Ground Water Monitoring&Remediation

A Multilevel System for High-Resolution Monitoring in Rotasonic Boreholes

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Abstract

A modular multilevel system was adapted for high-resolution, depth-discrete monitoring of hydraulic head and ground water quality in rotasonic boreholes or boreholes produced with similar dual-casing drilling methods. The system accommodates up to 15 monitoring intervals within one hole and can be used to monitor overburden and/or bedrock to depths of 100 m (330 feet) or more. It is most effective where static water levels are shallower than 9 m (30 feet) below ground surface. Sand packs around each monitoring port define the monitoring interval, and bentonite seals placed above and below each sand pack isolate the intervals. Each sand and bentonite layer has a practical minimum length of 0.5 m (1.6 feet); therefore, a 15 port system can monitor, with maximum detail, a minimum vertical span of 15 m (50 feet). All system components, primarily flush joint polyvinyl chloride (PVC) casing segments, stainless steel ports, Teflon® tubing, and PVC centralizers, are commercially available and require little preconstruction. An open 6-mm (¼-inch) inner diameter tube is connected to each port for manual hydraulic head measurements and water sampling with a peristaltic pump. To assess installation and performance of the new system, nine rotasonic holes in overburden and bedrock between 20- and 30-m (65- and 100-feet) deep were monitored at two sites. This detailed vertical monitoring provided important information on hydraulic head and contaminant distributions that would have been missed with fewer monitoring intervals. The monitoring system offers unique advantages where detailed monitoring in heterogeneous settings is needed to understand ground water flow and contaminant migration or evaluate the performance of remediation efforts.

Introduction

Ground water systems commonly display complex hydraulic head, geochemical, and contaminant distributions due to influences such as geologic heterogeneity and spatial and temporal variability of contaminant mass input, microbiology, and recharge (e.g., LeBlanc et al. 1991; Smith et al. 1991; Bjerg et al. 1995; Rügge et al. 1995; Heron et al. 1998; McGuire et al. 2000; Guilbeault et al. 2005). Despite this complexity, most ground water monitoring at contaminated sites is accomplished using conventional, single-interval monitoring wells with one well, usually with a 3-m (10-feet) screen or larger, in each borehole. This type of monitoring does not adequately describe the nature and extent of contamination in multiple dimensions and often yields samples that understate the maximum concentration of contaminants that occur in the portion of the aquifer screened by the well (Einarson 2006). Installing clusters of closely spaced conventional wells, each screened at a different depth, is sometimes employed in an attempt to better describe the plume in three dimensions. However, installing a sufficient number of these clustered wells to adequately quantify the system maybe cost-prohibitive at many sites. Therefore, alternate sampling and monitoring systems are increasingly used for depth-discrete multilevel monitoring in single boreholes, with the goal of generating sufficiently detailed vertical profiles of hydraulic head and water chemistry to better define the flow system and contaminant distribution in three dimensions.

One approach to multilevel, depth-discrete sampling is collection of ground water and soil samples from the bottom of boreholes drilled with hollow-stem augers and rotary drills as the drilling proceeds deeper (Yare 1975) or collecting ground water samples using driven direct-push (DP) probes (e.g., Semprini et al. 1995; Pitkin et al. 1999; Cho et al. 2000). These methods are quick when used in permeable zones (e.g., sand or gravel) and avoid permanent installations. However, many investigations at contaminated sites involve low-permeability zones or require multiple sampling episodes as well as the collection of additional data, particularly hydraulic head measurements required to define temporal variations in ground water flow directions. In these cases, depth-discrete, multilevel monitoring systems (MLSs) are efficient, cost-effective tools for collection of ground water samples and measurement of hydraulic head at many depths.

Several systems for detailed multilevel sampling of contaminated zones in unconsolidated sandy aquifers are reported in the literature. Merritt and Parsons (1960) describe the first such MLS, which consists of welded aluminum tubes with a system of thimbles for ground water sampling in a sandy aquifer. More recent MLS designs consist of bundles of small-diameter tubing either attached to the outside of a rigid support (polyvinyl chloride [PVC], aluminum, etc.) or encased within PVC. Pickens et al. (1978) describe an MLS in which 15 small-diameter polyethylene tubes, each connected to a separate monitoring interval, are contained inside PVC casing. LeBlanc et al. (1991), Smith et al. (1991), and Hess et al. (2002) used versions of this system to examine the effects of geologic heterogeneity on the transport of tracer solutes in sand and gravel aquifers. These systems using small-diameter tubing do not allow water level measurements to be made by inserting a probe down the inside of the tubing because the tubing diameter (inner diameter [ID] 2.4 mm) is too restrictive. Possibilities exist for relative water level measurements to be made using an aboveground suction manifold; however, this is tedious and unsuitable for cold weather.

Cherry et al. (1983) turned the Pickens et al. (1978) design inside out by attaching up to 20 tubes to the outside of PVC casing. This design was further modified and used by Parker et al. (2002) to monitor the progress of permanganate remediation in a sand deposit and by Guilbeault et al. (2005) to monitor solvent plumes in three sand aquifers. These MLS are used in cohesionless sand aquifers that do not require seals between the ports. Collapse of sand around the device is relied on to avoid preferential vertical flow along the outside of the tubing bundle. This type of monitoring system cannot prevent preferential vertical flow in the borehole annulus when installed in geologic materials such as rock, clay, or layered sediments that do not provide rapid, complete collapse. In addition, they are generally not well suited for measurements of hydraulic head.

In the 1980s, MLSs were developed for other geologic systems and a few designs became commercially available. Black et al. (1986) described the first commercially available multilevel system (Westbay Multiport System; www.westbay.com) for monitoring hydraulic head and ground water chemistry. The Waterloo System™, as described by Cherry and Johnson (1982), became available commercially from Solinst Canada Ltd. (www.solinst.com) in 1987. The Water FLUTe System™ (Parker et al., in submittal; www.flut.com) was next to gain acceptance in North America, followed by the Continuous Multichannel Tubing (CMT) System™ presented by Einarson and Cherry (2002; and www.solinst.com). The commercial availability of these diverse types of multilevel systems provides different options for measuring hydraulic head and collecting ground water samples in many types of hydrogeologic conditions. Most are designed for use in relatively deep holes where additional instrumentation such as pumps and transducers are often needed. Einarson (2006) provides a summary of depth-discrete MLSs in common use.

Cherry and Johnson (1982) extended the original Pickens et al. (1978) design for applications in bedrock boreholes and included inflatable packers to form the seals between each monitoring interval. They also incorporated a larger-diameter PVC casing and larger-diameter polyethylene tubing than the Pickens et al. (1978) system, thereby providing access for small-diameter, electric water level probes, but these modifications reduce to seven the maximum number of possible monitoring intervals for sampling and water level measurement.

The MLS described in this paper involves further modification of the Waterloo System. The modified version includes a much larger number of monitoring intervals in each hole to facilitate collection of ground water samples and water level measurements. Reliable, high-resolution seals between intervals are created, so this MLS can be used in shallow holes (<100 m [330 feet]) drilled through both consolidated and unconsolidated material. Alternating layers of sand and bentonite added to the borehole annulus at ground surface form the monitoring intervals and seals, respectively. Einarson and Cherry (2002) describe this method of installing annular seals with MLS.

The new MLS design facilitates manual collection of ground water samples and measurement of hydraulic head. The development of this system was prompted by the recent availability of rotasonic drilling in most parts of North America. Other casing driven methods could be suitable; however, rotasonic has proven to be fast and effective in a wide variety of geologic environments. Rotasonic drilling uses high-frequency vibration to quickly core through unconsolidated soil (Barrow 1994). An outer casing is advanced incrementally to keep the borehole from collapsing, while the core barrel is retrieved. The outer casing minimizes cross contamination of the borehole during drilling, which is especially important when installing MLS in a single borehole. Einarson (2006) provides further discussion of drilling methods used to install MLS. The continuous core and dual casing approach offered by rotasonic drilling complements the on-site design and installation of this MLS. Furthermore, the moderate cost of small-diameter Teflon tubing and increased commercial availability of small-diameter coaxial water level probes permit manual hydraulic head measurements in the smaller-diameter tubing of this new system. Use of tubing with a very low friction coefficient, such as Teflon, is necessary due to the small diameter of the tubing needed to monitor many discrete zones within the MLS, as discussed later.

This version of the Waterloo System allows up to 15 depth-discrete zones for ground water sampling and hydraulic head measurements. It is intended for sites with water levels < 9 m (26 feet) below ground surface (bgs), which are suitable for suction-lift pumping through the small-diameter tubing; the bottom of the monitoring system can be as deep as 100 m (330 feet) and perhaps deeper. The maximum number of intervals (15) is more than double the number used with the original Waterloo System (seven) and the CMT System (seven). In addition, the number of monitoring ports included per borehole in our field studies considerably exceeds those previously reported for multilevel systems in shallow ground water systems where seals are placed between each monitoring interval. Considering the heterogeneous nature of geologic materials and dissolved-phase contaminants at many sites, an additional objective of this paper is to illustrate the importance of the detailed vertical profiles of hydraulic head and contaminant concentrations made possible by this system. Therefore, introductory data acquired with the new MLS at contaminated sites in Ontario, Canada, and Wisconsin are also presented. As the goal of this paper is to introduce the modified Waterloo System, detailed descriptions of collection, analysis, and discussion of the data from the two field sites are reserved for future papers.

Description of the Multilevel Monitoring System

Like the original Waterloo System, this modified version consists of a bundle of tubes contained within a 56-mm outer diameter (OD) by 50-mm ID (2 3/8 by 2 inches) hollow casing (Figure 1). The casing is available in three different lengths of flush joint PVC pipe (0.3, 0.6, and 1.5 m [1, 2, and 5 feet]) and has port segments that are 15 cm (6 inches) long made of stainless steel or PVC (Figure 2B). There is a bore plug at the bottom. The casing sections, ports, tubing, and other necessary materials are all commercially available off the shelf. The ends of each section of casing fit any of the other sections and include an o-ring to keep water from moving in and out of the riser casing (Figure 2A). Nylon shear wires further hold the interlocking sections together, completing a leakproof joint tested to a tensile load of 900 kg (1984 pounds) and leak tested to 1375 kPa (200 psi) (www.solinst.com). The combined sections form a continuous, rigid, sealed casing that prohibits water from getting in or out, and encases and protects tubes extending from the ports to the surface. However, if a leak occurs at any joint, there is still hydraulic isolation between the ground water in the formation (i.e., outside the casing that is being subjected to sampling) and any water inside the casing because the tubes connect only at the ports.

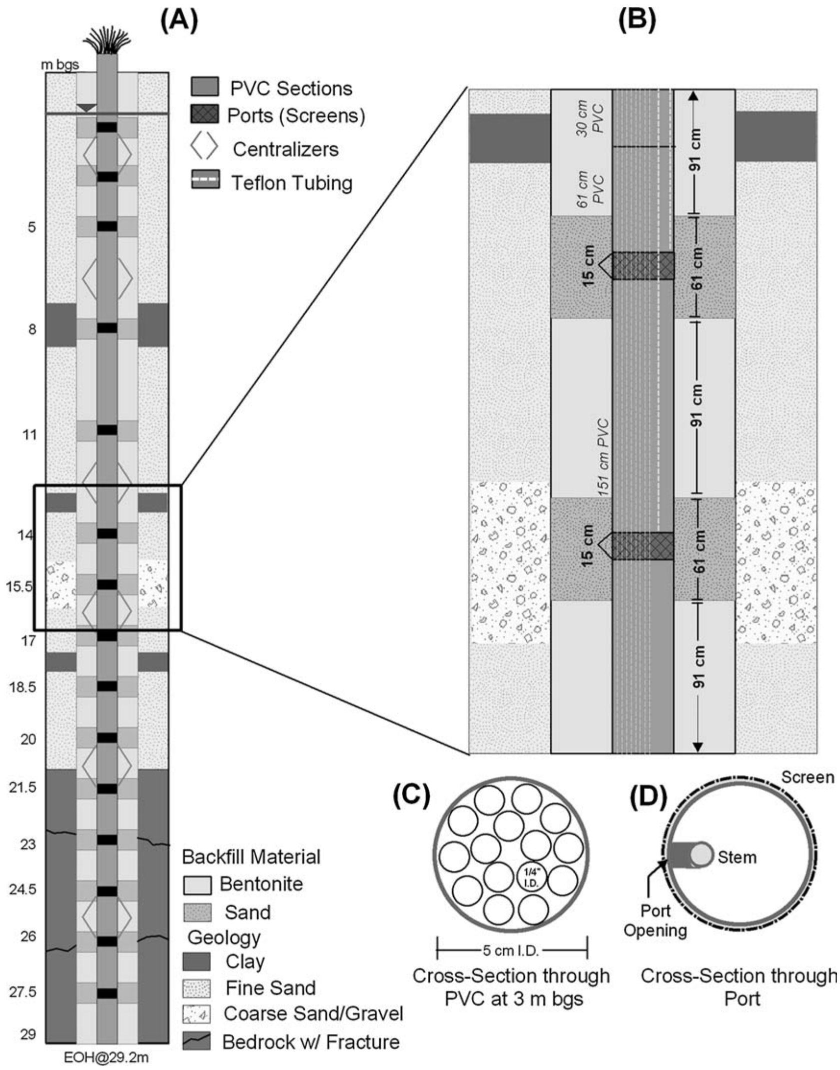


Figure 1. Schematic representation of the modified Waterloo System (not to scale). (A) Fifteen ports system with monitoring intervals finished at different depths and monitoring varying geologic features (gravel, clay, fractures, etc.); (B) sand pack screens and bentonite seals form the monitoring intervals; (C) cross section through PVC at 3 m bgs shows bundle of 15 tubes inside the 5-cm-ID–PVC riser casing; (D) cross section through port showing wire-mesh screen wrapped around the outside and the stem on the inside.

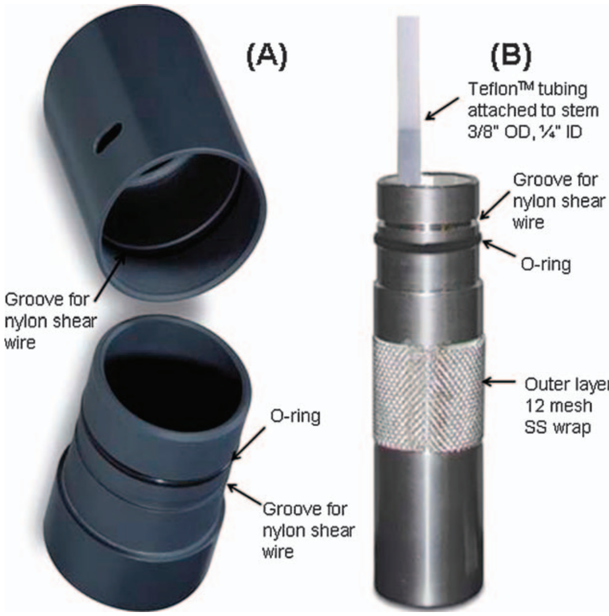


Figure 2. (A) Waterloo System flush-mount PVC joints showing o-ring and channel for nylon shear wires; (B) photograph of single stem, stainless steel Waterloo System port section. Courtesy of Solinst Canada, Ltd.

Each port (Figure 2B) has a hole that is open to a monitoring interval. A 90° elbow stem, contained inside the port unit, connects this opening to a piece of 10-mm-OD × 6-mm-ID (3⁄8 × ¼ inch) Teflon tubing, which extends from the port to ground surface. An Oetiker® clamp attaches the tubing to the stem inside of the casing. The outside of the port section is wrapped in fine, stainless steel wire mesh (double wrapped with 50 mesh and single outside wrap with 12 mesh) that covers the stem hole, keeping out sand from the formation or sand pack placed during well construction.

A sand pack placed in the annular space between the port section and borehole wall connects each port hydraulically to a vertical section of the subsurface outside the casing. The length of sand pack establishes the monitoring interval, with the port typically placed near the center. Bentonite seals are placed between successive sand packs to hydraulically isolate monitoring intervals. The modular construction and the varying lengths of PVC sections allow ports and, therefore, monitoring intervals, to be placed at almost any desired depth within a hole, provided the spacing between each interval is large enough to accommodate a sufficient seal. Based on the dimensions of the monitoring ports, each monitoring interval can have a minimum length of 15 cm (6 inches); however, this minimum leaves little room for measurement errors or other problems encountered during the backfilling process, such as settling or the addition of too much annular fill material. The practical experience obtained at the two study sites indicates that lengths substantially longer (i.e., 46 cm [1.5 feet]) than the minimum for the sand pack and bentonite seals are needed to provide sufficient vertical space to properly place the annular fill material. Sand pack lengths should be kept as close to this practical minimum as possible to avoid blending of contaminant concentrations and hydraulic head within the monitoring interval, thereby keeping the intervals discrete.

The smaller-tubing diameter allows for a maximum of 15 tubes within the PVC riser casing, providing 15 monitoring intervals. Each individual tube acts as a miniature well finished at a different depth. The tubing connects the monitoring interval to the top of the well where vertical hydraulic head measurements (water levels) can be obtained using a commercially available, small-diameter coaxial water level probe (e.g., available from Solinst Canada, Ltd., www.solinst.com; Slope Indicator, www.slopeindicator.com; and Heron Instruments Inc., www.heroninstruments.com). Ground water samples can be retrieved using a peristaltic pump.

Because Teflon has one of the lowest coefficients of static and dynamic friction of any solid and is also relatively inert to most chemicals (www.teflon.com), use of Teflon tubing facilitates insertion of water level measurement probes to great depth and also reduces adverse interactions between contaminants and tubing walls (Parker and Ranney 1997, 1998). At the initial trial MLS in Wisconsin, a Solinst 3-mm (1⁄8-inch) diameter coaxial water level measurement probe was inserted to 14 m (45 feet) bgs within one of the Teflon tubes, a depth that we have found difficult to achieve using polyethylene tubing of the same diameter. If fewer monitoring depths are required, larger-diameter tubing can be used in this system. Larger tubing reduces frictional resistance between water level probes and tubing walls, making water level measurements easier and allowing the use of less expensive tubing materials (e.g., polyethylene). Additional pumps and instruments, such as check valve (Waterra™) pumps, bladder pumps, or pressure transducers, can be inserted into tubes with inside diameters as small as 10 mm (3⁄8 inch), and larger diameters may allow for pumping tests or slug tests for each monitoring interval if appropriate consideration is given in the data analysis with regard to the geometry of the test conditions. However, increasing the diameter of the tubing by only 3 mm (1⁄8 inch), from 10 mm (3⁄8 inch) to 13 mm (½ inch), reduces the number of possible monitoring intervals by more than half.

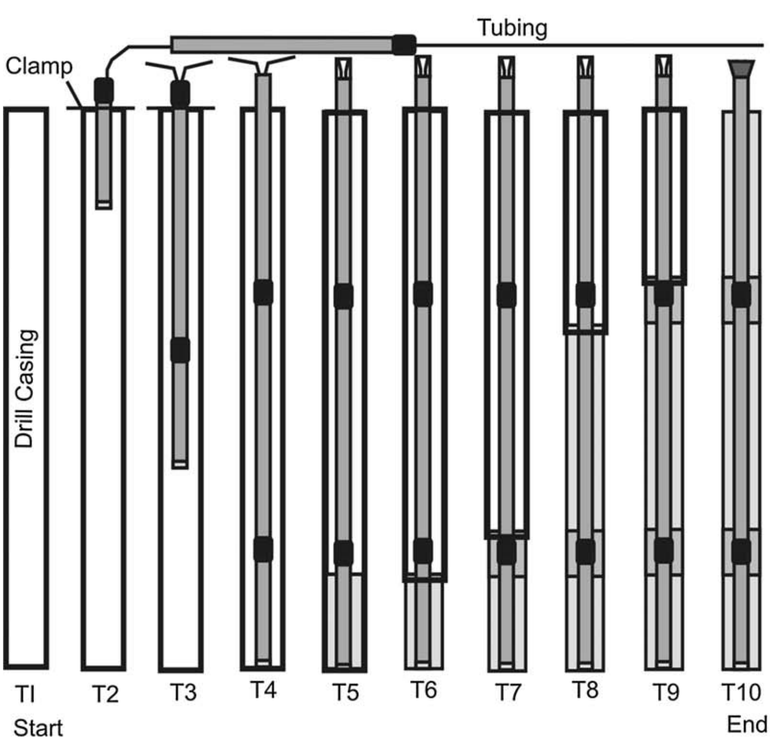
Installation

Installation of the modified Waterloo System with seals between each monitoring interval requires a temporarily cased borehole to allow accurate placement of sand packs and bentonite. The inside diameter of the casing should be 13 cm (5 inches) or larger for proper placement of the sand packs and bentonite seals installed by the backfill method described subsequently. To date, installations have relied on rotosonic drilling using a 16.5-cm-OD × 15.2-cm-ID (6.5 × 6 inches) core barrel. The rotasonic drilling method is well suited for the installation because it advances temporary steel casing down the borehole as drilling progresses and is capable of drilling through boulders and into bedrock (Einarson 2006). The casing keeps the borehole open during the insertion of the multilevel system and placement of the bentonite seals and sand packs. The outer steel casing is incrementally retracted as the seals and sand packs are placed. Rotasonic drilling also provides continuous cores for logging and subsequent MLS design. Six-inch-diameter core barrels (16.5-cm OD × 15.2-cm ID) are relatively standard on rotasonic drill rigs and provide the optimum-sized annulus to deliver the sand and bentonite with this MLS. Borehole diameters > 20 cm (7.5 inches) are a disadvantage because of the excessive purge volumes imposed by the sand pack. Other drilling methods, such as hollow-stem auger and mud rotary, may create conditions conducive to borehole cross contamination, reduced permeability, and other difficulties (see Einarson 2006). These methods may also produce holes either too large (e.g., hollow-stem augers) or too small (e.g., DP) to place reliable seals via the backfill method.

Another advantage of rotasonic drilling is that the continuous core can be geologically logged immediately as it comes out of the hole. Core logging is usually done as drilling progresses, but if more detailed observation is required, most field conditions allow the hole to be left open overnight with the drill casing in place. The borehole log can be used to tailor the design of the MLS to the site-specific conditions, a process that takes about 1 h. Ports can be positioned to monitor specific zones of interest identified in the core description.

The multilevel system is assembled in sections and lowered down the borehole incrementally (Figure 3, T1 to T4). This process begins by fitting together appropriate sections, including an end cap attached to either blank casing or the bottom port. The initial assembled unit is then lowered down the hole until this first port is situated just above the top of the drill casing, where it is temporarily clamped in place. The next port and its associated PVC sections are then assembled, slid over the previously connected tubing, attached to the first port, and then lowered until the second port is just above the top of the drill casing. A new monitoring tube is connected to each new port as the port is put into position. The process is repeated until all the ports are in the ground and the system rests on or is suspended near the bottom of the hole. Centralizers are attached to the MLS casing every 3 m (10 feet) as it is being assembled and inserted. Centralizers are used to hold the casing in the center of the hole, thereby avoiding gaps in the bentonite seal. An as-built checklist is valuable to verify and document the sequence of MLS components as they are put together and lowered down the borehole.

Proper management of the tubing is essential during system installation. Tubing is cut a few meters longer than the designed depth (including the final riser casing stickup height) and marked with its corresponding port number at both ends. During installation, tubing is kept as straight as possible, avoiding kinks and twists that hinder the later insertion of water level probes and add to measurement errors. These errors should be small if the casing is nearly full of tubing, thereby limiting the space inside the casing for the tubes to twist, kink, or sag during assembly and installation. Using fewer small-diameter tubes increases the free space inside the casing, which increases the possibility of producing these tubing problems. Once the MLS is built, the tubing should be cut to just above stickup height, taped into a tight bundle, and then covered with plastic and an extra PVC section with the top sealing taped



Step	*Description of Installation Activities*
T1	•Empty drill casing ready for instrument installation
T2	•First port unit (base-plug, PVC, Port) inserted and clamped at top of hole. •Second unit slid over tubing of first unit.
T3	•Second unit inserted and clamped at the top of the drill casing.
T4	•Entire instrument installed and placed down the borehole.
T5	•Tubing is capped and bentonite is poured down the annulus forming the first seal.
T6	•Drill casing is lifted to just below the top of the first bentonite seal.
T7	•Sand is poured down the annulus forming the first monitoring interval. •Casing is lifted to just below the top of the sand pack.
T8	•Bentonite is poured down the annulus forming the second seal. •Casing is lifted to just below the top of the seal.
T9	•Sand is poured down the annulus forming the second monitoring interval. •Casing is lifted to just below the top of the sand pack.
T10	•Bentonite added to surface and casing removed. •Tubing is arranged in the manifold. •Installation complete.

Figure 3. Well installation sequence. T1 to T4 show well installed into hole, and T6 to T10 depict general sand pack and bentonite seal formation as the casing is withdrawn.

closed. This cap ensures that no backfill material enters the tubing as it is poured down the annulus.

In the field, assembly and insertion, prior to backfilling, of a 25-m (85-feet) long MLS with 15 ports took a five-person team composed of three technicians and two drill rig personnel between 1.5 and 2.5 h. One person fits the ports and casing sections together, one cuts and attaches tubing, one strings each successive port unit over previously attached tubing, and the drill rig operator and assistant keep the tubing straight and lower the system down the hole. Smaller teams can accomplish an installation, but more time is needed to complete the task (Randy Blackburn, personal communication, 2005). The drill rig must remain over the hole during the installation, which creates a trade-off in different time costs between fewer persons performing the installation at a slower pace and the accumulation of drill rig standby time.

Once the MLS is fully inserted into the borehole, the annular space between the MLS and the borehole is backfilled with alternating layers of sand and bentonite. At the two demonstration sites, industrial drillers' sand and 3/8-inch bentonite chips (Holeplug™) were used to form the monitoring intervals and seals, respectively. The layers were formed by pouring the sand pack material and bentonite chips down the water-filled annulus as the steel drill casing was gradually removed (Figure 3, T5 to T10). At each stage and after waiting the appropriate length of time for settling to the targeted fill-depth, a measuring tape attached to a steel weight was used to determine the depth of the top of the annular fill material in the casing and to ensure complete settling before the casing was pulled up to the next interval. Confirming the depth of the annular fill materials after each addition of sand and bentonite was required to avoid the addition of too much or too little of each type of material and to provide the "as-built" dimensions for each of the port and seal lengths. This critical step was needed to ensure that the borehole is sealed between the monitoring zones, thereby preventing vertical flow of ground water and cross contamination between zones. Each port was positioned near the middle of the sand pack, and the sand packs were separated from one another by at least 46 cm (1.5 feet) of bentonite. The uppermost sand pack was capped by a bentonite seal to the ground surface. Backfilling typically took approximately 1 h for every 3 m (10 feet) of borehole, although deeper holes took longer due to the longer settling rate of the bentonite chips in the water column in the casing.

Pouring sand and bentonite chips down the borehole annulus to form the sand packs and seals imposes practical limits on the depths of these types of multilevel well installations. Deeper holes require longer settling times for the annular fill material falling through the water-filled casing, and the swelling and softening of bentonite chips also increases with increasing fall distance within the borehole water column. This swelling may increase the likelihood of smearing bentonite over the port screens or forming bentonite bridges between the MLS casing and the steel drill casing. Borehole depths at the two field sites where these multilevels were installed ranged between 18 and 33.5 m (60 and 110 feet) deep, but experience with the CMT System indicates that depths of 100 m (330 feet) or more are achievable (M.D. Einarson, personal communication, 2005).

The formation of bentonite bridges inside the temporary casing, where bentonite collects and blocks the annular space between the MLS casing and the steel drill casing at a shallower depth than desired, can easily occur when using this backfilling method. Great care and patience are required as backfilling progresses. Bentonite chips must be added slowly and allowed to settle, and frequent depth measurements must be performed to ensure that the material is in the correct location and that a good seal will form. If minor bridging occurs, it can be remedied by vibrating the casing with the rotosonic drill rig, which is an advantage of the rotasonic drilling method over other drilling methods, or by using water or compressed air to blow out the bridge through a tremie pipe. However, it is best to avoid bridging by gradually adding the annular fill materials (i.e., slow, steady feed) and verifying position of top of fill by tamping every few feet and when transitioning from sand to bentonite or visa versa. Although not used at the demonstration sites, coated bentonite pellets are available that provide advantages for deeper holes with long water columns. The coating on the pellets limits bridging by slowing the swelling of the bentonite pellets as they fall through the water in the annulus. Additional precautionary measures include calculating sand or bentonite volumes required for each layer (to avoid pouring too much material down the annulus) and determining settling velocities of the annular fill materials to estimate the timing of additional pouring.

During installation of the first multilevel system at the Ontario demonstration site, one port was lost due to the suspected smearing of bentonite over a port screen. At the Wisconsin site, the initial trial MLS, MP9, lost the upper five ports due to bentonite bridging and likely collapse of the bridge due to the weight of the overlying annular fill material. Pouring bentonite down the annulus too quickly, primarily due to the inexperience of the installation crews, created both problems. Further problems were averted by reducing the speed and volume of each bentonite addition to the annulus.

After the entire construction process is complete (including backfilling), the tubing should be attached to a manifold that separates and clearly identifies the tubes and associated monitoring depths. Then, it is commonly necessary to purge the system before collecting samples for analysis. For purging, the port tubes can be connected to a peristaltic pump via a tubing connector or pump tubing and developed by pumping the wells for an extended time (e.g., 20 min or more). In a sand pack with 30% porosity in an interval 90-cm (3-feet) long with 5 cm (2 inches) separating the riser casing from the drive casing, the volume of water is 4.4 L. An additional 0.5 L is stored in 15.2-m (50-feet) long by 6-mm (¼-inch) ID tubing, for a total of 4.9 L, which is the estimated value representing one purge volume of this port. For monitoring intervals in permeable zones, purging of one or more purge volumes is readily accomplished by continuous peristaltic pumping until the desired volume is acquired. However, for monitoring intervals in low-permeability zones, the purge time is much longer. When purging, the water level in the tube should not be lowered so deep as to cause dewatering of the sand pack. Therefore, it is necessary to draw water from the tubing and then wait for recovery in the tubing and draw water again until the desired total purge volume is accumulated. The waiting time is inversely dependent on the hydraulic conductivity of the formation around the sand pack. For example, for the port dimensions indicated previously, 1 m of tubing provides 0.03 L, and a 10-m drawdown in the tubing in a very low conductivity interval (e.g., 5×10^{-8} cm/s) will require 0.74 d for 90% recovery and 0.22 d for 50% recovery. If the monitoring interval is longer, the recovery times will be shorter.

In some hydrogeologic settings, it may be feasible to install the modified Waterloo System in small holes, for example, using 1.5-cm (3-inches) ID DP casing. However, the smaller casing creates difficulties with installation of the sand packs and seals, and the smaller-diameter sand pack also increases the time necessary for slug tests and purging from low hydraulic conductivity zones. For example, for the case indicated previously (where a 10-m drawdown in a 5×10^{-8} cm/s zone requires 0.74 d for 90% recovery and 0.22 d for 50% recovery), the smaller-diameter sand pack results in 0.93 and 0.29 d, respectively.

The appropriate volume of water that should be purged from any particular monitoring interval prior to sample collection depends on several factors, and the specification of this volume is not subjective. Typically, the goal of sampling is to determine the concentrations of contaminants or other constituents in the formation (i.e., in the geologic medium) in the domain immediately beyond the sand pack. Hence, in concept, it is desirable to remove all of the initial water in the sand pack and tubing once before the sample is collected. However, this will likely not be accomplished by pumping one system volume because there will be heterogeneity of hydraulic conductivity in the formation causing preferential flow from the most conductive zones into the sand pack. Depending on the position of the port relative to the most conductive zones, the purging of one system volume will likely result in some prepurge water (i.e., initial water) persisting in the sand pack. Therefore, the second purge volume and even later purge volumes could be a mixture of the initial water and formation water. This conceptual consideration of the purging issue leads to the conclusion that ground water samples providing results most representative of the formation hydrochemistry are acquired from monitoring intervals that are relatively short. Therefore, use of monitoring intervals that are at or not much longer than the practical minimum can be appropriate, particularly for monitoring in hydrogeologic environments with substantial heterogeneity in hydraulic conductivity and/or spatial variability of chemical concentrations.

Quantitative Considerations

The MLS described in this paper is designed to obtain information about the hydraulic head distribution and the water chemistry in geologic media where reliable borehole seals are needed between the monitoring intervals. The modified version of the Waterloo System offers distinct advantages for overburden applications, particularly at sites where low hydraulic conductivity zones (i.e., aquitards) occur above aquifers, or separate shallower and deeper aquifers.

Cherry et al. (2006) indicate that aquitards commonly have substantial hydraulic head differences from top to bottom because they provide the main resistance to flow in aquifer-aquitard systems. Those authors draw attention to two field studies (Einarson and Cherry 2002; Eaton and Bradbury 2003) showing aquitards where almost the entire head differential occurs across a thin zone within the aquitard. The portion of the aquitard with the largest head decline (i.e., largest vertical component of the hydraulic gradient) corresponds to the zone with the lowest vertical hydraulic conductivity (K_v). In the two aquitards indicated previously, the zones most resistive to vertical flow had vertical hydraulic gradients much larger than one (7.5 m/m and 10 m/m, respectively). The zones of high resistance to vertical flow could only be identified from head profiles that were defined using a large number of small-length monitoring ports in the aquitards.

For situations where the vertical head differential causes ground water flow across an aquitard to be primarily vertical, the highest hydraulic gradient must exist across the zone or layer with the lowest K_v. The use of the harmonic mean to represent the bulk K_v incorporates all of the vertical K_vs for the layers constituting the aquitard (Freeze and Cherry 1979, 33). For example, consider a hydrogeologic unit comprising a horizontally layered sequence of beds each with vertical hydraulic conductivity designated as K_1, K_2, K_3, …, K_n and with corresponding thicknesses of l_1, l_2, l_3, …, l_n. If steady state, vertical flow occurs across the hydrogeologic unit, the ground water flux (i.e., Darcy velocity) q is the same across each layer ($q_1 = q_2 = q_3 = q_n$). Therefore, the total head differential (Δh_T) across the layered hydrogeologic unit is:

$$\Delta h_T = \Delta h_1 + \Delta h_2 + \ldots + \Delta h_n \tag{1}$$

Using Darcy's Law gives:

$$\Delta h_T = q_1 \frac{l_1}{K_1} + q_2 \frac{l_2}{K_2} + \ldots + q_n \frac{l_n}{K_n} \tag{2}$$

which can be rearranged to:

$$\frac{\Delta h_T}{q} = \frac{l_1}{K_1} + \frac{l_2}{K_2} + \ldots + \frac{l_n}{K_n} \tag{3}$$

Therefore, for a hydrogeologic unit in which the individual bed thicknesses do not differ greatly from one another, a bed with a K_v2 orders of magnitude smaller than any of the other beds is responsible for nearly all (>99%) of the total head drop. Because aquitards can consist of silty sand, silt, or clay, variations in K_v from bed to bed exceeding 2 orders of magnitude are likely common because the K_vs typical of these materials span several orders of magnitude.

The continuous core provided by rotasonic drilling and the additional ports available with the modified Waterloo System offer a means of detecting and directly monitoring these low hydraulic conductivity zones above, below, and within an aquitard. As discussed previously, vertical profiles of hydraulic head are essential data for understanding the ground water system that cannot be obtained from geologic core alone. In addition, detailed vertical head profiles *by themselves* can often be extremely useful to identify thin aquitards that constitute strong impediments or barriers to vertical ground water flow. The vertical head profile may identify a thin, low hydraulic conductivity unit in an interval where no core was recovered, and even when core does exist, there are unidentified core textures such as fractures that can govern vertical ground water flow and therefore have strong influence on the head profile.

Where monitoring head and water chemistry *within* low hydraulic conductivity layers is necessary or appropriate (e.g., Cherry et al. 2006), time lags and low sampling volumes associated with slow water level recovery times must be considered. Time lags are introduced into water level measurements if the volume of water required to register a head change in a piezometer standpipe is large relative to the rate of entry at the intake (Freeze and Cherry 1979). To entirely circumvent this problem, downhole pressure transducers must be used, but at increased cost for the MLS, particularly those with many monitoring intervals. Although the modified Waterloo System does not eliminate time lags when used in low hydraulic conductivity media, the lag is minimized due to the combination of small-diameter tubes and the larger sand pack diameter created by installation of the system in rotosonic holes.

Relatively short-term lags are achieved when 6-mm (¼-inch) ID tubes are used in combination with large-diameter sand packs. Flow across the large surface area of the OD of the sand pack supplies water relatively rapidly to the small reservoir offered by the tubing. For example, consider a monitoring interval in a clayey layer with a very low hydraulic conductivity of 5×10^{-8} cm/s. The static water column in the 6-mm (¼-inch) tube is 10 m, the sand pack diameter and length are 15 cm (6 inches) and 61 cm (2 feet), respectively. A slug test is performed in which a 1-m (3.3-feet) head rise in the tube is imposed instantaneously. In this case, 90% water level equilibration toward the initial static level occurs in 0.9 d and 99% after 1.8 d (Table 1). Therefore, a slug test to measure hydraulic conductivity can be performed by measurement of a few water levels during a day or two (50% equilibration is commonly adequate to calculate the K value). In contrast, if the tubing diameter in the previous scenario is increased to 13-mm (½-inch) ID and the hole diameter reduced to 76 mm (3 inches), then the equilibration time will be much longer (10 d for 99% equilibration for a 1 m [3.3 feet] slug test; see Table 1).

Results and Discussion

Ontario Site

The first modified Waterloo Systems were installed at an agrichemical facility in Cambridge, Ontario, in May 2004. Various herbicides, insecticides, fungicides, fertilizers, and other chemical products were formulated and packaged on the property, and accidental releases of some of these chemicals caused soil and ground water contamination in the immediate area. The contamination, primarily metolachlor and trichloroethylene (TCE), reached the underlying dolostone bedrock, which is also the regional aquifer that functions as the primary water supply for the City of Cambridge (Carter et al. 1995).

The geology consists of a complex sequence of unconsolidated Quaternary glacial sediments overlying Silurian dolostone (Carter et al. 1995). The unconsolidated material is primarily fine sand, coarsening to medium sand toward the base of the unit. There are, however, discontinuous layers of clay, silt, and gravel within the Quaternary sediments. The total thickness of these Quaternary deposits ranges from 25 to 40 m (80 to 130 feet). Carter et al. (1995) also describe a layer of glacial till composed of a mixture of silt, sand, gravel, and clay lying on the bedrock surface. The lateral continuity of this unit and its characteristics are important with respect to the migration of contaminants through the Quaternary deposits into the underlying dolostone aquifer. Although many boreholes were drilled through the overburden during previous

Table 1
Equilibration Times and Sample Volumes Provided by Two Multilevel System Designs: (1) 6-mm (¼ inch) ID Tubes and 15-cm (6 inches) Diameter Sand Packs of Two Lengths, 61 cm (2 feet) and 122 cm (4 feet) and (2) 13-mm (½ in) ID Tubes with 7.6-cm (3 inches) Diameter Sand Packs, Also with 61-cm (2-feet) and 122-cm (4-feet) Lengths

	Hole Diameter	7.6 cm (3 inches)				15.2 cm (6 inches)			
		90%	99%	$\Delta h = 1$ m 100 mL	$\Delta h = 5$ m 100 mL	90%	99%	$\Delta h = 1$ m 100 mL	$\Delta h = 5$ m 100 mL
Sand Pack Length	Recovery (%) Tubing Diameter (ID)	Recovery Time (d)				Recovery Time (d)			
61 cm (2 feet)	6 mm (¼ inch)	1.2	2.4	**	0.12	0.90	1.8	**	0.09
	13 mm (½ inch)	4.9	9.8	1.4	0.24	3.7	7.4	1.1	0.18
122 cm (4 feet)	6 mm (¼ inch)	0.75	1.5	**	0.07	0.60	1.2	**	0.06
	13 mm (½ inch)	3.0	6.0	0.90	0.15	2.4	4.8	0.72	0.12

Note: ** = greater than three recovery periods required.

investigations, there has been much uncertainty about ground water flow within the complex glacial deposits, especially concerning the degree to which the basal till layer may impede the flow of ground water (and hence dissolved contaminants) from the Quaternary deposits into the underlying dolostone aquifer.

Three rotasonic holes were drilled to determine the presence and continuity of this glacial till unit, and 15 port modified Waterloo Systems were installed in each of the holes to collect hydraulic head data for examining ground water flow throughout the full thickness of the ground water zone between the water table and bedrock, especially through the basal till. The holes were located adjacent to existing bedrock monitoring well clusters. Most ports were placed with similar spacing through the thick layers of sand found throughout the Quaternary deposits, but some were positioned at changes in sediment type. The length of the monitoring intervals ranged between 35 and 160 cm (1.2 and 5.2 feet), with an average of 75 cm (2.4 feet). Bentonite seals ranged between 20 and 240 cm (0.6 to 8 feet) in length.

Vertical profiles of hydraulic head measurements were obtained from the three MLS (Figure 4). The profiles from UW2-OB and UW4-OB show two distinct segments: a large downward and constant gradient in the upper zone and almost no vertical gradient in the lower zone. Conventional well clusters on-site substantiate the occurrence of minimal vertical gradient across the lower zone over much

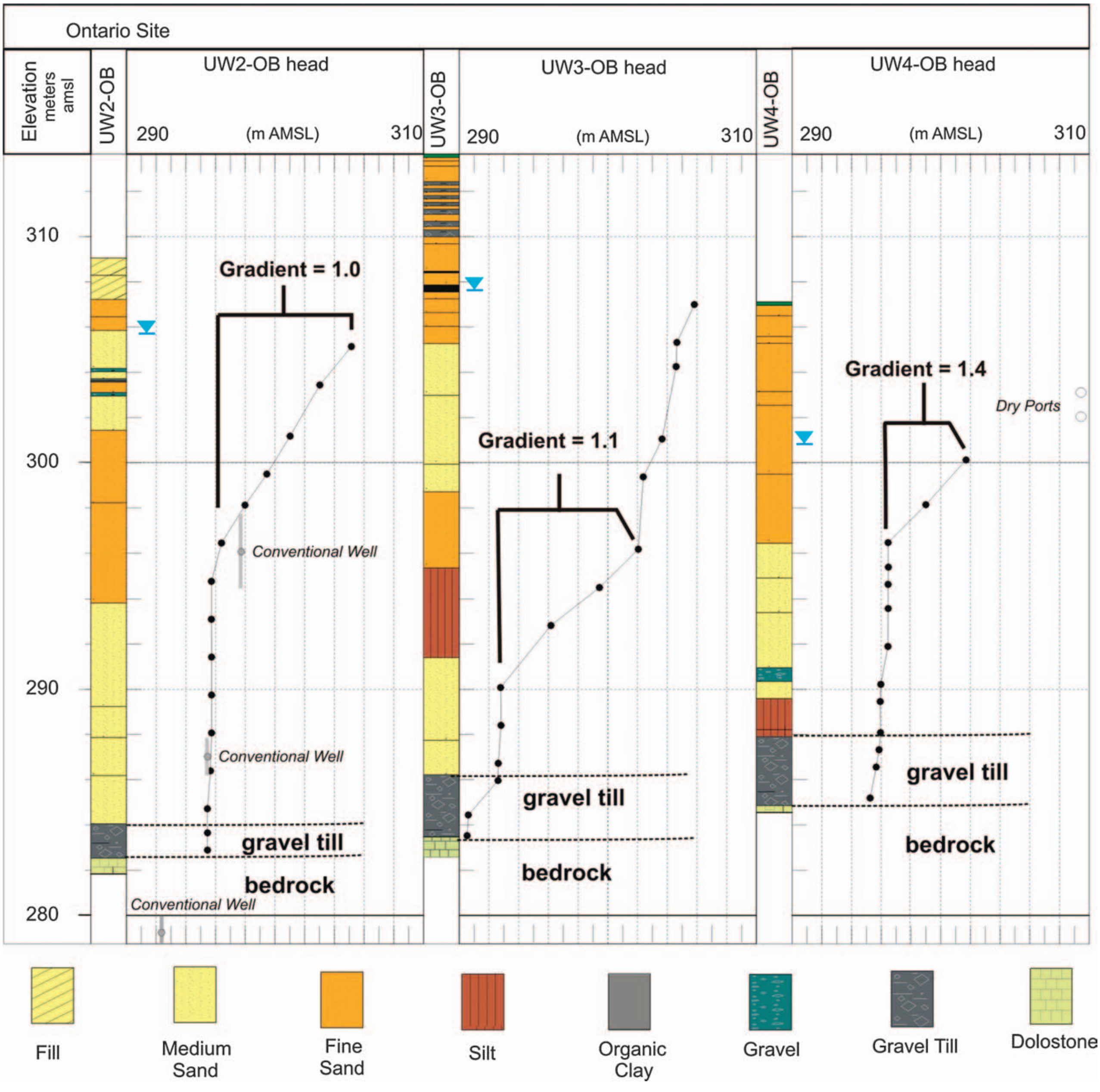


Figure 4. Hydraulic head profiles for the Ontario site show little head differential across the basal gravel till (UW2-OB and UW4-OB). Each MLS exhibits a zone of high head differential with downward vertical gradients > 1 m/m. The presence of the silt layer in UW3-OB could be used to predict a high-gradient zone, but the head profile for UW2-OB and UW4-OB could not be predicted by the log.

of the site. The third profile (UW3-OB) exhibits two zones of steep downward gradients: one at intermediate depth and one at the bottom. The vertical hydraulic gradients indicated by each of the highest head differential zones are greater than one. Furthermore, the location of these head drops in UW2-OB and UW4-OB indicates that changes in vertical conductivity were not predictable from the core log as the grain size distribution differences responsible for the order of magnitude decrease in hydraulic conductivity values necessary to create the observed head drop are generally not noticeable during core logging. For example, core inspections provided no expectation that there would be a large vertical component of hydraulic gradient in the shallow zone in UW2-OB or in the shallow zone in UW4-OB. However, in UW3-OB, the largest hydraulic gradient occurs across a distinct silt layer. Perhaps, the fine sand indicated by the core logs for UW2-OB and UW4-OB where the large gradients occur has sufficient silt content to cause lower hydraulic conductivity. Two conventional wells near UW2-OB also show a large drop in head with depth, but they do not provide details as to where within the glacial material the drop occurs. This example further supports the need for numerous ports to appropriately establish hydraulic conditions at sites.

The glacial till unit at the bedrock interface was observed in the rotosonic cores at all three holes; however, the lack of strong head decline across the unit at two of the three MLS indicates that this unit does not provide a laterally continuous, low vertical hydraulic conductivity zone along the bottom of the overburden and, therefore, it is likely not a significant barrier to vertical ground water flow between the overlying Quaternary sediments and the underlying dolostone aquifer. Parker et al. (in submittal), who examined the origin of the bedrock contamination, provide additional evidence for this lack of continuous aquitard to impede downward contaminant migration.

Wisconsin Site

From 1950 to 1970, a chemical distributor and recycler operated at the Wisconsin site. Various organic chemicals were handled at the property, including chlorinated aliphatics, aromatics, and ketones. On-site operations led to multiple releases of these chemicals, resulting in pooled and residual nonaqueous phase liquids accumulating in the subsurface, and a subsequent plume of multiple, aqueous-phase contaminants forming within the ground water (Meyer et al. 2004). The ground water plume intersects a man-made pond and drainage ditch situated 330 m (1000 feet) downgradient of the site (Figure 5). The geology at the site is complex, consisting of unconsolidated Quaternary glacial deposits comprising sand with lenses of silt and clay overlying weakly cemented sandstone and dolomite layers. Ground water flow in the glacial unit is primarily east-southeast, with localized flow toward the pond from the north and west and out of the pond to the south (Figure 5).

In an effort to characterize the ground water flow system and dissolved contaminant plume in the vicinity of the pond, six modified Waterloo Systems were installed using the methods described previously. Four of these systems (MP11, MP12, MP13R, and MP14) were placed along a cross section (transect) upgradient of the pond, perpendicular to the predicted ground water flowpath. They are spaced between 45 and 60 m (150 and 200 feet) apart and are set back from the pond between 15 and 18.5 m (50 and 60 feet). The other two multilevels, MP9 and MP10, were

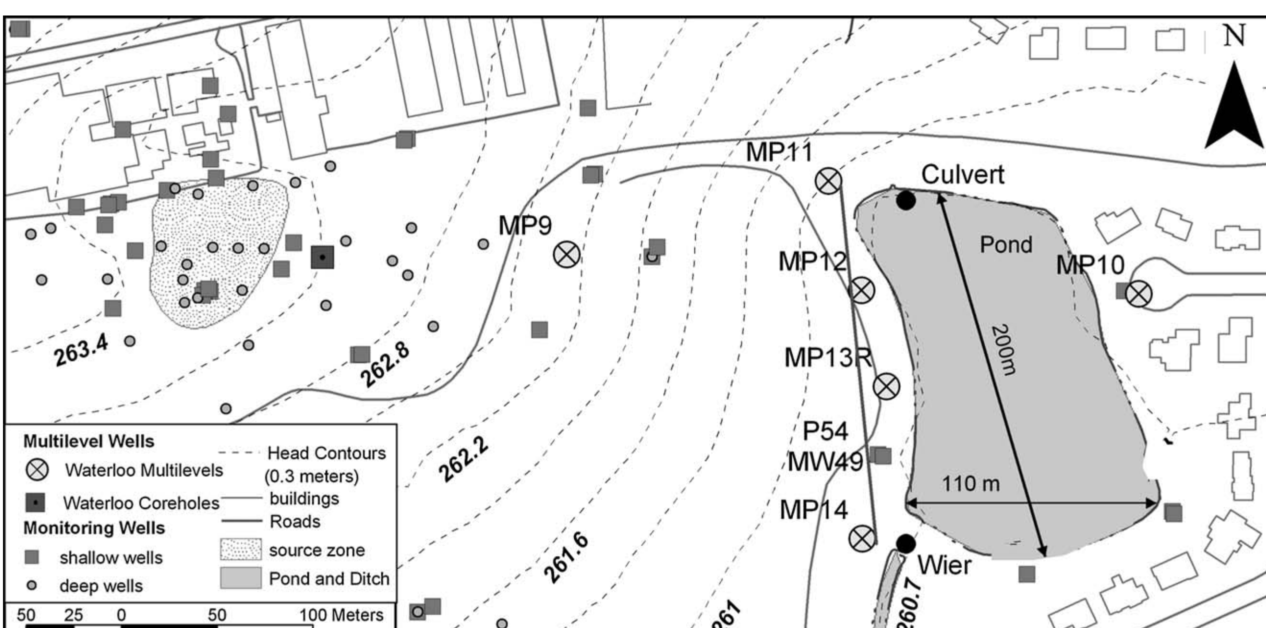


Figure 5. Site map of the Wisconsin field area. Large circles indicate Waterloo MLS locations, and thick black lines are hydraulic head contours for the Quaternary deposits from shallow conventional wells screened between 5 and 15 m bgs (September 7, 2004). The gray line roughly connecting MP11, MP12, MP13, and MP14 represents the transect shown in Figures 6 and 10. Horizontal flow is to the east-southeast from the source zone to the pond. The pond is also receiving ground water from the north and east and losing ground water to the south.

placed along the axis of the plume as part of a longitudinal cross section comprising other on-site monitoring wells located in the "Waterloo Coreholes" (Figure 5).

Each system has 15 ports, although the 5 highest ports at MP9 were unusable (due to bentonite bridging and collapse, as mentioned previously), and the highest port at the other MLS was consistently dry. Ports were located where field screening indicated the presence of contaminants and where features of interest were noted in the cores. The remaining ports were evenly distributed throughout the borehole. Borehole depths ranged from 18.2 to 38.3 m (60 to 110 feet). Sand pack interval lengths ranged from 50 to 170 cm (1.6 to 5.6 feet), although most were between 60 and 75 cm (2 and 2.5 feet); bentonite seal lengths ranged from 30 to 240 cm (1 to 8 feet).

The transect holes were drilled through 16 to 18 m (50 to 60 feet) of glacial sediments and the top 3 to 4.5 m (10 to 15 feet) of bedrock. Although the glacial deposits consist mostly of sand, the rotasonic cores revealed the sediment varies substantially both vertically and horizontally (Figure 6). Thin layers of gravel, sand, silt, and clay were found throughout each core and most could not be correlated to any one layer in the other cores. However, some general groups were delineated and are presented with summary boring logs in Figure 6. Clay till layers, ranging between 15 and 100 cm (0.5 and 3.3 feet) thick, were found in the northernmost transect MLS (MP11), and monitoring intervals were placed above, below, and, in most cases, between these finer units to examine how they affected the hydraulic gradients and contaminant distributions.

Water level measurements were made many times during the field campaign, and Figures 7 and 8 show representative hydraulic head profiles alongside the geologic columns based on core inspection. Each of the eight head profiles shows one or, in three of the MLSs, two distinct intervals exhibiting relatively large hydraulic head differentials (i.e., intervals with largest vertical components of hydraulic gradient). Out of the total of 11 distinct head differential intervals, only 5 coincide with fine-grained layers (e.g. clayey zones) identified on the core logs. The other six intervals occur where the core descriptions provide no evidence of geologic zones with relatively low hydraulic conductivity. For example, in the head profile for MP-13R (Figure 7), the interval of large head differential occurs in a zone of fine sand. However, this is not inconsistent with the geologic log because fine sand is the finest textured

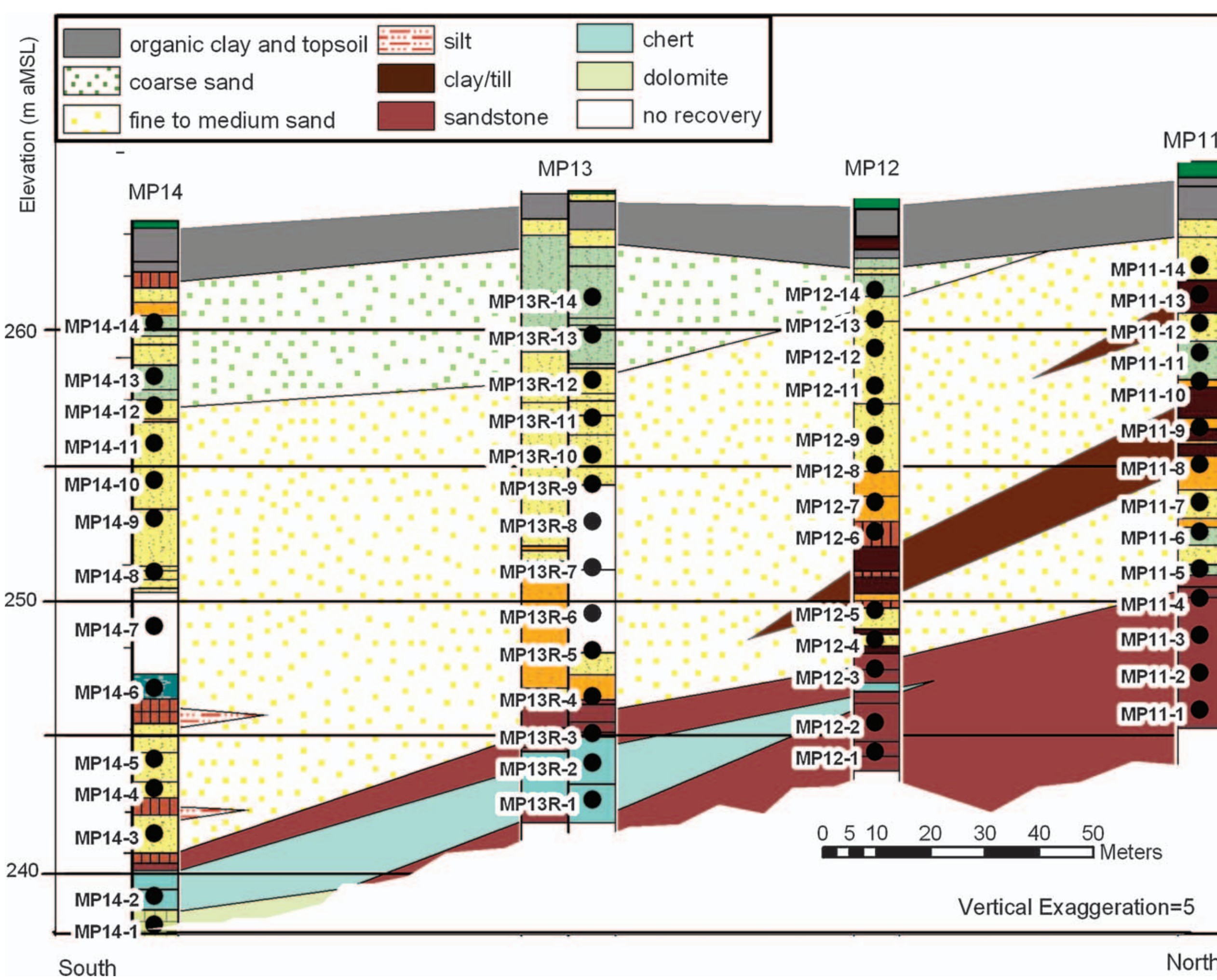


Figure 6. General geology and port locations along the south-north transect, MP14 to MP11. The transect is located just west of the pond at the Wisconsin site. Sand packs range from 0.3 to 1.3 m, averaging 0.7 m (2.3 feet) per port. Labels indicate the locations of the MLS ports discussed in Figure 10.

material in the entire log for this hole. The head profile for MP-10 (Figure 7) also shows a single interval of large head differential. However, in this MLS, a shallow clay layer has no head differential, whereas a deeper zone with thin clay layers just above the top of the rock has a large head differential. The head profile for MP-11 (Figure 7) shows a single interval of large head differential coinciding with a clay layer; however, two other clay layers in this hole with similar thickness have no noticeable head differential across them. Therefore, only one of the clay layers is providing strong resistance to vertical flow at this location. The purpose of measuring hydraulic head in ground water flow systems is to achieve a useful degree of understanding of the ground water flow system.

In addition to water level measurements, ground water samples were collected at each port in all of the MLSs and analyzed for a suite of 20 volatile organic contaminants, including chlorinated ethenes (e.g., TCE, tetrachloroethene, cis-1,2-dichloroethene, vinyl chloride), chlorinated ethanes (e.g., 1,1,1-trichloroethane, 1,1-dichloroethane, chloroethane), ketones (e.g., acetone, methyl ethyl ketone, methyl isobutyl ketone), and BTEX compounds (e.g., benzene, toluene, ethylbenzene, xylene). A peristaltic pump drew water from the port, through a length of Teflon tubing dedicated to the port, and a stainless steel sampling manifold containing 40 mL volatile organic analysis sample vials. The pump was connected downstream of the manifold, thereby avoiding contact between the ground water sample and the pump tubing, as well as any exposure to air. Also, the samplers took care to eliminate air pockets (no headspace) when screwing on sampling lids, and the lids were sealed with Teflon tape. Between

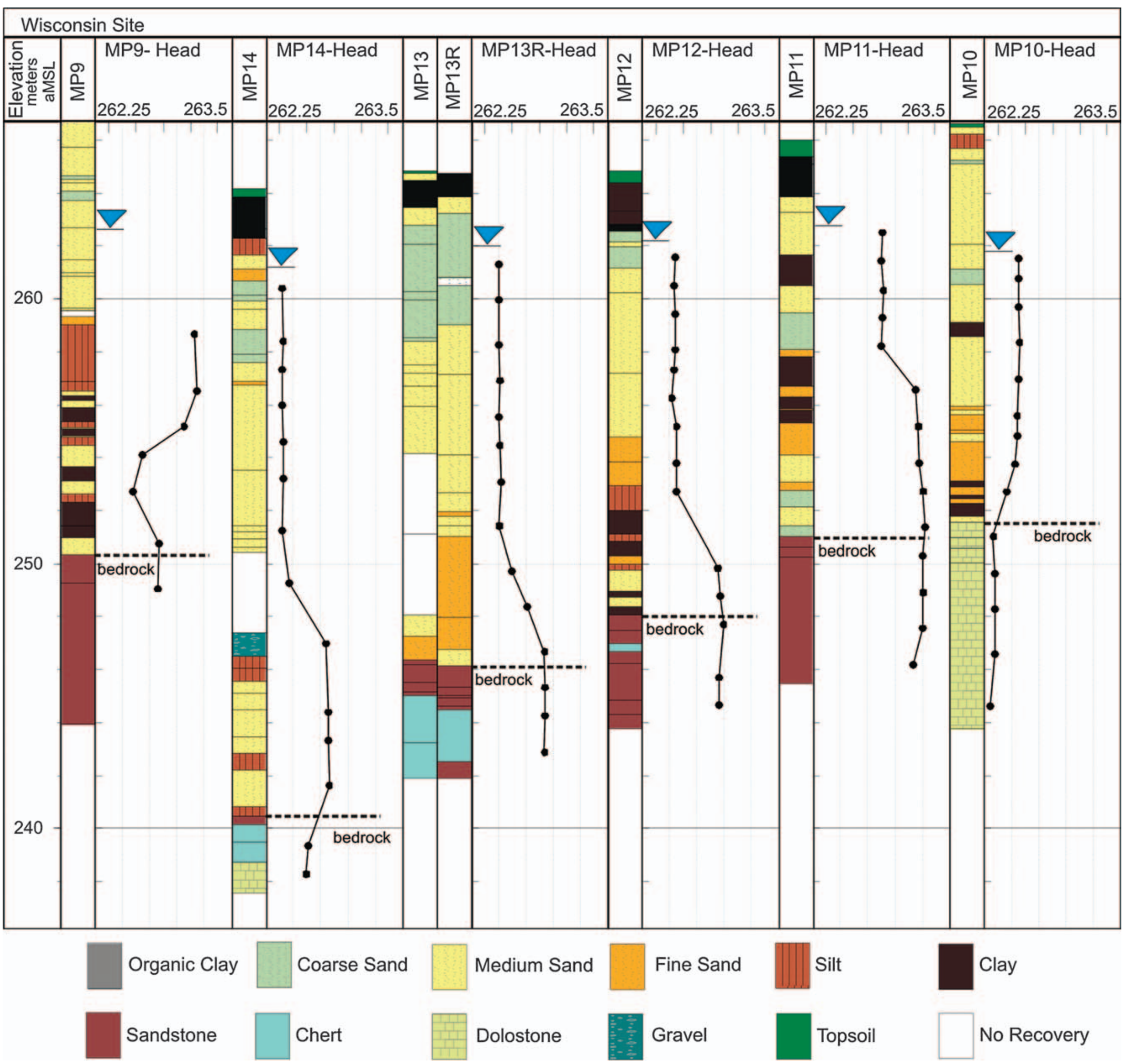


Figure 7. Hydraulic head data for MP9 to MP14, Wisconsin site, show upward gradients along transect wells (MP14 to MP11, center) and downward gradients in longsect wells (MP9 an MP10). Steep hydraulic gradients exist across clay layers in MP9, MP11, and MP12, and across the fine sand in MP13R. Water levels were measured on September 7, 2004.

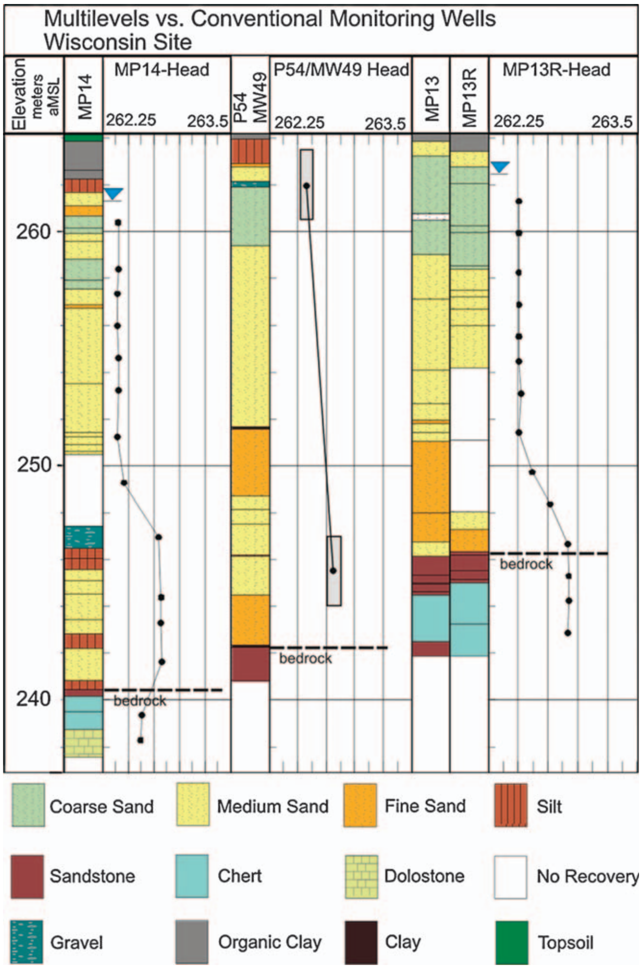


Figure 8. Comparison of head data from multilevels MP14 and MP13R with conventional well pair P54 and MW49 (September 7, 2004). The conventional well pair and the MLSs all show upward gradients, but the MLSs indicate where the head changes are occurring and provide information on general flow patterns. MP14 also shows a downward gradient into the underlying bedrock not reached by the conventional wells.

sampling each port, the manifold and pump tubing were washed with 50 mL of methanol, followed by 500 mL of distilled water, and then flushed with purge water. Purge volumes were between 1.4 to 7.8 L, with an average of 4.9 L (±1.2). Samples were packed on ice and sent overnight to the organic chemistry laboratory at the University of Waterloo where they were analyzed using standard EPA preparation method SW846 5030B and EPA analytic method SW846 8260B.

The vertical profiles representing contaminant concentrations in the MLSs on the transect have strong concentration variability with depth. Figure 9 shows large distinct peaks in concentration existing for each of the contaminant groups in each of the MLSs. For example, the MP11 profiles show three sharp low-concentration peaks for the chlorinated ethenes and one for the total ketones; MP12 and MP13R each show two distinct much higher concentration peaks of total ketones. Nearly all of the peaks are identified based on high values in only one or two monitoring intervals. If typical conventional monitoring were done, involving fewer monitoring intervals, most or perhaps all of the peaks would have been missed or blended with low-concentration water to much lower concentrations, masking the real distribution of the contaminants. Prior to the detailed monitoring with MLSs, there was no basis a priori for judging where the peaks would occur, and, therefore, the only way to find them was to monitor using many sampling intervals in each hole. The 15 ports in these MLSs are a large number relative to standard practice; however, the profiles shown in Figure 9 indicate that this large number was necessary to find the highest concentration zones.

Einarson and MacKay (2001) and Guilbeault et al. (2005) indicate that detailed determination of the contaminant distributions along a plume cross section positioned orthogonal to ground water flow (i.e., transect) is critical for accurate determinations of plume mass discharge using the cross-sectional method. For studies of plumes in cohesionless sandy aquifers at contaminated sites, these investigations show that detailed multilevel monitoring is required to find the local high-concentration zones in organic contaminant plumes and that these zones, even if they occupy a small part of the plume cross section, provide most (or in some cases nearly all) of the total mass discharge. Figure 10 shows the distribution of total chlorinated ethanes along the transect at the Wisconsin site, exhibiting only one high concentration zone, and this zone is identified based on only 4 of the 42 sampling points on the transect. There is no indication that too many monitoring intervals were used to locate this important zone. Guilbeault et al. (2005) accomplished their transect monitoring intervals using very detailed depth-discrete sampling with 18 and 32 sampling points per profile demonstrating large variability in concentrations over short distance increments even within sandy aquifers without much textural variability in the deposits. In another type of multilevel system described by Cherry et al. (1983), the tubes were bundled around conventional flush joint PVC pipe; however, because they were installed in a cohesionless sand aquifer, sand readily caved in around the tube bundles, and therefore sand packs and seals were not needed. These systems can accommodate up to 20 sampling tubes. However, at the Wisconsin and Ontario sites, the complexity of the geology with occurrence of silt and clay layers as well as sand necessitated sand packs and seals. At sites with greater complexity or plume thickness, it can be envisioned that more than 15 monitoring intervals would be necessary to adequately delineate the concentration variability and plume mass flux distributions on cross sections, in which case it would be necessary to install two multilevel systems side by side at each profiling location.

Conclusions

The modified Waterloo System combines the advantages of rotasonic drilling with commercially available components to accomplish high-resolution ground water monitoring of both hydraulic head and ground water chemistry. Although other drilling methods may be used, rotasonic is relatively fast and effective in a wide variety of geologic environments. Rotasonic equipment facilitates

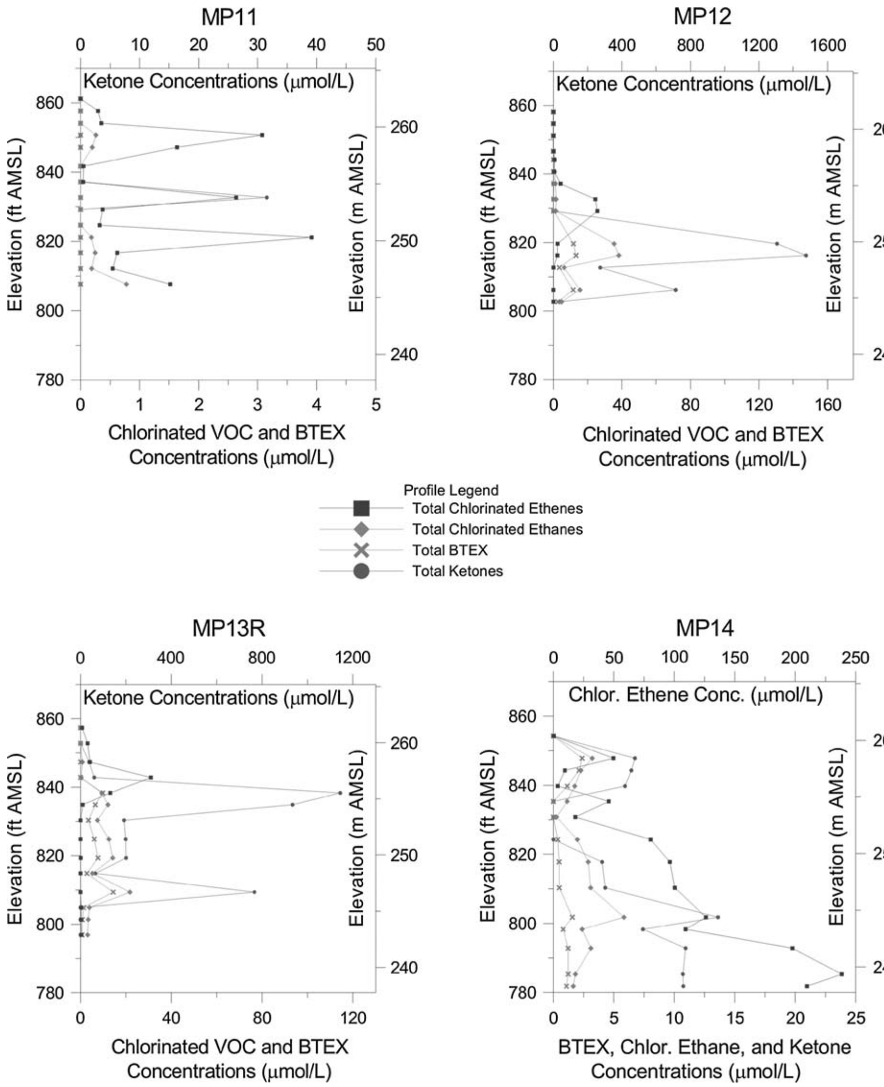


Figure 9. Vertical contaminant concentrations in the transect MLS, Wisconsin site. Concentrations vary by 1 to 3 orders of magnitude over small vertical distances of 1.5 to 3 m (4.5 to 9 feet). Large peaks in contaminants occur over one or two adjacent monitoring intervals. See Figure 6 for MLS port locations.

avoidance of bridging of sand and bentonite pellets during installation of these critical components of the system. The practical minimum sand pack and bentonite seal lengths are both 0.5 m (1.6 feet), but beyond these practical minimum length limits, the spacing of sand packs and seals can be adapted to site-specific geological conditions.

Detailed resolution is needed at sites where heterogeneous hydrogeology causes hydraulic head and/or chemical concentrations to vary over small vertical distances. In general, the most appropriate number of monitoring intervals needed for effective delineation of head and/or contaminant distributions at any particular field site is unknown a priori. The MLS described here provides a large number of intervals in each borehole and can greatly reduce the number of boreholes needed in site investigations because this MLS provides so much information from each hole. Other multilevel systems allowing 15 or more ports intended for shallow ground water monitoring are described in the literature, but this new system, when used with rotasonic drilling, offers advantages for installation of sand packs and seals that have proper positioning and integrity. The large-diameter sand packs and small-diameter tubes result in relatively fast water level response times, even in low-permeability materials.

At each of the field sites, the high-resolution monitoring of hydraulic head vs. depth showed one or two intervals in each borehole where large head differentials existed, identifying zones of relatively low vertical hydraulic conductivity. At the Ontario site, these zones have vertical hydraulic gradient components exceeding one (>1 m head/1 m vertical distance). Even with the availability of the core logs prior to installation of an MLS, most of the specific depths at which the highest head differentials occurred could not be anticipated from the core logs, indicating the essential and unique role of the high-resolution head monitoring. For example, at the Ontario site, the lack of head differential at the bottom of the Quaternary deposits in two of the holes indicated the absence of a laterally continuous zone with relatively low vertical hydraulic conductivity lying on top of the dolostone aquifer. Vertical

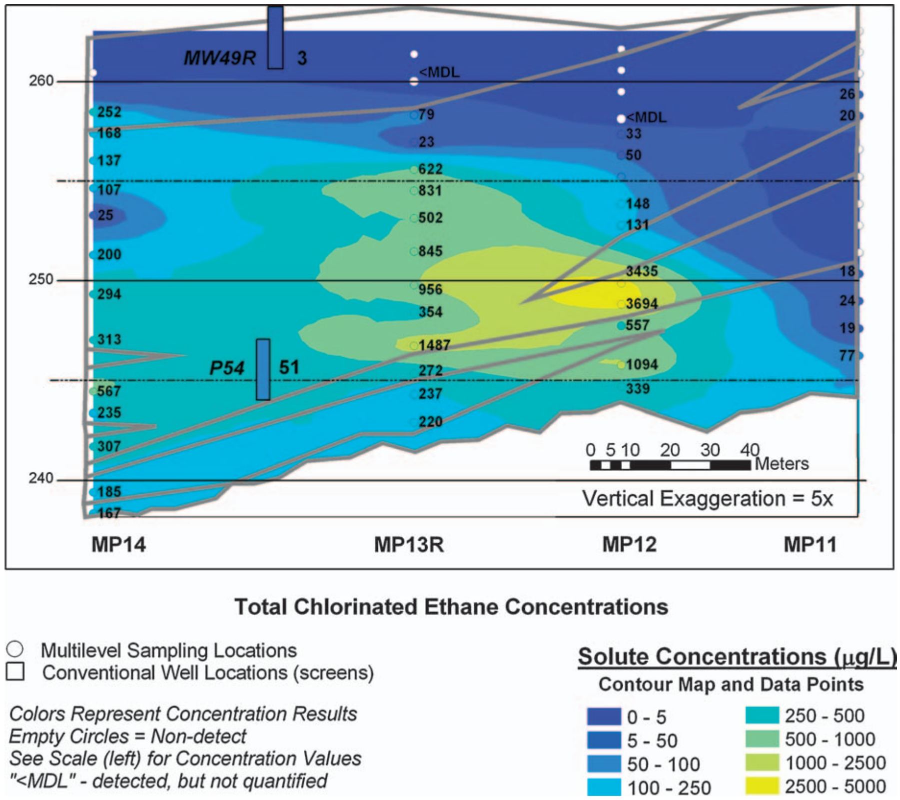


Figure 10. Distribution of chlorinated ethanes along the MLS transect, Wisconsin site (Figure 5). Light lines show geologic strata from Figure 6. Port labels provide total chlorinated ethane concentrations at each location. Conventional well screens and chlorinated ethane concentrations for wells P54 and P49R are also indicated. High concentrations are centered around the middle monitoring intervals of MP13R and the lower intervals in MP12.

gradients exceeding one are rarely reported in the hydrogeologic literature. This is likely because larger vertical distance between the monitoring points produces much smaller apparent gradients, and therefore the thin, low hydraulic conductivity zones that cause large local head differentials go unidentified. It has become common at sites where substantial investment is made in ground water flow modeling to divide the hydrogeologic system into various hydrogeologic units or layers represented in the model. In these models, the layers are often created based primarily on borehole logs and the models are typically calibrated using hydraulic head measurements from conventional monitoring well clusters consisting of two, three, or perhaps four wells. Based on the head profiles obtained from the Ontario and Wisconsin sites, it is easy to envision that such ground water flow modeling would capture little of the reality of the flow system.

At the Wisconsin site, four of the six multilevel systems identified zones < 3-m (10-feet) thick containing high contaminant concentrations. These contaminated zones included two vertically adjacent ports, but the concentrations were strongly diminished or are below detection in ports immediately above and below these discrete zones of contamination. Some of these zones would not have been identified or quantified if the multilevel systems had contained half the number of ports. This would result in grossly underestimated plume contaminant mass discharges (i.e., high-flux zones missed).

The MLS described in this paper provides detailed hydraulic head profiles well suited for identifying the zones of lowest hydraulic conductivity (e.g., key aquitards) in geologically layered environments, and this can generally be accomplished using a small number of MLSs at a site. Further subsurface characterization could therefore focus on defining the areal extent and integrity of those units. This should result in a more focused higher quality and less expensive characterization program.

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Editor's Note: The use of brand names in peer-reviewed papers is for identification purposes only and does not constitute endorsement by the authors, their employers, or the National Ground Water Association.

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