from around the interior geophysical access tubes along joints in the concrete casing. CTH1 does not have any mastic sealant between the casing sections and had much more visible smoke emitting from the joints. ETH3 (galvanized casing) had smoke emitting from around the joint between the concrete and the galvanized casing. When pressure was applied to this test well black air bubbles and dark coloured water appeared along the seams of the galvanized casing. Both ETH1 and ETH2 have similar construction methods and had air leaks in similar places. Both had small air leaks around the electrical conduit and around the Poly-Lok. Table 2 provides an overall indication of the observations from the first smoke test.

Table 2. Observations from smoke tracer test 1.

Air leak Location	CTH1	ETH1	ETH2	ETH2
Poly-Lok lid seam	NA	Yes	Yes	Yes
Interior geophysical access tube portal	Yes	Yes	Yes	NA
Electrical conduit	NA	Yes	Yes	Yes
Water line entry at pitless adaptor	No	No	No	No
Casing joints	Yes, more	Yes	Yes	Yes
Annual sealant	No	No	No	No
Exterior geophysical access tube	No	No	No	No

NA – Not Applicable

The smoke tracer test showed that all the test wells have pathways between the atmosphere and the interior of the test well and thus it is possible for airborne contaminants to enter. Another series of smoke tracer tests is planned to be completed when the ground has thawed and the test wells are not surrounded by snow. This series of tests will help determine if any leaks exist in the annular sealant, waterline entry at the pitless adaptor, and exterior geophysical access tube.

3.5 Baseline water quality

The general water quality results from the upgradient monitoring well are similar to the test well results with the exception of the higher concentration of iron in the monitoring well and high concentrations of zinc found in ETH3. The high concentration of zinc (2230 µg/L) in ETH3 can be attributed to the use of galvanized steel as a casing material. CTH1 is the only test well to use some galvanized fittings in the plumbing of the pump and water line, which may explain the higher concentration of zinc (80 µg/L) present in water from this well compared to the other concrete cased wells. Given the results of bacterial testing the disinfection procedures killed all bacteria in the water sampled from the test wells. The only presence of bacteria found, was in the monitoring well (10 cfu/100 mL) which was not disinfected. Interim water quality samples also show high levels of zinc (9800 µg/L) in ETH3. CTH1 did not have a pump or galvanized plumbing fittings at the time of sampling and was below the detection limit for zinc. This confirms that the galvanized fittings cause the elevated zinc concentration in CTH1. These previous water quality results support the baseline water quality results from February 2009. The main difference is the concentration of zinc in ETH3 has dropped by almost 80 % in the span of 11 months.

4 CONCLUSIONS

The susceptibility of large diameter drinking water wells to contamination caused by surface water impacts is clear from the many residential drinking water well investigations that have been performed on existing wells. With further study and monitoring it will be determined whether one design is more prone to contamination.

At the time of writing smoke tracer tests have shown that pathways for airborne contaminants do exist, the bentonite chip annular sealant used at ETH2 is hydrated, the wells have been disinfected and baseline water quality results prove that the galvanized casing material and fittings used for ETH3 and CTH1, respectively cause elevated levels of zinc. Structural integrity of various annular sealant designs will be tested in the laboratory for vertical load bearing capacity and hydraulic conductivity (centrifugation method). Methods for the removal of biofilm from the interior walls of casing materials (concrete, fiberglass and galvanized steel) will be assessed in the laboratory. A complimentary set of geophysical data will be collected and an aqueous tracer test will be used to determine if casing material, annular sealant or construction methods provide pathways for surface water to enter the well.

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