ASSESSMENT AND REMEDIATION OF CREOSOTE CONTAMINATED GROUND WATER

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Abstract

During the early 1900's creosote was used to treat wood at a property located in South Vancouver. Subsurface contamination of a small portion of the property located next to the Fraser River occurred at that time. A five phase environmental assessment was undertaken through a series of field investigations carried out between 1991 and 1996 to identify the source, extent and degree of polycyclic aromatic hydrocarbon (PAH) contamination from creosote.

The detailed investigation included the completion of boreholes at over 40 locations using a variety of drilling methods. Soil samples from continuous cores were submitted for laboratory analysis. Ground water monitoring wells were installed in the boreholes for ground water sampling and water level measurement.

PAH contaminated soil from the historical use of creosote was found in three discrete areas located in close proximity to each other. Free-phase (dense non-aqueous phase liquid (DNAPL)) product was evident at a few drilling locations. A dissolved plume of creosote (PAH) contaminated ground water was also found to be present over a slightly larger area with discharge occurring to the river.

A remediation plan for cleanup of the site was developed and implemented in 1997. The remediation plan included a ground water flow model developed to optimize the placement and operation of a series of recovery wells.

Site Background

The subject property includes about 30 hectares (ha) and is bounded to the south by the North Arm of the Fraser River and to the north by the Canadian Pacific Railway. The property is located on a relatively flat flood plain with topographic relief not exceeding two metres. Surface drainage on the site flows in a southerly direction towards the Fraser River. The site is almost entirely paved with asphalt.

A cedar sawmill currently operates in the western and central portions of the property. A former owner manufactured creosote-preserved wood products on the property in the early 1900's. Creosote contamination of soil and ground water from historical industrial operations was identified in the 1990's during a multi-phased environmental assessment.

Site Assessment Methods

Environmental assessment of the property was conducted as five phased investigations over several years. Field investigations included the installation of more than 40 boreholes with 30 monitoring wells. At six locations the ground water monitoring wells were nested to assess vertical gradients. Twenty boreholes were drilled from a raft to collect foreshore sediment samples and ground water just before it discharged to the river.

A variety of drilling techniques were used during the various phases of work including: solid stem augers, hollow stem augers, sonic rig with continuous core, auger drilling from a raft in river and the use of a hand held portable vibratory drill to collect sediment samples from the foreshore. A cable tool drill rig was used for the ground water collector well installations.

Soil and /or sediment sampling was conducted during drilling. Ground water samples were collected from all monitoring wells on several occasions. Other sampling and assessment included: storm sewer sampling, electromagnetic geophysical surveys and a soil vapour survey.

Slug tests and pump tests were conducted and compared to grain size distributions to assess the hydraulic conductivity of the sand aquifer. Detailed ground water level surveys using transducer and manual readings were conducted during several tidal cycles in order to assess tidal influences on ground water flow directions and velocities.

Identified Contaminants

Creosote is slightly heavier than water and is present in the subsurface as a dense non-aqueous phase liquid (DNAPL). Creosote adsorbs onto soil particles and is also found in the dissolved phase in ground water. The main Polycyclic Aromatic Hydrocarbons (PAHs) identified in the creosote from this site include naphthalene and phenanthrene as well as lesser concentrations of acenaphthene, anthracene, fluoranthene, fluorene, and pyrene. No significant benzene, toluene, ethylbenzene, xylene or chlorophenol concentrations were associated with the creosote at this site.

Out of more than 100 soil samples, 28 samples from 12 borehole locations contained PAH concentrations greater than the BC Contaminated Sites Regulation residential standard. Table 1 presents the mean and maximum PAH concentrations in soil.

Table 1. PAH Concentration in Soil (mg/kg)

PAH	**Mean**	**Maximum**
Naphthalene	409	2,680
Phenanthrene	278	3,140
Benzo(a)pyrene	3.36	41
PAH TEQ	5.73	66.9

Out of more than 30 ground water monitoring wells, 16 contained PAH concentrations in excess of the BC Contaminated Sites Regulation standard for protecting aquatic life. Table 2 presents the mean and maximum PAH concentrations in ground water.

Ground water was also sampled and analyzed for BTEX, metals, anions and nutrients. During sampling the wells were checked for floating phase (LNAPL) on the water surface and sinking phase (DNAPL) at the bottom of the well. DNAPL creosote was found in several wells. High concentrations of iron (20 to 30 mg/L) are present in many of the wells, particularly the shallow wells.

Table 2 PAH Concentrations in Ground Water (mg/L)

PAH	Mean	Maximum
Naphthalene	2.70	29.5
Phenanthrene	0.88	13.7
Benzo(a)pyrene	0.008	0.146
Total PAHs	4.82	61.2

Hydrogeological Conditions

Stratigraphy

Most of the property has had fill placed on it with the thickest areas of fill occurring along the shoreline. The main stratigraphic units underlying the site are described in Table 3 below:

Table 3 **Main Stratigraphic Units**

Approximate Depth	Stratigraphic Unit	Description
0 to 2 m	Fill	♦ generally sand and gravel fill on top, with increasing amounts of wood/silt fill near the river
2 to 4 m	Clayey Silt Aquitard	♦ clayey silt to sandy silt flood plain overbank deposits interbedded with natural organics and peat in some areas
4 to 5 m	Silty Sand	♦ gradational unit between clayey silt and underlying sand aquifer
5 to >20 m	Sand Aquifer	♦ medium to fine grained, deltaic, sand layer, with gradually decreasing grain size with depth and occasional thin silt seams

The contact between the silt aquitard and sand aquifer is gradational, consisting of interbedded fine sand and silts. It is described as a silty sand and averages 1.5 m in thickness.

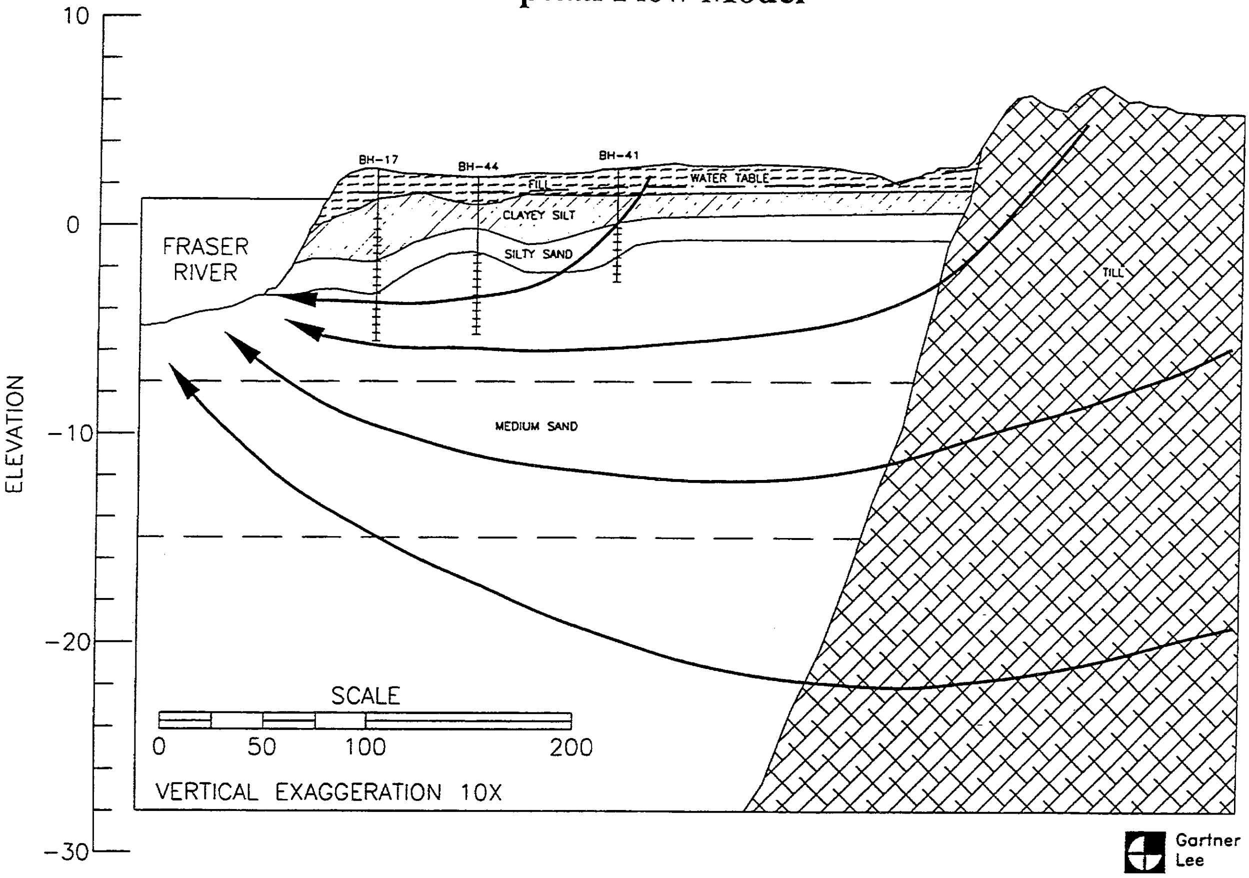
To the north of the site, glacial tills outcrop on the highlands that rise with the topography. The glacial till dips steeply to the south and underlies the silts and sands encountered at the site.

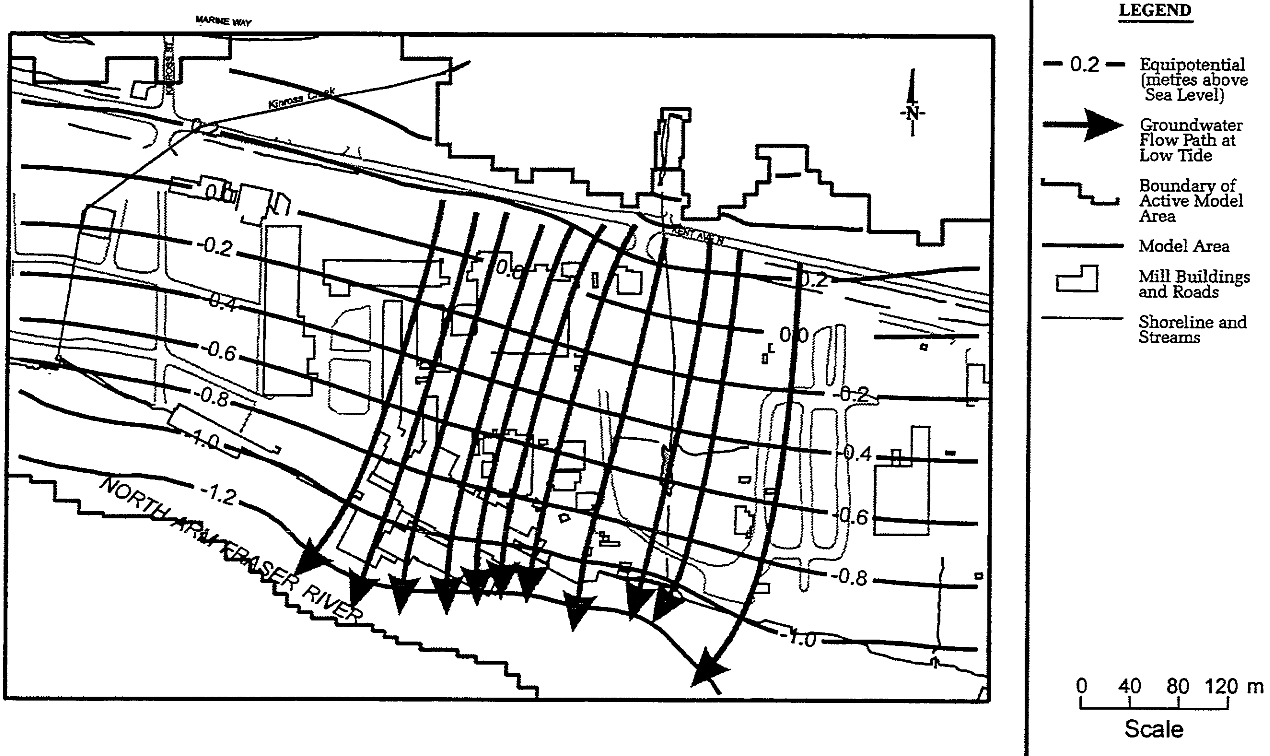
Ground Water Flow

Ground water flows from the higher land southward towards the Fraser River. On the Fraser River flood plain that includes the subject property, the water table becomes much flatter. Depending on location, season, and tides, the water table on the CWP properties generally occurs in the lower part of the fill unit or in the upper part of the clayey silt aquitard, between 1 and 4 m below grade. Vertically downward flow is considered to be the dominant ground water flow direction in the aquitard. Figure 1 is a cross section sketch that illustrates the conceptual model of ground water flow.

Tidal fluctuations within the river affect ground water levels within the sand aquifer, and to a lesser extent, in the overlying clayey silt aquitard. During high tide, the ground water flow near the river reverses direction and for a brief period of time moves in a northerly direction away from the river (based on transducer hydrographs). At low tide, the flow is southward toward the river. The water levels in the sand aquifer vary by up to 1.7 m daily in response to tidal fluctuations in the Fraser River estuary.

Figure 1
Conceptual Flow Model





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Groundwater Flow Paths
At Low Tide - Model Layer 3

Figure 2

The tidal high and low ground water levels occur at similar times for all monitors within 50 m of the river with only a slight time lag between the river levels and ground water levels. This indicates that the sand aquifer is well connected to the river. The water level elevation in the Fraser River was higher than ground water levels at high tide and lower at low tide. This confirms that essentially no water discharges from the site to the Fraser River at high tide and that the largest flows to the river (worst case) occur at low tide. Although the sand aquifer is permeable, the rate of flow is slow (0.05 m/day) because the hydraulic gradient is very flat and tidal fluctuations within the river actually reverse the flow directions twice a day.

Hydraulic Conductivity

The hydraulic conductivities of the stratigraphic units were determined from slug tests, grain size analyses, laboratory permeability tests and pump tests. Slug tests in the sand aquifer were performed using a datalogger and pressure transducer to measure the water level throughout the test because the monitors were known to respond very quickly to water level changes. Water level recovery to static levels occurred within a 1 second time interval in the sand aquifer. It was not practical to perform a slug test analysis on these results, therefore, a pumping test was performed.

The pumping test was conducted using a Rediflow submersible pump. The pumping rate was adjusted to 0.57 L/sec and maintained at this constant rate. The drawdown in the well stabilized after approximately 2 minutes at 0.22 m until the test was terminated. The quick stabilization and small drawdown reflects the highly permeable nature of the sand aquifer.

The results of the test was analyzed using the software package Aquifertest. The calculated transmissivity was 4.5×10^{-3} m^2/sec.

Remediation Plan

A Remediation Plan was prepared to prevent off-site movement of creosote contaminated ground water to the river and to remove creosote contaminated soil "hot spots" where feasible. The main elements of the plan were ground water collection and treatment combined with soil excavation and exsitu bioremediation.

The primary objective of the ground water remediation plan was to prevent discharge of creosote contaminated ground water from leaving the site and moving southward to the Fraser River. This hydraulic control was accomplished by a ground water pump and treat system.

There were a number of constraints that needed to be addressed in the remedial design. The proximity of the creosote contamination to the river meant that pumping wells or drains could potentially draw in large volumes of clean river water, which would have to be treated at substantial cost with no benefit to the environment. The contaminated area is underlain by a highly transmissive aquifer more than 20 m thick. Furthermore, dense non-aqueous phase liquid (DNAPL) creosote, which can sink downward through water table because it is more dense than water, is present in places.

Ground Water Flow Model

A ground water flow model was developed for the creosote contaminated area and vicinity. The model served as a quantitative tool for evaluating site conditions and aided in the design of remedial measures to recover contaminants and prevent their discharge to the Fraser River. The model was used to estimate the required pumping rates and well spacing for a "pump and treat" system of recovery wells intended to capture contaminated ground water.

Specific modelling tasks included:

a) developing and calibrating a numerical model based on the available hydrogeologic data;
b) applying the model to calculate rates and direction of ground water flow under low tide conditions;
c) applying the model to evaluate changes in ground water flow rates and pathways under various remedial scenarios including the use of ground water recovery wells to recover and treat contaminated ground water; and
d) using flow path analysis (particle tracking) to delineate the contaminant capture zones for the ground water recovery wells.

A three-dimensional ground water flow model was developed to simulate ground water flow in the study area. Flow in the sand aquifer was of primary concern but all hydrogeologic units were represented in the model. The model was run assuming steady-state flow. While it was recognized that water levels are changing constantly in response to tidal fluctuation in the Fraser River, the model was used primarily to analyze the "worst-case" condition that occurs at low tide. Under this condition, the gradients towards the river are steepest and therefore the rates of ground water discharge to the river are also high. Pumping by recovery wells would have to be sufficient to overcome these natural gradients in order to ensure capture of the contaminated ground water.

The computer code selected for this study was the U.S. Geological Survey modular ground water flow model, MODFLOW (McDonald and Harbaugh, 1988). MODFLOW is a three-dimensional finite-difference code capable of simulating both transient and steady-state flow in confined or unconfined aquifer systems. The computer code is widely recognized and has been tested and verified.

Model Construction and Calibration

The MODFLOW code solves the ground water flow equation at the centre of each active cell in the finite-difference grid used to represent the study area. The grid contained 114 rows and 115 columns and was designed to provide finer resolution in the area of ground water contamination. The maximum finite-difference cell size is 20 m by 20 m. Smaller cells, 2.5 m by 2.5 m, were used in the centre of the study area. The same grid design was used for each model layer.

In some parts of the study area, the model grid extended beyond the hydrologic boundaries selected. Cells which fell outside the lateral boundaries of the study area were designated as "inactive". There was no ground water flow into the active areas from these cells.

Five layers were used in the ground water flow model to represent the aquifer units identified in the study area. One clayey silt, confining unit (aquitard), with vertical flow was also modelled. The aquifer layers and the confining unit are described below:

Layer 1 – Fill

- Silt soils and fill material (wood waste and imported or dredged sand and gravel) which overlies the clayey confining unit.
- Model hydraulic conductivity 1×10^{-3} m/s.
- Layer 1 was extended out into the Fraser River with constant head boundaries were applied to simulate the known head in the river.
- Recharge in vegetated areas was 820.5 mm/yr (2.6×10^{-8} m/s)
- Recharge to areas covered by mill buildings, roads and parking lots was 250 mm/yr (8.0×10^{-9} m/s)

Confining Unit 1 - Clayey Silt Unit

- Laterally extensive, clayey silt aquitard
- Model vertical hydraulic conductivity of 1×10^{-8} m/s
- Average thickness about 1 m.
- Discharge to the Fraser River was simulated by extending the confining layer into the Fraser River with a vertical conductance of 1×10^{-5} m/s per m.

Layer 2: Silty Sand Unit

- Fine silty sand unit, gradational contact between the clayey silt aquitard and the underlying sand aquifer.
- Thickness of 1m or more
- Model hydraulic conductivity of 1×10^{-5} m/s

Layers 3 through 5: Sand Aquifer

- Layers 3 through 5 represented the sand aquifer
- Consists mostly of medium sand but slightly finer with depth.
- Ground water flow in this aquifer is mostly horizontal towards the Fraser River
- Recharge occurs as leakage from the overlying fill unit across the clayey silt aquitard
- Discharge from the aquifer occurs as leakage across the riverbed deposits in the near shore area.
- Split into three layers to better represent flow patterns resulting from vertical anisotropy and from partially-penetrating remedial wells.
- Model hydraulic conductivity of 5×10^{-4} m/s for Layer 3, 2.5×10^{-4} m/s for Layer 4, and 1.0×10^{-4} m/s for Layer 5.

Model calibration is a procedure in which initial estimates of aquifer properties and recharge rates are adjusted and refined to produce a better match between simulated and observed conditions. Model calibration was done to match water levels and flow directions in the ground water system that were observed during low tide in the Fraser River.

After numerous simulations and model adjustments, a close match was achieved between simulated and observed water levels and flow patterns. All adjustments to the initial estimates fell within reasonable limits based on the range of observed parameter values and published estimates for similar soils.

Table 4 below presents the calibration statistics related to the difference between observed and simulated water levels:

Table 4 Model Calibration Statistics For Layer 3 (Sand Aquifer)

Total Number of Observation Wells	11
Average Difference	-0.109 m
Standard Deviation	0.022 m2
Average Absolute Difference	0.114 m
Sum of the Squares of the Differences	0.3478 m2
Root Mean Squared Error	0.178 m

The error is seen to be small and most of it can be attributed to the fact that some wells are screened across multiple layers and to the simplifying assumptions inherent in applying a steady state model to a highly transient system.

Simulations of Remedial Scenarios

Four remedial scenarios were investigated with the calibrated model. The remedial scenarios focused on the design of a pump-and-treat system that had one or more remedial wells intended to capture contaminated ground water and help retain contaminants within the property boundaries.

The MODFLOW model was used to determine the change in heads and flow directions as a result of pumping. After each simulation, the MODPATH post-processor (Pollock, 1992) was used to determine the capture zone of the recovery well system. The MODPATH code uses results from MODFLOW to track fictitious particles (representing water particles or contaminants) forward from their point of entry to their point of discharge. The flow directions under low tide conditions shown in Figure 2 were determined using a forward tracking technique. Particles can also be tracked backward from the discharge point (e.g., a recovery well) to determine their point of entry. Both forward and backward tracking were used to test whether all particles from the contaminant source areas would be captured by the recovery wells. A trial and error procedure was employed in which various combination of pumping rates and well locations were tested. Constraints imposed on this process included limiting pumping to a maximum rate of 5 L/s, a cutoff point beyond which a significant increase in the size and cost of treatment facilities would be incurred, and limiting the amount of clean ground water and river water to be captured by the wells.

Remedial Scenario 1

The first remedial scenario illustrated here consisted of one remedial well located near the centre of the contaminated area. To achieve the best possible capture, the pumping rate was set at 5 L/s. The simulated drawdowns and capture zones for the one well system are presented in Figure 3. Results of this simulation showed that capture was achieved over most, but not all, of the contaminated areas.

Remedial Scenario 2

The second remedial scenario illustrated here considered the effect of adding five additional wells pumping at either 0.5 or 1.0 L/s for a total withdrawal of 5 L/s. The simulated drawdowns and capture zones for the six well system are presented in Figures 4. The results show that capture of all contaminants would be achieved. Further analysis indicated that water would also be drawn from the lower portion of the sand aquifer which would have the added benefit of capturing dissolved contaminants that may have migrated deeper over time.

Remedial Scenario 3

The first two scenarios assumed that the treated water would be discharged to a sanitary sewer or disposed of off site. The third and fourth remedial scenarios considered the effect of recharging the treated waters to trenches constructed north of the study area. Two alternate recharge locations were selected, Site A and Site B (shown on Figures 5 and 6). The four infiltration trenches were assumed to be 2.5 m wide and 50 m long. It was further presumed that the clayey silt layer would be removed during excavation and that the trenches would be backfilled with coarse gravel. No loss of water was considered to occur during the treatment process so a recharge rate of 1×10^{-5} m/s was applied over the trenches to balance the 5 L/s withdrawal.

The model indicated that recharge from the trenches at Site A would affect the ground water flow patterns in the contaminated area. The number of wells, well locations and pumping rates were adjusted until all the contaminated water and almost all of the treated water was captured. The simulated drawdowns and capture zones for the seven well system are presented in Figure 5. Aside from the savings achieved by recycling the treated water on-site, the potential exists to speed up the recovery process by amending the recharge water with surfactants and/or nutrients to encourage dissolution and biodegradation of the contaminants

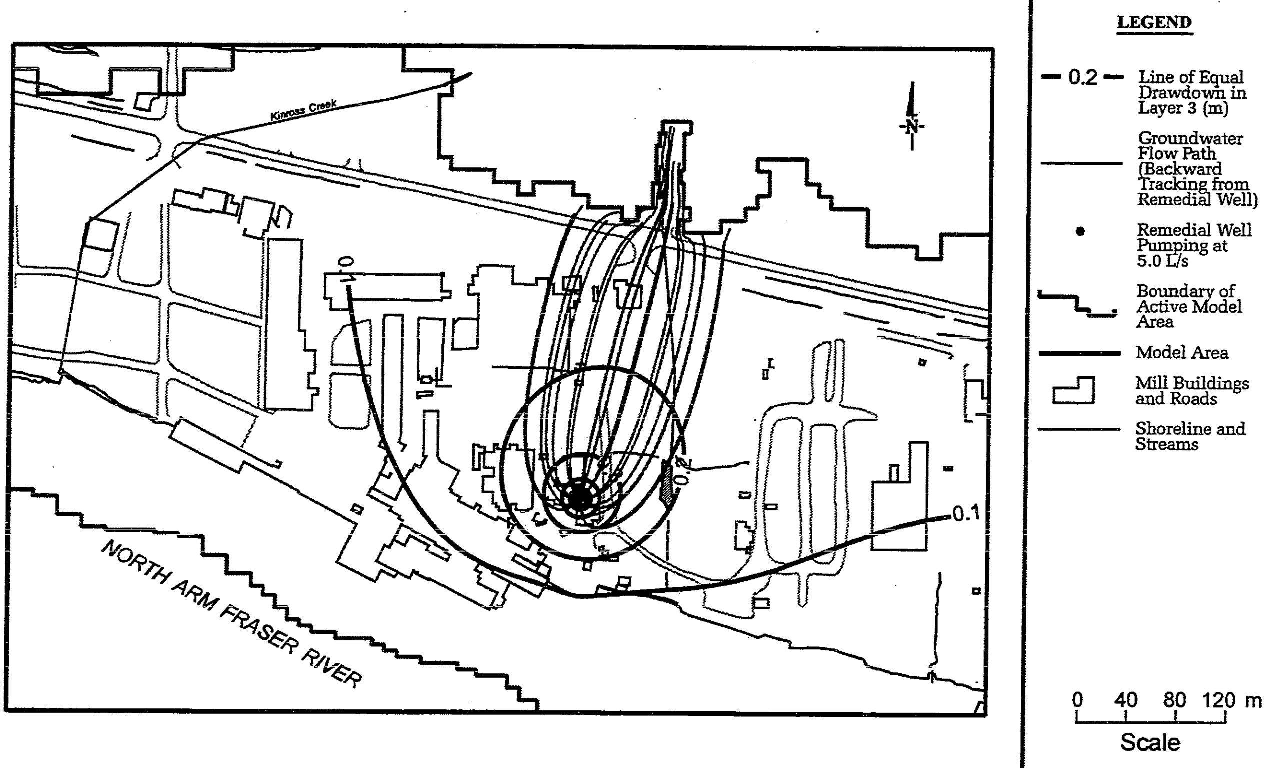
Remedial Scenario 4

In the fourth remedial scenario, discharge of treated water was presumed to occur at Site B. This location was further from the contaminated area and interference effects were smaller. A six well scheme using the same pumping rates and well locations as Scenario 2 was found to be adequate to achieve capture of the contaminants. The simulated drawdowns, and capture zones for the six well system are presented in Figure 6.

Pump and Treat System

Three dimensional ground water flow modelling indicated that that all creosote contaminated ground water could be captured by pumping six wells located more or less in a line parallel to the river with treated effluent discharge to the sanitary sewer. The eastern portion of the contaminated area was excavated to reduce the required area of ground water capture and a five well ground water collection system was installed.

The five collector wells were constructed 12 m deep on average by drilling a 250 mm (10") diameter, cased borehole with a cable tool rig. The upper 6 m was constructed of 250 mm diameter steel casing. A 4.6 m long stainless steel wire wound well screen (200 mm diameter) was installed in the medium sand aquifer below the upper casing. A 1.5 m long tail pipe was installed at the bottom of the screen to capture any DNAPL creosote product that enters the well and sinks to the bottom.



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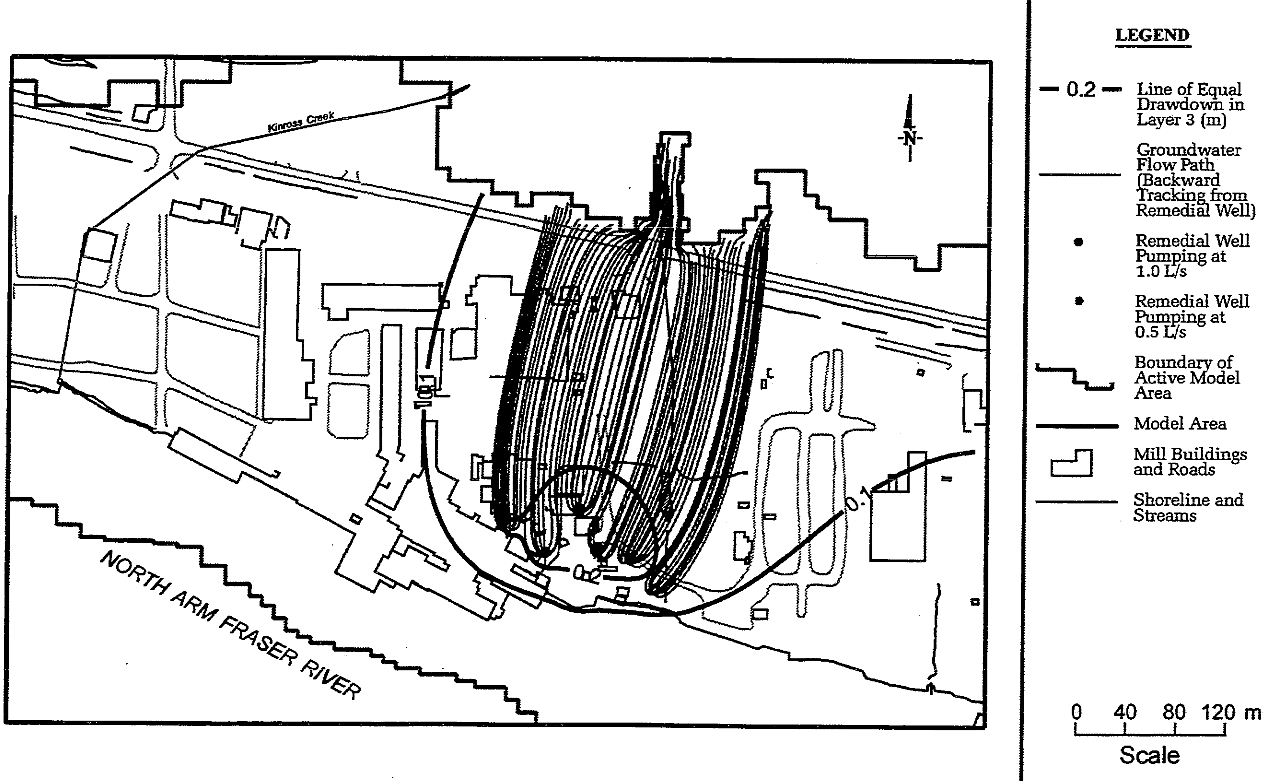
Simulated Drawdowns and Groundwater Flow Paths with One Well Pumping at 5.0 L/s

Figure 3



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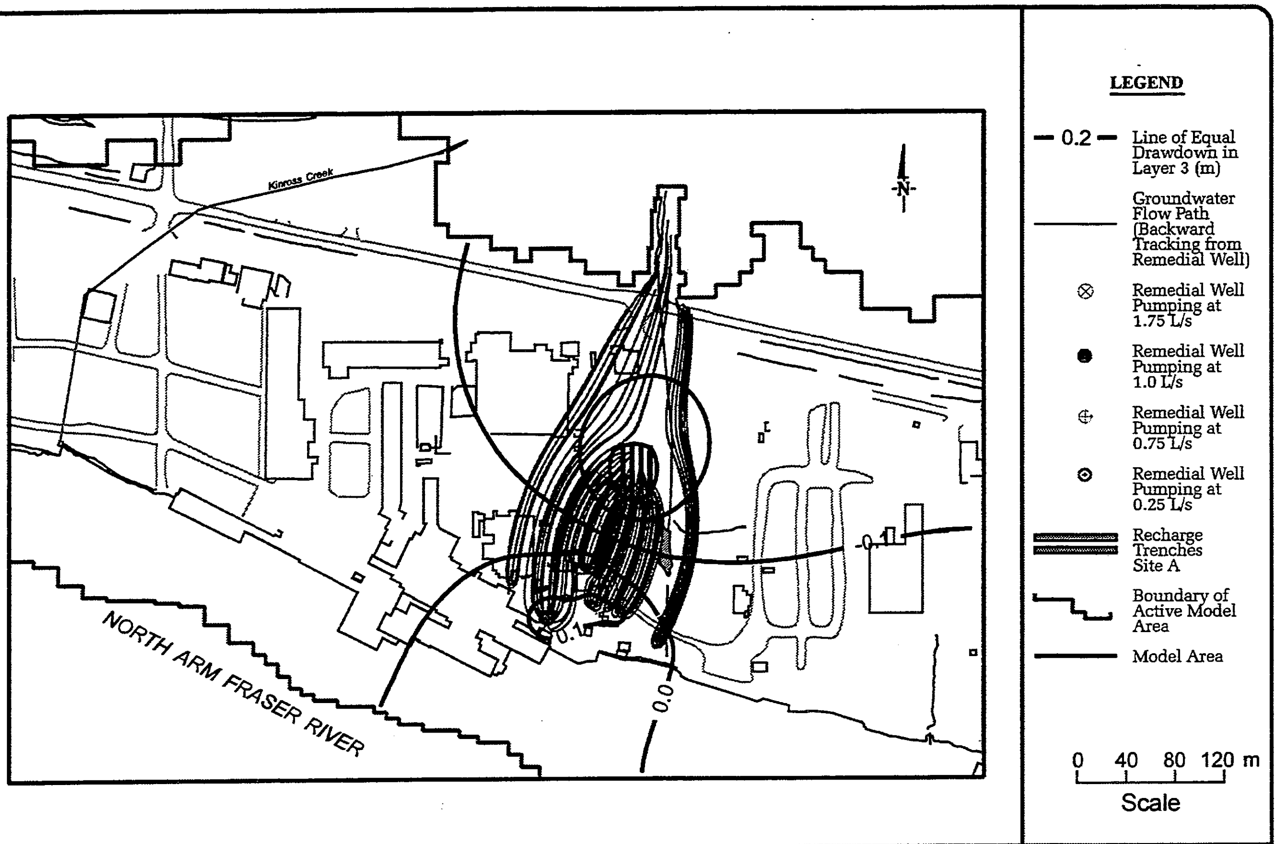
Simulated Drawdowns and Groundwater Flow Paths with Six Wells Pumping a Total of 5.0 L/s

Figure 4



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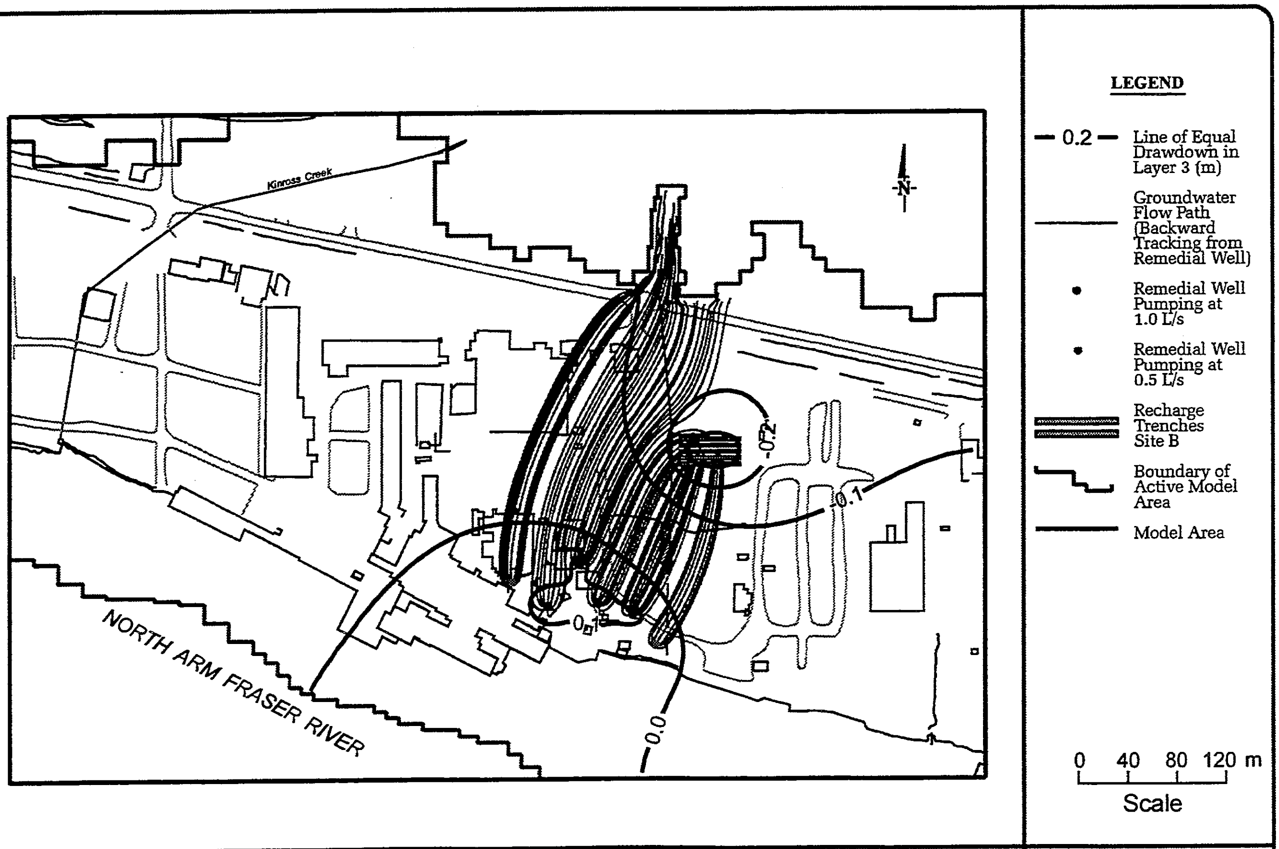
Simulated Drawdowns and Groundwater Flow Paths
with Seven Wells Pumping a Total of 5.0 L/s
Treated Water Recharged at Site A

Figure 5



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Simulated Drawdowns and Groundwater Flow Paths
with Six Wells Pumping a Total of 5.0 L/s
Treated Water Recharged at Site B

Figure 6

A 100 mm diameter submersible pump was be installed in each well just above the well screen to collect contaminated ground water. A small portable air driven pump was installed through a 50 mm conduit pipe to the sump at the bottom of the well, to collect DNAPL creosote product. DNAPL collection is done as required depending upon the rate of accumulation in each well. The well caps allow access for water level monitoring and there is a sample valve on the water discharge line. The wells are completed flush to grade with steel, lockable enclosures. Pump controls and flow meters are located at the water treatment facility. Power lines (air and electrical) and water discharge lines are in buried conduits installed in trenches.

During low tide the individual wells are pumped at rates of 1 L/s (+/- 50%) and the total flow is 5L/s or less. During slack tide and high tide the flow rates is reduced based on the differential between river levels and ground water levels which is continuously monitored with pressure transducers. The pumping rate is controlled electronically and varies in response to the differential between river levels and ground water levels monitored with electronic transducers.

A modular water treatment system treats the collected ground water so that the effluent is acceptable for disposal to the sanitary sewer. The treatment system consists of the following components:

- oil/water/DNAPL separating equipment
- iron removal equipment
- suspended solids removal equipment
- trace organic removal equipment (2 stage granular clay adsorbent and granular activated carbon)
- ancillary equipment

The system was designed to provided effluent concentrations which meet the Sanitary Sewer discharge criteria of 0.050 mg/L total PAH (City of Vancouver Sewer Use Bylaw).

The pump and treat system has been in operation for more than 6 months. The only significant problem has been the high iron concentrations which cause increased maintenance costs.

REFERENCES

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