In Situ Ground Water Remediation Using the Trench and Gate System

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Abstract

The trench and gate remediation system is a funnel and gate design modified for installation in tills and other low permeability sediments. Modifications include the addition of high hydraulic conductivity trenches along the upgradient side of the funnel walls and a discharge reinfiltration gallery downgradient from the treatment gate. Preferential ground water flow through the high permeability trenches and reinfiltration gallery prevents mounding, which otherwise forces flow beneath and around funnel walls. The resultant capture zone is larger, both horizontally and vertically, than the cross-sectional funnel area and is significantly larger than the capture zone of a similar funnel and gate system. The system constitutes an economical, in situ, long-term contaminant plume capture and treatment method. In effectiveness and cost, the trench and gate system compares favorably with, or outperforms, other remediation systems in near-surface, low permeability dissolved contaminant scenarios. A prototype trench and gate system was installed at the East Garrington Gas Plant, Alberta, Canada, in 1995. The installation demonstrated the effectiveness of the concept, and the system has successfully prevented off-site migration of dissolved hydrocarbon contaminants.

Introduction

Contamination of shallow ground water is one of the most serious problems facing industry. Contaminated ground water often occurs in fine-grained deposits such as silt and clay tills. Effective and economical treatment of contamination in these low permeability media is problematic due to slow ground water flow velocities. As a result, capture and remediation of contaminated ground water in these media is often cost prohibitive. Thus, there is a need for an economical and practical method of preventing off-site migration of ground water contamination in low permeability sediments.

Pump-and-treat wellfields are not viable for this contaminant scenario as capture zones are small, requiring closely spaced extraction wells. Excavation and treatment techniques may also be used to clean up contaminant sources, but high costs and the potential for recontamination at operating facilities make this solution less than optimal. Passive mitigation systems present an attractive alternative to the more aggressive solutions. In higher permeability environments, the funnel and gate system (Starr and Cherry 1994) is a possible alternative. In the funnel and gate system, a permeability barrier forces ground water to pass through a gate in which it is treated. After flowing through the treatment gate, the treated water returns to the ground water system. However, the funnel and gate system is not suitable for low-conductivity sediments because ground water mounding behind the funnel walls can cause contaminants to flow around or underneath the walls.

A modified funnel and gate interception system, named the trench and gate, has been engineered for use in lower hydraulic conductivity sediments. The trench and gate consists of an impermeable funnel with the addition of high hydraulic conductivity "drainage trenches" along the inside edges of the funnel, and a high permeability downgradient discharge reinfiltration gallery. The modifications improve drainage of the contaminated zone, increase the size of the capture zone, and prevent damming effects such as mounding that force contaminants around or under funnel walls. The modified system allows for treatment of ground water using any technique that can be installed in an open gate. Centralized treatment of dissolved contaminants in the readily accessible gates facilitates infrastructure repairs and reduces long-term maintenance costs. An open gate system also provides the flexibility to treat multiple contaminants. A pilot scale trench and gate system was installed at the East Garrington Gas Plant, Alberta, in September 1995 and has been operating successfully since.

East Garrington Study Site

The Amoco-operated gas plant, in Red Deer County, Alberta (Figure 1), was constructed in 1975 to process raw gas. A series of hydrogeological site investigations confirmed the presence of dissolved BTEX (benzene, ethylbenzene, toluene, and xylenes) over much of the site and local areas of LNAPLs (light nonaqueous phase liquids). Contaminant sources on-site include former leaks and spills from the tank farm, an underground produced water storage tank, an underground lube oil storage tank, the former flare pit, and the holding pond (Figure 1). Contaminant plumes from several of these sites coalesce to form one larger plume that had to be prevented from leaving the site.

The East Garrington project site is just east of the Rocky Mountain Foothills. Relief is moderate with undulating topography typical of glaciated plains. The plant is located on the side of a broad hill that slopes gently northeast. Regionally, the surface drainage is

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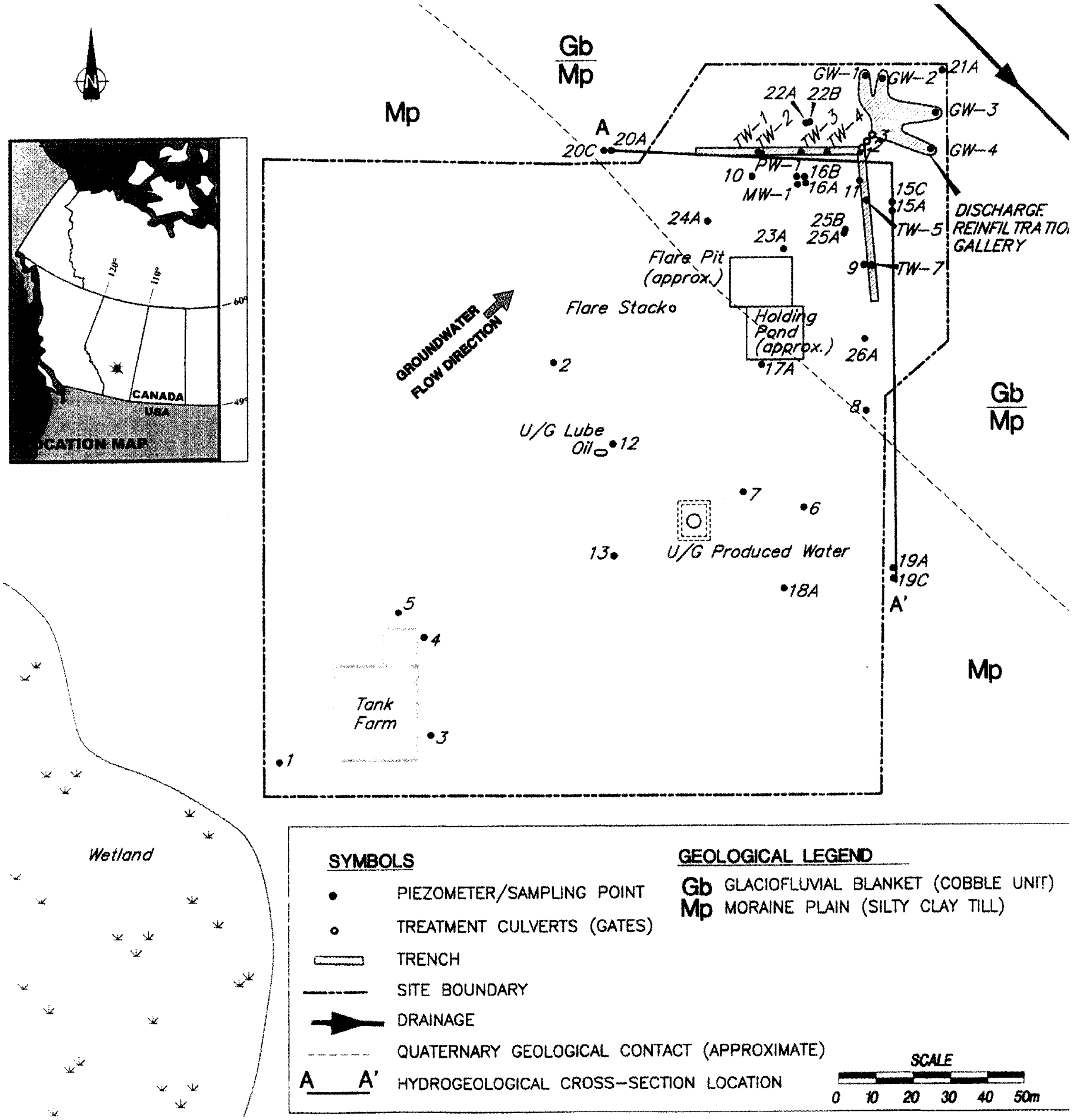


Figure 1. Plan view of East Garrington Gas Plant site showing position of the trench and gate system, hydrological features, Quaternary geological units, and location of hydrogeological cross section transect A-A′.

also toward the northeast, reflecting the topographic gradient. However, local surface water and near-surface ground water from the northeast end of the plant drain to the southeast along an intermittent stream channel (Figure 1).

An on-site weather station was operated for the first three years of the project. Monthly mean temperatures range from –15.4°C in January to 15.8°C in July. The mean annual temperature is 2.6°C. The mean annual precipitation is approximately 350 mm and potential evapotranspiration exceeds precipitation from May to October (Thomas 1999; Ozoray and Barnes 1977).

Stratigraphy

Quaternary deposits are largely of glacial origin and form a relatively thin veneer over the underlying bedrock. The depositional history of the Quaternary deposits is complex and reflects the combined influence of Cordilleran and Laurentide ice sheets, and the apparent reworking of the earlier glacial sediments by a different ice sheet. Glacial deposits near the plant site, especially to the south and west, consist primarily of draped moraine and stagnation moraine till (Figure 1). Locally, as determined from drill logs completed during drilling of the 32 piezometers on-site, the till is com-

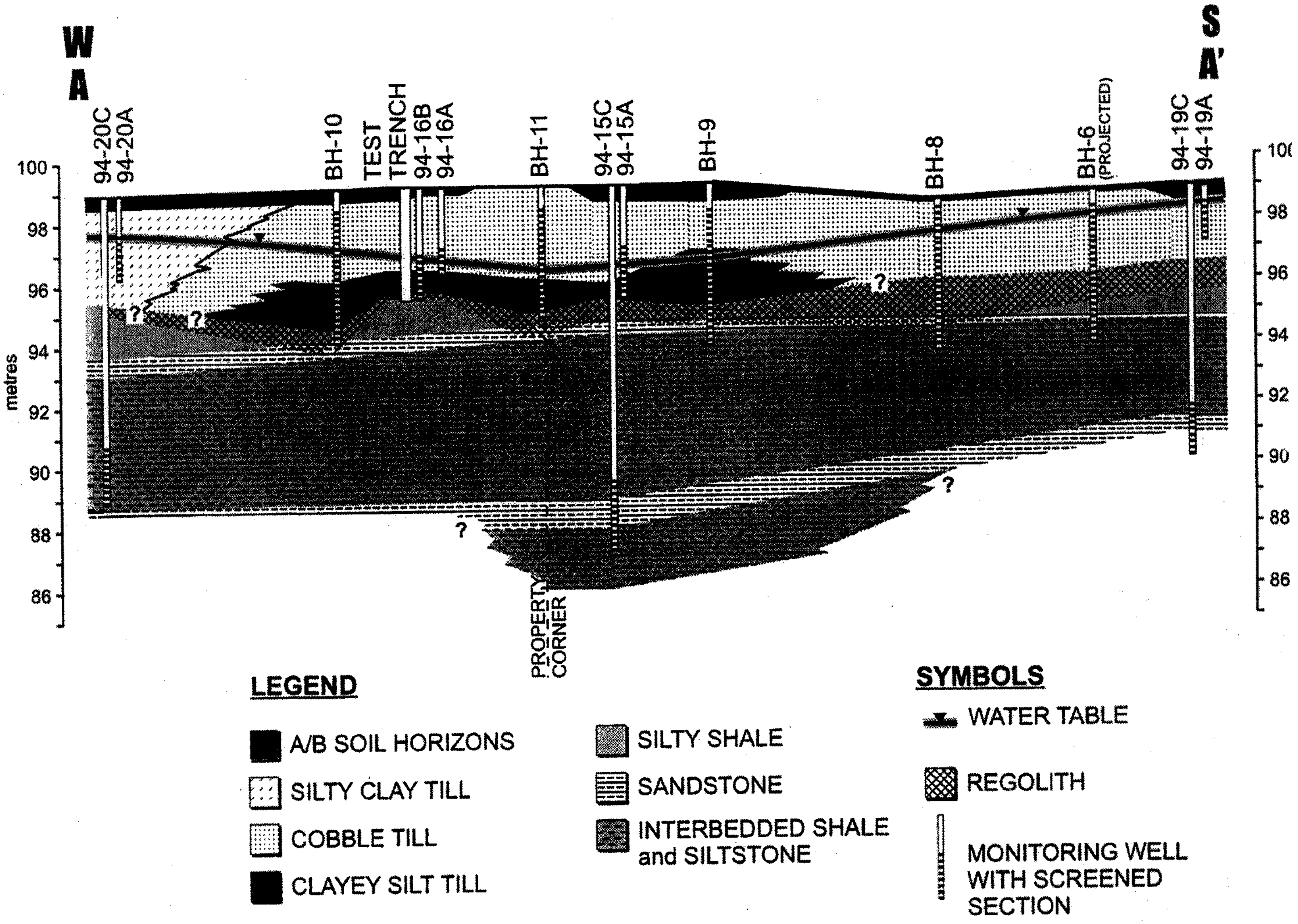


Figure 2. Hydrogeological cross section A-A′ along parts of the northern and eastern portions of the plant. The location of the transect is shown in Figure 1.

posed of a mottled yellow brown silty clay that grades to an unweathered gray with depth. It may contain from 5% to 35% or more fine gravel to cobble-sized rounded to subrounded rocks, composed primarily of siltstone, sandstone, quartzites, and other sedimentary rocks. The till is typically fractured near the surface and contains minor sandy lenses, gypsum, coal, and iron staining.

Northeast of the plant, two or more gravel rich deposits are associated with an old southeast-trending glacial melt water channel (Figure 1). These deposits are interpreted to be reworked glaciofluvial or periglacial sediments deposited on top of the earlier tills. One of these units has a high cobble content and is referred to as the "cobble till." In places it is clast supported. It shows no evidence of imbrication and contains appreciable fines. X-ray diffraction analyses showed that the cobble till matrix is composed primarily of a clay-sized fraction dominated by quartz and containing few clay minerals. The contact between the cobble unit and the silty clay till was approximated using electromagnetic geophysical techniques. The contact strikes roughly northwest and cuts across the northeastern corner of the plant site (Figure 1). Paleochannels within this unit have a profound influence on ground water and surface water flow at the site.

A gray clay-rich sandy silt basal till that contains abundant bedrock chips (Figure 2) underlies both the silty clay till and the cobble-rich deposits. This till, which may be up to 2.2 m thick, overlies bedrock at a depth of approximately 5 m.

The subcropping bedrock unit throughout the region is the Paleocene Paskapoo Formation, which is composed predominantly of interbedded mudstone, siltstone, and fine-grained sandstone (Glass 1990). At East Garrington, near-surface sedimentary rock consists primarily of a silty shale, shale, and siltstone with occasional interbedded sandstone units.

In the area of the plant, the bedrock topography is undulating but appears to dip gently to the north. The erosional contact of the Paskapoo Formation with the overlying Quaternary deposits is marked by a zone of relatively higher permeability weathered bedrock regolith less than 1 m thick (Figure 2).

Hydrogeology

The near-surface hydrogeological setting of the plant site is controlled by the interaction of the cobble unit and the less permeable tills and bedrock. Hydraulic conductivity (K) values, as calculated from monitoring well drawdown tests, range from less than 1×10^{-10} m/s in the shale bedrock to upward of 2×10^{-5} m/s in tills containing discontinuous sandy stringers or fractures. The K of the cobble till varies over several orders of magnitude due to its heterogeneous nature. In general, hydraulic conductivities of the various units increase in the following order: shale < unweathered till < weathered till < cobble till. In addition to the monitoring well drawdown tests, K testing was carried out using laboratory permeameter tests and a trench pumping test. Estimates of K varied

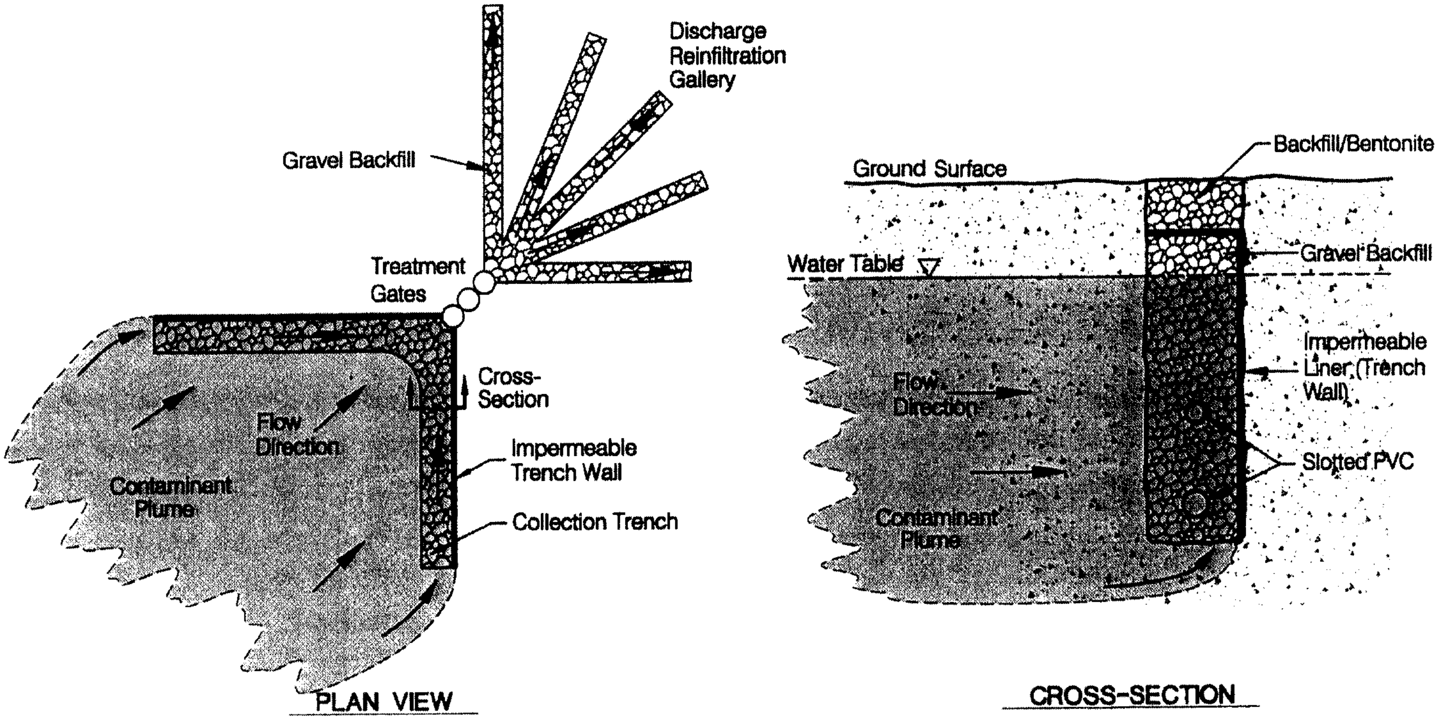


Figure 3. Plan view and cross section conceptual schematics of the trench and gate system.

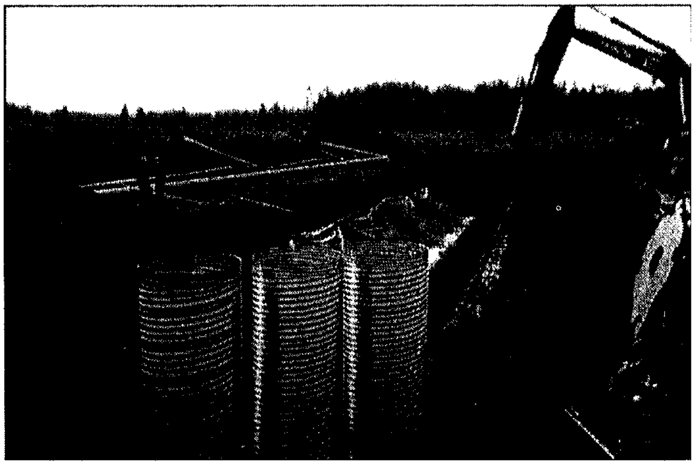


Figure 4. Photograph of trench and gate installation. Points to note: (1) trench with downgradient impermeable liner installed and ready for backfilling with gravel; (2) cobble rich unit to base of cut-back on slope underlain by clay till with vertical cut trench walls; (3) ground water seepage at base of cobble unit; (4) vertical culverts (treatment gates) complete with dual pipe connections; and (5) L-shaped PVC monitoring wells and main drainage pipe on ground ready for installation in the trench.

depending on the method used, but in general increased when larger volumes were tested.

Ground water flow is toward the northeast and is controlled by bedrock topography and gradient. Some of the shallowest ground water flowing out of the facility discharges to a gravel streambed that drains toward the southeast. Recharge to the uppermost ground water-bearing zone is derived from on-site precipitation and a wetland immediately southwest of the facility (Figure 1).

Near-continuous automated monitoring of ground water potentiometric levels at the site shows that a steady ground water recession occurs throughout the winter. As a result, horizontal gradients are seasonally dependent and vary from approximately 0.02 in winter to 0.04 in spring and summer for the central part of the facility. Gradients are substantially flatter in the northeast corner of the facility where the gravel-rich sediments are located.

The Trench and Gate System

Theory

Modification of the funnel and gate system to create the trench and gate system is based on the concept of focusing ground water flow through media of comparatively higher hydraulic conductivity (Bowles 1998; Bowles et al. 1995, 1997). Just as ground water flow through a highly permeable lens of sand can be significantly more than in a surrounding clayey till (Bear 1979), so, too, can the trench and reinfiltration gallery focus flow in the trench and gate system.

Plan view and cross section schematics of the trench and gate system are provided in Figure 3. The trench and gate system was originally designed as an in situ method for treating hydrocarbon-contaminated ground water in low hydraulic conductivity glacial sediments. The capture component of the system is composed of a cut-off trench excavated into till (Figure 4). The downgradient side and the top of the trench can optionally be sealed with a synthetic liner, and the trench is backfilled with a permeable aggregate such as gravel or drain rock. The aggregate encourages flowline deflection into the center of the system, preventing ground water mounding along the walls of the trench. Slotted PVC can be added along the length of the trench to act as a preferential ground water flowpath, thus reducing fluid potential losses due to friction and tortuosity. Two such trenches are constructed at an angle to each other and hydraulically downgradient of the contamination. The width of the capture zone increases as the angle between the trenches approaches 180 degrees. The optimum angle will be less than 180 degrees and is a function of site-specific criteria including horizontal hydraulic gradient, the permeability contrast between trench backfill and the surrounding sediments, and the orientation of the installation relative to the ground water flow direction (Starr and Cherry 1994).

At the intersection of the trenches, natural hydraulic gradients channel contaminated ground water through a treatment gate. Following treatment, the ground water flows back into the till through a discharge reinfiltration gallery designed to maximize the area of till contact. The gallery is designed to have a large till contact area to facilitate reinfiltration of ground water in case the treated water is incompatible with the native ground water or sediments, resulting in the precipitation of minerals and a concomitant reduction in porosity. Monitoring wells can be installed upgradient, downgradient, and along the trench to measure hydraulic head changes due to the interception system and to facilitate hydrochemical monitoring.

Construction

The East Garrington trench and gate collection trenches are 5 m deep, excavated to bedrock, and lined with a reinforced arctic grade geosynthetic on the bottom and downgradient side. Due to sloughing conditions, slit trenches could not be used and the top portion of the trench had to be sloped back. The trench is backfilled with screened gravel and instrumented with PVC monitoring wells (Figure 4). Trenches were constructed at an approximate 90 degree angle due to site limitations and not because this angle yielded the optimum capture zone geometry.

Monitoring wells are constructed in an "L" shape with a long "foot" extending down the trench. The horizontal section of the L, as well as the vertical portion below and slightly above the water table, is constructed of slotted PVC and connected to a solid riser pipe running to surface. These monitoring wells (labelled TW for trench wells) are installed approximately every 15 m along the trench (Figure 1) and are capped at the downgradient end of the foot. The wells were designed to serve as monitoring wells and their L shape and position near the water table allow them to act as conduits for injecting remediating or other fluids. Prior to construction, it was unknown whether there might be problems with biofouling or mineral precipitation within the trenches. The L-shaped wells were added as a provision for injecting and distributing along the length of the trench a biocide, acid, or other type of fluid. After four years of operation, fluid addition has not proven necessary.

Underlying these monitoring wells is a continuous length of 0.25 m diameter, slotted PVC pipe that discharges into the first gate. This pipe was designed with a large diameter to facilitate clean-outs if they become necessary. It has a riser located near the end of the trench so it can also serve as a monitoring well. Its primary function is to act as a submerged tile drainage system. Ground water entering the trench preferentially flows along the PVC pipe to the treatment gate, thus reducing fluid potential losses. Such losses are of particular concern at this site because the low gradient within the small pilot system produces a minimal (i.e., < 2 cm) head drop along the trench arms.

Since aerobic biodegradation reactions for BTEX are typically much more rapid than anaerobic ones, aerobic biodegradation was chosen as the mechanism for remediation of the contaminated water in the trench and gate system. Biosparging studies (Lord et al. 1995; Hinchee 1994) have shown that oxygenation of contaminated ground water by bubbling air enables aerobic degradation of dissolved hydrocarbons (e.g., BTEX) by naturally occurring bacteria. Thus, biosparging was chosen for the East Garrington site. Biosparging was also considered an attractive option because atmospheric air contains an adequate supply of oxygen for the biodegradation process and a source of air was readily available from the instrument air compressor located on site.

Original plans called for construction of a permeable wall treatment system. This design was discarded in favor of a gate design due to easier field construction and suitability for long-term maintenance. The gate residence time was calculated based on the expected flux and treatment zone volumes. Gate sizes were chosen to ensure that there was sufficient time for ground water within the gates to become fully oxygenated and to allow for at least partial biodegradation of dissolved petroleum hydrocarbons within the gates prior to exiting.

Using the largest (worst case) K value as estimated from the trench pumping test, an approximation of the maximum expected flux (Q) through the trench and gate system was made using the formula:

$$Q = KiA$$

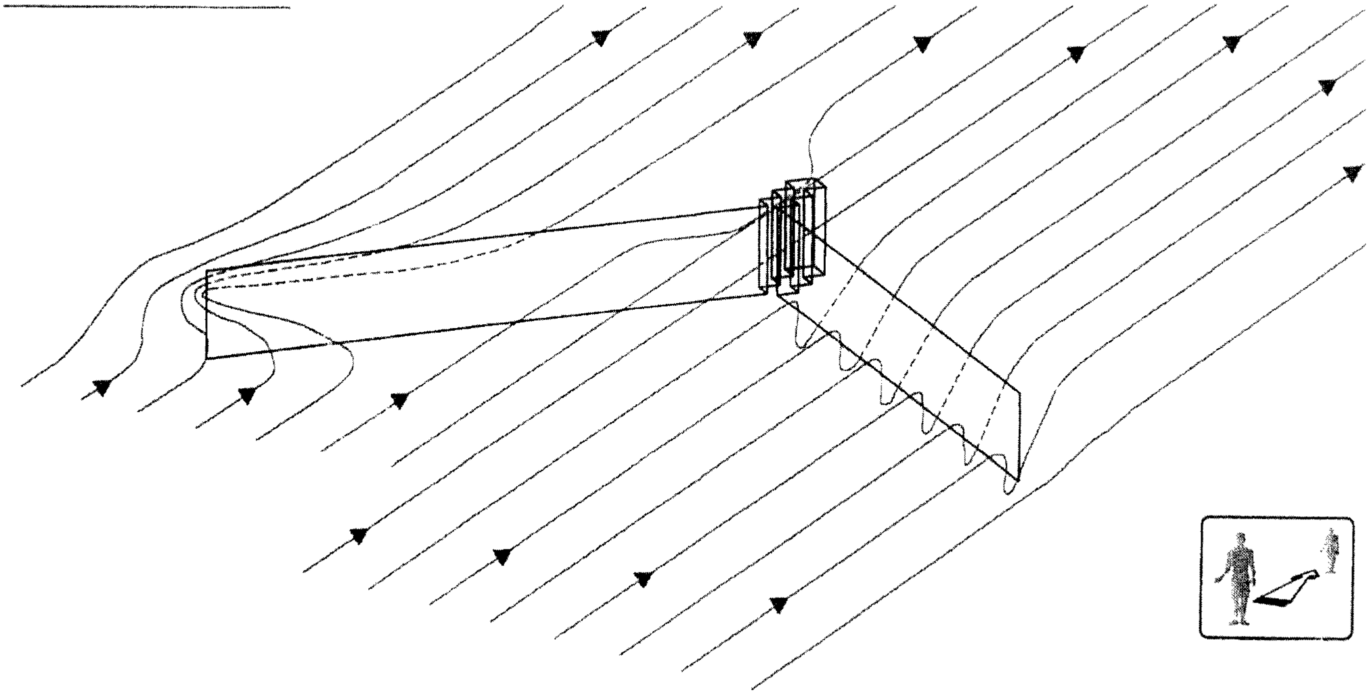
where A = the area ($l \times h = 248\ m^2$) calculated from the length 62 m (linear distance between two ends of the funnel) multiplied by the saturated thickness – h (approximately 4 m); i = the average horizontal hydraulic gradient (= 0.035); and K = 6.0×10^{-5} m/s. This calculation yields a Q of $5.2 \times 10^{-4}\ m^3/s$ or approximately 31 L/min.

Using a calculated volume for the three culverts that make up the trench gates of 31.52 m^3 and an expected flux of $5.2 \times 10^{-4}\ m^3/s$ yields a minimum residence time for water passing through the system of 16.8 hours, assuming no short-circuiting of flowpaths. This figure was deemed adequate for treatment as a worst-case scenario. The use of three in-series culverts was deemed preferable to using one large culvert, as it is ideal for the completion of field experiments and allows for measurement of concentrations before and after treatment. A lengthwise divider within the second culvert provides a method for monitoring of experimental (treated) and control (untreated) streams. Having three in-series gates also proves more economical in terms of made-to-order culvert costs and keystone valves between the gates allow for isolation of the gates or sections of the gates. Additionally, culverts can easily be filled with a substrate or growth medium for hydrocarbon-degrading bacteria.

The gate is constructed of three 1.8 m diameter by 6 m high cylindrical galvanized culverts set vertically into a cement base (Figure 4). The culverts are connected to the large-diameter PVC pipe in the trench arms, each other, and the reinfiltration gallery via a series of welded steel pipes and flanges. Pipes connecting the culverts are equipped with valves so that flow can be shut off and the culverts pumped out should repairs or the installation of additional equipment become necessary. Flowmeters are installed in the last culvert to measure the flux through the system. The flowmeters were calibrated by isolating the second and third culverts from the rest of the system and recirculating water from one culvert to the other using a submersible pump set to a predetermined flow rate. Based on this test it was determined that the flowmeters were accurate to within 15%.

The first culvert also contains the biosparging component, a spiralled micro-pore hose attached to a galvanized base that keeps it anchored to the floor of the first culvert. Air injected into the hose produces fine bubbles. Bubbling aerates and mixes the water. If simple aeration of the ground water is insufficient for biodegradation of hydrocarbons, the pressure can be increased and volatiles can be

FUNNEL AND GATE



TRENCH AND GATE

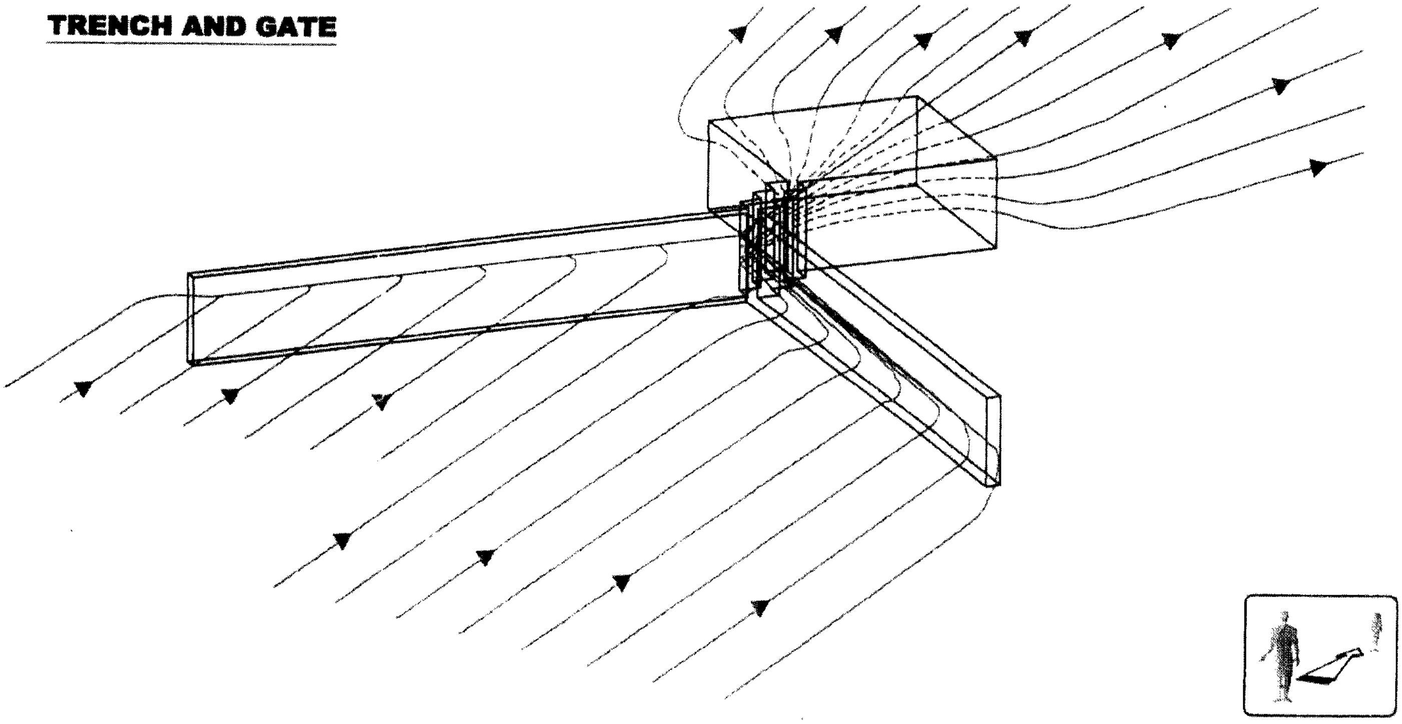


Figure 5. Streamlines derived from computer modeling results for (a) the funnel and gate system showing partial plume capture, and (b) the trench and gate system showing complete plume capture. (a) Streamlines on the left-hand side of the figure approach the funnel at the water table. Streamlines closer to the middle of the system flow into the treatment gate while streamlines further out are deflected around the outside of the wall. Streamlines on the right-hand side of the figure approach from above the bottom of the funnel and are deflected down beneath the wall. (b) Streamlines on the left-hand side of the figure approach the trench at the water table and are captured by the system including some streamlines that start outside of the funnel mouth. Streamlines on the right-hand side of the figure approach from below the bottom of the trench, are deflected upward into the trench, and are captured by the system. Streamlines fan out again after exiting the treatment gate and entering the reinfiltration gallery.

removed by sparging. If necessary, off-gasses would then be run into the nearby flare stack.

From the first culvert, oxygenated water flows through two pipes into the second and third culverts and is then directed into the reinfiltration gallery. Sample ports connected to the surface via PVC tubing, and instrumented with Waterra sampling systems, are built into each of the inlet or outlet pipes in every culvert, allowing for sequential sampling during treatment. The culverts are sealed with fiberglass lids with built-in manholes to allow easy access to sampling ports. Based on the current findings, nonresearch applications of the trench and gate system could probably be constructed with only one gate, thus substantially reducing the initial construction costs.

Treated water flows out of the last culvert into a reinfiltration gallery. The gallery is composed of a finger arrangement of slit trenches excavated into the glacial sediments and backfilled with washed gravel. At the end of each finger, monitoring wells are constructed in the backfill material to allow for ongoing hydrochemical and hydraulic monitoring of the system. The placement of the gallery fingers had to be altered from an idealized fan arrangement (Figure 3) due to the presence of an underground pipeline.

Computer Ground Water Modeling

To provide a greater level of confidence that the system would perform as predicted, the flow field around the trench and gate infrastructure was modeled using the University of Waterloo's FRAC3DVS program (Therrien and Sudicky 1996). FRAC3DVS is a three-dimensional ground water flow and solute transport model that can represent discretely fractured and low permeability media. A hypothetical funnel and gate system at the same site was also modeled to illustrate the differences in flow fields for the two systems.

Details of the modeling parameters used are provided in Hoyne (in prep.) and Hoyne and Bentley (1997). They used a simplified two-layer hydrostratigraphic model with constant head boundary (Dirichlet) conditions for the four sides and no-flow boundary conditions for the top and bottom of the model. The top layer, designed to represent an unconfined ground water–bearing glacial till, was assigned a K of 1×10^{-7} m/s. The underlying bedrock unit was assumed to have a K of 5×10^{-9} m/s while the gravel in the trenches and the reinfiltration gallery was assigned a hydraulic conductivity of 3×10^{-4} m/s. The impermeable barrier was modeled using the cut-off wall parameter in FRAC3DVS. Treatment zones were modeled as enclosed cut-off walls and the reinfiltration gallery is configured as a parallelepiped rather than the actual finger arrangement.

In some areas, it may not be practical to key the trench system into a low permeability bedrock, and the wall or trench portion of the trench and gate would be hanging. Modeled flow regimes for hanging wall versions of the trench and gate and funnel and gate models are presented in Figure 5. In the trench and gate model, ground water flow is focused toward the high permeability trenches and then along the trenches and into the treatment zone as long as the K of the trench material is at least an order of magnitude greater than the surrounding sediments. Following treatment and discharge into the reinfiltration gallery, the streamlines fan out again as the water is reinfiltrated into the till.

Modeling also confirmed that the trench and gate capture zone is wider than the width of the funnel mouth of the system, while the funnel and gate capture zone is much smaller. This is because the funnel and gate design essentially constricts flow in the area of the treatment gate and forces streamlines to short circuit underneath the funnel walls or to flow around the outside of the funnel walls, thus reducing both the horizontal and vertical extent of the capture zone.

Other modeling runs have demonstrated that the trench and gate system works well when installed without the impermeable barrier. However, while ground water capture continues when the liner is removed, site-specific conditions could potentially result in downgradient diffusion of contaminants across the trench.

Results

Hydrocarbon Treatment

As part of the research program, experiments were undertaken or measurements made to determine (1) what indigenous hydrocarbon-degrading bacteria were present; (2) what concentrations of total BTEX could be treated by the system; (3) whether biodegradation was nutrient limited; and (4) the distribution of dissolved oxygen (DO).

Experiments conducted to isolate and identify hydrocarbon-degrading bacterial species were completed on samples taken from the site. Four indigenous species were identified: (1) *Pseudomonas putida*; (2) *Pseudomonas fluorescens*; (3) *Stenitrophomonas maltophilia;* and (4) *Rhodococcus sp.*

Total BTEX concentrations around the site vary from nondetect to more than 10 mg/L. To date, the highest measured total BTEX concentration entering the system (not including the period when concentrations were artificially increased for experimental purposes) has been 0.183 mg/L. In this case, and most others, BTEX concentrations were reduced to less than the detection limit of 0.001 mg/L before the ground water exited the treatment gate. For rare occasions where BTEX components were still detectable in the reinfiltration gallery after treatment, these concentrations were low enough, and DO concentrations were high enough, that any remaining hydrocarbons would likely have been aerobically degraded over a short distance and time.

It appears that the treatment system has been able to degrade nearly all incoming hydrocarbons despite the fact that bacterial growth is limited to the walls of the culvert. In settings with higher concentrations of hydrocarbons, it may be necessary to add a stationary growth medium to increase the surface area available for bacterial growth. While it is likely that some hydrocarbons are volatilized instead of degraded, this probably represents a relatively small fraction as suggested by the following: (1) biosparging delivery pressure is kept to a minimum thus keeping agitation to a minimum; (2) measurement of off-gasses from the sparging culvert using an organic vapor analyzer with an effective detection limit of 5 ppm, yield background, or near-background concentrations of petroleum hydrocarbons; and (3) biodegradation experiments using the divided culvert and BTEX-spiked ground water showed that most hydrocarbon mass destruction is attributable to biodegradation.

Experiments were undertaken in both the laboratory and the field to determine what effect nutrient addition had on biodegradation rates (Granger 1997). Nitrogen and/or phosphate were added to one of the dual streams of contaminant-spiked water in the second culvert after sparging with pure oxygen to ensure the reactions were not limited by DO content. Comparisons of BTEX concentrations in the amended and control streams showed that phosphorus is the rate controlling nutrient.

DO values were routinely measured across the site and vary according to location and temporal recharge conditions. Background values were typically less than 2 mg/L, except immediately following a significant precipitation event when the DO values can increase temporarily to as high as 8 mg/L in isolated wells. Contaminated wells typically have negligible DO concentrations, as do the influent concentrations to the first culvert. Biosparging in the remediation system increases these values to fully saturated with respect to air or approximately 10 mg/L. Elevated DO concentrations persist into the reinfiltration gallery and results as high as 5 mg/L are not only common, but also provide indirect evidence of flow out of the treatment system.

Hydraulics

Installation of the trench and gate system altered the flow field at East Garrington. Potentiometric contours from the monitoring well network at the site for pre- and post-installation scenarios

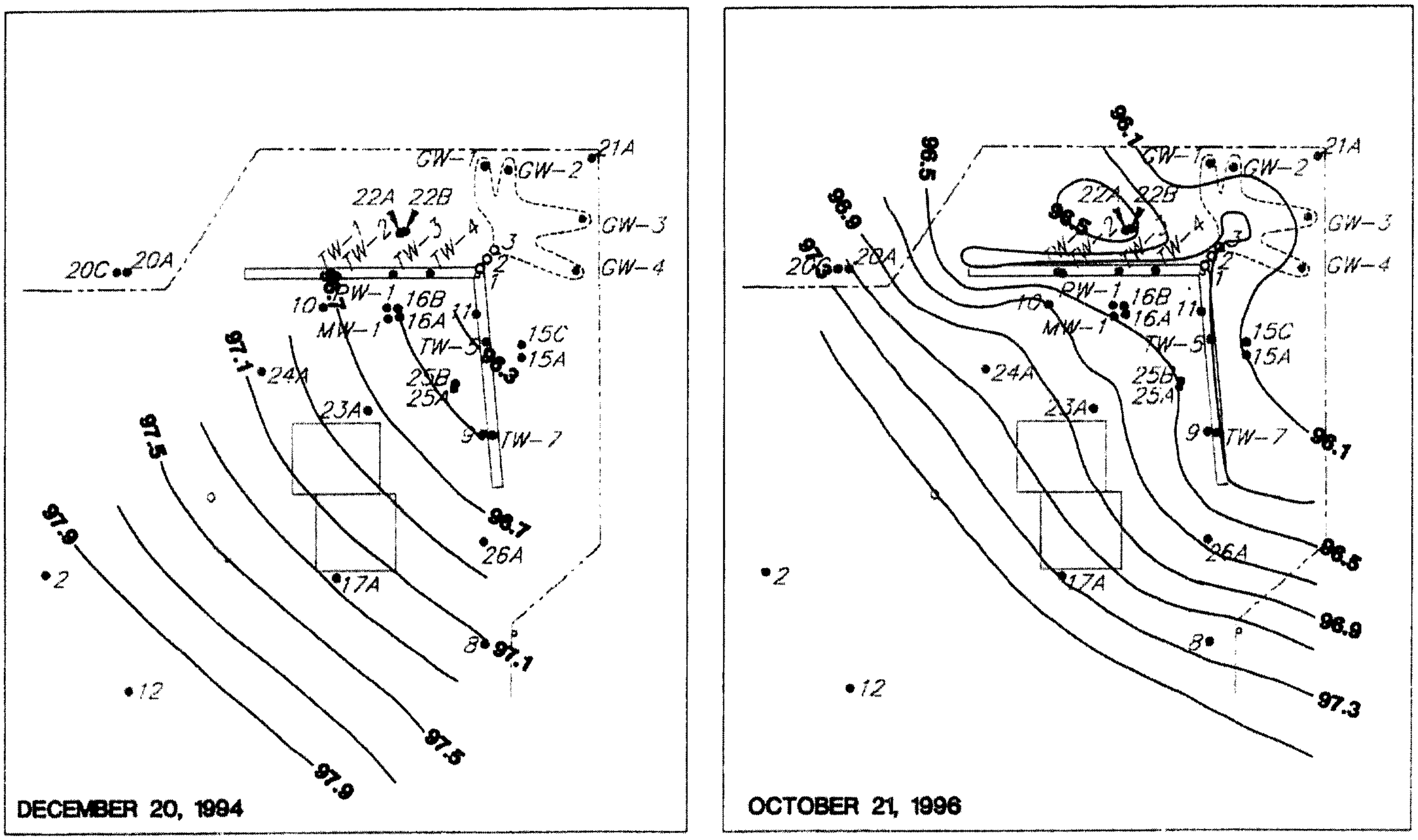


Figure 6. Ground water surface elevation contours for pre- (December 1994) and post- (October 1996) trench and gate installation. Contour interval is 0.2 m. Note how contours have been deflected by installation of the trench and gate system.

are presented in Figure 6. Even before the trench and gate system was installed, a natural flattening of the potentiometric surface is visible in the northeast section of the plant. This is attributable to the higher permeability of the cobble till. Post-installation ground water surface contours curve inward toward the apex of the trenches as predicted in the computer modeling. The effect is particularly noticeable in October 1996, when the water table dropped into the less permeable, more typical till underlying the cobble till. This allowed the system to operate in a manner more in keeping with the design parameters (with a greater K contrast between the trench and surrounding sediments), thus reducing the influence of the higher permeability cobble till. While the cobble till made this site less than perfect for demonstrating this new technology, it did facilitate reintroducing the treated ground water into the till from the downgradient reinfiltration gallery because it is a more permeable unit.

Long-term monitoring of flow rates through the system has yielded a number of interesting observations. In particular, the flux through the system, both in terms of contaminant concentrations and flow rate is highly variable. Changes in flow rate can be directly correlated to precipitation or melt-out events, and variations up to three times the average were not uncommon. Noteworthy is the speed of recharge. Changes in flow rates through the treatment zone were observed within 24 hours of precipitation events. While changes in flow can, in part, be attributed to rain water recharging directly into the trenches, monitoring of ground water levels in wells located well away from the trenches show a similar pattern of rapid recharge, suggesting that the water makes its way down to the water table quickly traveling through fractures and higher permeability zones. Variations in recharge rates obviously also have a significant effect on horizontal hydraulic gradients. During the winter when little or no recharge is occurring, the water table becomes quite flat but then steepens following recharge events. Variations in potentiometric levels of almost 2 m were noted within some piezometers. Variations were particularly evident during the spring thaw when the frost wedge can be seen to melt from the top down. Often this can be seen as two distinct events. The first occurs when the surface snow and ice melt. The second occurs when the buried frost melts out. Once the melting water intersects the screened interval in wells, or the open portion of the trench, water pours into these structures causing a large and rapid increase in the water table elevation, at least locally. Significant changes in water table elevations could serve to redirect flow at some sites or even cause a temporary back-flow condition due to recharge directly into the trenches and reinfiltration gallery.

Table 1
Dissolved Oxygen Values (mg/L) in Reinfiltration Gallery Piezometers

	Piezometer			
Date	GW-1	GW-2	GW-3	GW-4
May 16, 1996	9.6	5.7	7.2	7.2
May 31, 1996	7.3	3.3	0.8	0.4

Measured flow rates through the system vary from between approximately 80 L/hour to in excess of 240 L/hour with a mean around 100 L/hour. Variations in DO content within reinfiltration gallery wells illustrate changes in flow directions through the year with ground water discharge preferentially occurring down different fingers of the reinfiltration gallery. Low DO concentrations in

Table 2
Ground Water Remediation Technique, Hydrogeological Setting, and Hydrocarbon Contaminant Type Treatment Feasibility Matrix

Hydrogeological Setting	Low K Media		High K Media		Fractured System[1]	
Hydrocarbon Contaminant	**Dissolved**	**LNAPL**	**Dissolved**	**LNAPL**	**Dissolved**	**LNAPL**
Treatment Technology						
Trench and Gate[2]	Good	Potential			Potential	Potential
Funnel and Gate[3]			Good	Potential	Potential	Potential
Permeable/Reactive Wall[2]	Potential		Good		Potential	
Pump and Treat			Good	Potential	Good	Potential
Free Product Pumping				Good		Potential
Multiphase Extraction[4]	Good	Good	Potential	Potential	Potential	Potential
Soil Vapor Extraction		Potential		Good		Good
Air Sparging[4,5]			Good		Potential	
Enhanced Bioremediation	Potential		Good		Potential	

Definitions:

Low K Media	Represents typical tills or similar sediments with a maximum hydraulic conductivity of approximately 1×10^{-6} m/s.
High K Media	Represents typical sands and gravels with hydraulic conductivities of approximately 1×10^{-5} m/sec or greater.
Good	Chances of using the system to successfully remove or treat dissolved or LNAPL contaminants are high. However, achievable end points will vary depending on the method chosen and site-specific hydrogeological conditions.
Potential	Probability of the system being used successfully is highly dependent on site-specific hydrogeological conditions and desired end points.
Blank	The technique is not likely to be applicable, suitable, cost-effective, or feasible for the scenario represented by the cell, although in some cases minor improvements in ground water quality may be attainable using the technique.

Notes

[1] This includes both naturally fractured materials such as bedrock and other low K sediments that have been artifically fractured using hydrofracturing or other techniques.

[2] Limited to excavatable materials and attainable excavation depths (typically <7 m).

[3] Limited by subsurface conditions and attainable sheet piling depths.

[4] Depth limitations (<20 m for multiphase extraction and <10 m for air sparging techniques).

[5] Ozone, oxygen, air, etc.

GW-3 and GW-4 (Figure 1) at the end of May stand in contrast to the values from the other two wells, and to values in the same wells earlier in the month (Table 1). This indicates that these reinfiltration gallery arms were receiving little oxygenated ground water discharge flow from the gates at this time but had been earlier.

Discussion and Conclusions

The trench and gate system offers some significant advantages over other remediation and containment systems. It can be used to isolate trouble areas subject to multiple contaminant releases and save the cost of repetitive cleanups. Simple modifications to the open gate system make it suitable for treating a variety of contaminants (e.g., metals removal or chlorinated solvents). The open gate configuration also facilitates routine maintenance while the semipassive nature of the system minimizes operating expenses. Modifying the inlet for a two gate system to facilitate water table entry may also allow for its use as an LNAPL separator. The system can also be used effectively in combination with other treatment techniques. Adding a pump to the downgradient end of the gate(s) and reinjecting treated ground water upgradient can speed flushing of a contaminated area. Systems modified in this manner have been installed at sites in western Canada. Trench and gate systems do require a significant upfront investment for installation and are practical only for situations where a long-term passive remediation approach is feasible. Once installed, however, the system requires minimum maintenance and is significantly cheaper than a comparable pump-and-treat system in the long run.

Based on the ground water modeling (Hoyne, in prep.) and contouring of potentiometric data, it would appear that, except for where the system was significantly influenced by units with naturally high permeability, the trench and gate system works as designed. Based on an average flux through the treatment system of 100 L/hour and a total BTEX concentration on the order of 0.15 mg/L, total mass removal will average approximately 130 g/year for a plume approximately 70 m wide and 4 m thick. However, experiments have shown that concentrations up to 2.5 mg/L are treatable if adequate phosphate is available, which equates to a total mass removal of approximately 2200 g/year of dissolved BTEX (Granger 1997).

Research indicates that the flow regime within glacial sediments is extremely dynamic. Infiltration and recharge rates can be rapid and variable over small areas as illustrated by large, short-term fluctuations in water table elevations. Variations in hydraulic head and concomitant changes in horizontal gradients can change the flux through a cross-sectional area significantly and quickly. These results illustrate that a thorough characterization and understanding of site geological heterogeneities will significantly improve the chances of designing a successful remediation system.

Observations made during the initial period of operation confirm that the trench and gate system offers a viable, long-term remediation system capable of treating contaminated ground water plumes hosted by low to moderate hydraulic conductivity sediments, and that the system can be equally well applied at numerous other sites. The system also offers several advantages in terms of increased vertical and horizontal capture zone size as compared with the funnel and gate system.

The trench and gate system has proven to be economical and effective in removing dissolved phase hydrocarbons from ground water, especially as compared with other more traditional remediation methods. It has also efficiently prevented off-site migration of dissolved hydrocarbon contaminants. A matrix illustrating the suitability of the trench and gate system as compared to other remediation techniques for a variety of contaminant scenarios is provided in Table 2.

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