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PREDICTIVE MODELLING AND MONITORING NATURAL ATTENUATION TO SAVE REMEDIAL COSTS

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Abstract

This paper describes the multidisciplinary components of a spill remediation. The spill had occurred because of a pipeline break, which contained oil and produced water. The initial spill response was conducted by assessing the soil and surface water quality. Three geophysical surveys were conducted followed by an ecological assessment to determine the evolution of a dissolved salt water plume beneath the site and potential impact on the growth and regeneration of white spruce trees in and adjacent to the spill area. The electromagnetic (EM) surveys showed decreasing terrain conductivity responses with time. The ecological assessment indicated the age of the spill post-dated the age of the deceased trees and water logging conditions have potentially caused the tree kill.

A review of historical aerial photos for the area confirmed the results of the ecological assessment. Potentially, construction (roads and well sites) downgradient of the spill area had restricted surface water flow downgradient of the site resulting in water logged conditions, consequently damaging the trees in the area.

Based on the available information, it was decided to further assess and characterize the hydrogeologic regime beneath the site and observe prevailing natural processes which potentially decrease the salt concentration.

The results of the site assessment indicated that groundwater was discharging (i.e., upward vertical groundwater flow) downgradient of the primary spill area. Potentially recharged through infiltration, horizontal and vertical groundwater flow had been diluting chloride concentrations significantly.

A contaminant mass transport model was generated using step-wise mixing calculations to estimate the rate of dilution of the chloride mass. A good calibration was observed, where the measured concentration lie within the predicted range two years after the spill. Furthermore, predicted calculations suggest that the concentrations will decrease to acceptable concentrations and will not affect the nearby off-site water resources.

The key processes contributing to natural attenuation chloride mass by dilution were recharge, vertical upward and horizontal groundwater flow. These processes enhanced soil flushing, dilution, and restricted transport of chloride to deeper geologic units.

The model results were confirmed with the groundwater monitoring results in 2006. All the shallow groundwater monitoring wells had chloride concentrations less than the drinking water criteria of 250 mg/L. No salt impacts were observed in deeper wells.

The foregoing site assessment and predictive modelling efforts resulted in remedial cost saving of approximately $900,000 to $2.3 million Canadian dollars.

Key Words: Salt spill, Electromagnetic survey, Chloride, Site Assessment, Predictive modelling, Remedial cost savings.

Introduction

In the fall of 2002, an instrument technician identified a poor test result for a pipeline running north-south between two well sites 12-15 and 13-15 (Figure 1). The well sites are located in central Alberta, Canada. On visiting the site, the technician encountered standing oil and water. The pipeline failure occurred in peaty soils used as summer pasture. It is not known for how long the pipeline leaked. The cause of the break was understood to be badly corroded pipe. The line was shut in and produced fluids were routed elsewhere.

Figure 1: Site Plan

The topography surrounding the site is generally flat, sloping approximately 0.5% to the northeast.

The dominant soil type in the area is dark gray to gray mesisol. This is an organic soil material at a stage of decomposition intermediate between fibric and humic materials. The material is partially physically and biochemically altered. This material usually occurs in depressional areas where there is ponding water.

Initial Pipeline Spill Response

As part of the initial spill response, standing fluid (reportedly oil and saltwater) was removed from the site using a vacuum truck. Four trenches were cut along the pipeline right-of-way (ROW) to collect fluids and prevent further runoff. Shallow groundwater was encountered in the area. A geophysical survey (EM31 and EM38) was completed in the vicinity of the spill area in September 2002. The impacted area was found to extend along the pipeline ROW with a north-eastward extension.

Water samples collected from the collection trenches had chloride concentrations ranging between 63 mg/L to 225 mg/L. Soil samples within the top 20 cm of salt-impact peaty soils in the spill area had a chloride concentration of 39,100 mg/kg, SAR value of 49.7, and EC value of 29.90 dS/m. The salt-impacted peaty soil was excavated and piled within the affected area and removed later in December 2002 (approximately 2,200 tonnes of peat soils were landfilled off site). The cut-off trenches were backfilled once laboratory analysis of soil confirmed that the trenches met applicable criteria. The trench along the east-west fence line was left open. At the time, laboratory testing confirmed that the produced salt water had not reached the trench.

Remedial Alternatives

One of the remedial options to cleanup the salt impacted soil and groundwater was to excavate and dispose off the soil and pump and dispose off/treat the groundwater. The area and volume of in-situ impacted soil was estimated as approximately 5,225 m^2 and 16,000 m^3, respectively. The approximate costs for the traditional remedial efforts were in the order of approximately 2.1 million to 3 million Canadian dollars.

The alternate option was to conduct additional site assessment and review the hydrogeologic regime for any prevailing natural process which may be contributing to the attenuation (dilution) of chloride mass beneath the site.

Adjusting the EM survey in 2002 and in 2003 to similar terrain conductivity scales (Figure 2 and Figure 3), it was observed that the area of the greater terrain conductivity decreased over a year and the plume had migrated downgradient towards the northeast. The trends in the terrain conductivity changes supported the hypothesis of natural process for the attenuation (dilution) of chloride mass. Therefore, it was decided to proceed with the alternative option of additional site assessment and monitor the natural attenuation (dilution) processes.

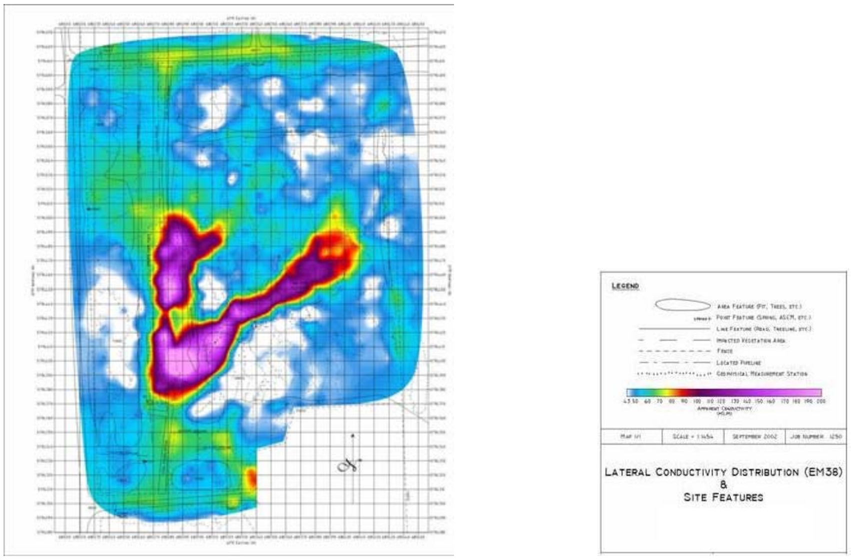

Figure 2: 2002 EM38 Survey – Adjusted Scales

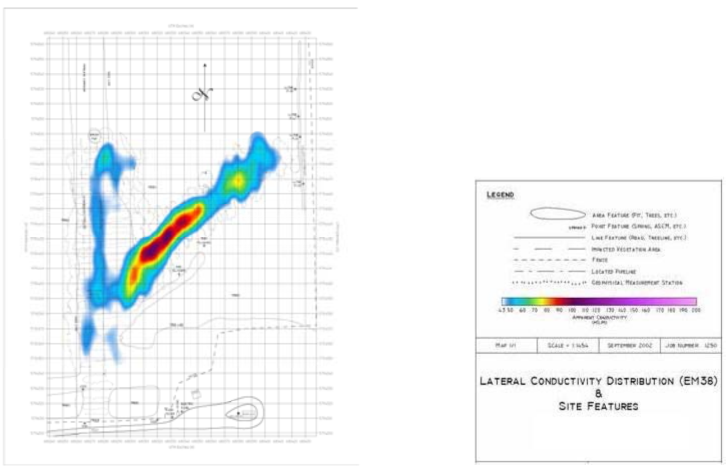

Figure 3: 2003 EM38 Survey – Adjusted Scale

Site Assessment

The methodology adopted for the site assessment was to evaluate vegetation on site, review the water wells records and nearby water bodies for the identification of domestic use aquifer and other nearby receptors, combined with additional EM survey in 2004 to monitor the trends in changes in terrain conductivity. A soil and groundwater investigation was also conducted to characterize the hydrogeologic regime and impacts of chloride on groundwater.

The following sections briefly describe the results obtained during the site assessment.

Vegetation Evaluation

The results of vegetation evaluation indicated that the mature white spruce trees have been dead for greater than five years and predate the spill of produced water. Tree mortality is thought to be the result of a rise in the local water table. However, white spruce regeneration has been affected by the pipeline spill.

The cause of the rise in the local water table was investigated by reviewing the drainage pattern and historical aerial photographs.

Review of drainage flow pattern and historical air photographs

The natural surface drainage was observed from southwest to the northeast towards the affected vegetation area. There were numerous constructions (roads and well sites) within the natural surface drainage path (i.e., upgradient and downgradient of the affected vegetation area), which potentially had restricted the natural flow pattern. The upgradient construction increased the surface runoff to the site and downgradient construction restricted the flow off of the site; consequently resulting in the rise in the water table and ponding of surface water.

Figure 4 A, B, C, and D show the aerial photographs of the area for the year 1983, 1993, 1994, and 1998, respectively.

The aerial photographs show dense vegetation in the affected area till 1993 and some effect in 1994. In the next available photograph (1998) sparse vegetation in the northeast of the spill area was observed, which suggests the vegetation stress in the northeast of the spill area occurred between 1993 and 1998 prior to the spill. Construction of downgradient roads and well sites may also be observed during that period, which supports the earlier assumption that the numerous construction activities had restricted the flow off of the site, consequently resulting in the rise in the water table

Figure 4A

Figure 4B

Figure 4 C

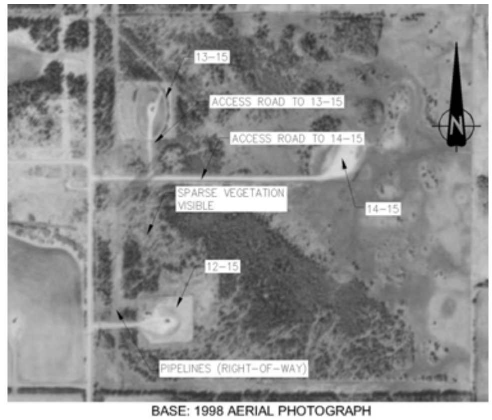

Figure 4 D

Water Wells and Nearby Receptors

There are 12 industrial water wells and 1 domestic/livestock well in an approximate 1 km radius of the site. Based on the completion details of the wells there is a domestic use aquifer beneath the site. Other nearby receptors includes surface water bodies (an intermittent lake or slough and a river). An intermittent lake or slough is within 100 m to 200 m northeast of the site. A tributary of a river drains the intermittent lake and flows southeasterly towards the river. The river is approximately 4 km northeast of the site and flows to the southeast. A lake, approximately 15 km northeast of the site, has approximately the same elevation as the site (945 m AMSL). The river prevents surface water flowing from the site to the Lake.

2004 EM survey

The 2004 EM 38 map is shown on Figure 5. Similar to the previous EM 38 maps (Figure 2 and Figure 3), the 2004 EM 38 map suggests two potential produced water pathways towards the north and northeast extending from the area of pipeline break. However, the 2004 EM 38 shows a further reduction and migration of the terrain conductivity towards the northeast.

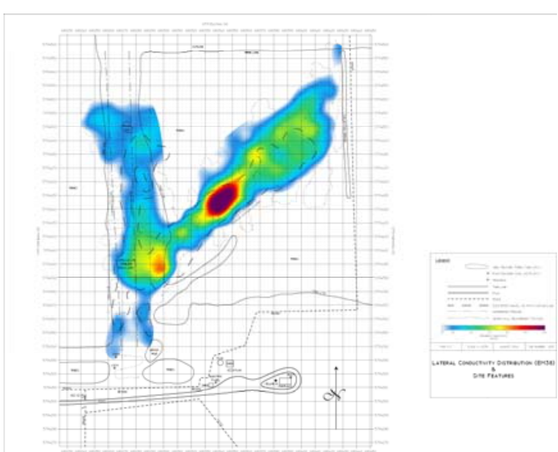

Figure 5: 2004 EM38 Survey

Soil and Groundwater Assessment

Eleven boreholes were drilled in the area along the pipeline spill pathways (north and northeast of the pipeline spill). Groundwater monitoring wells were installed in all the boreholes.

The stratigraphy encountered generally consists of a thin fibric organic material overlying medium to dark gray, wet, soft to firm silty clay till to an approximately depth of 2.4 m depth. Fine brownish gray sandstone bedrock was encountered underlying the silty clay till. The bedrock was encountered to a total drilled depth of 4.4 m.

Soil Quality

The soil quality in three areas affected by the spill is described below.

Vicinity of the Pipeline Break Area

Figure 6A and Figure 6B show the chloride concentrations and SAR values versus depth, respectively, in the vicinity of the pipeline break area (05MW03). The chloride concentrations to a depth of 1.8 m ranged between 309.39 mg/kg (0.9 m) and 55.65 (1.5 m) mg/kg. Beneath the depth of 1.8 m, chloride concentrations decreased from 270 mg/kg (1.8 m) to 36 mg/kg (4.2 m).

No SAR exceedances were detected in this area.

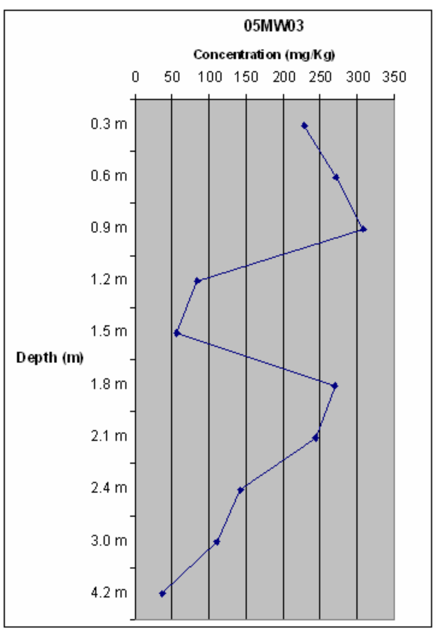

Figure 6A

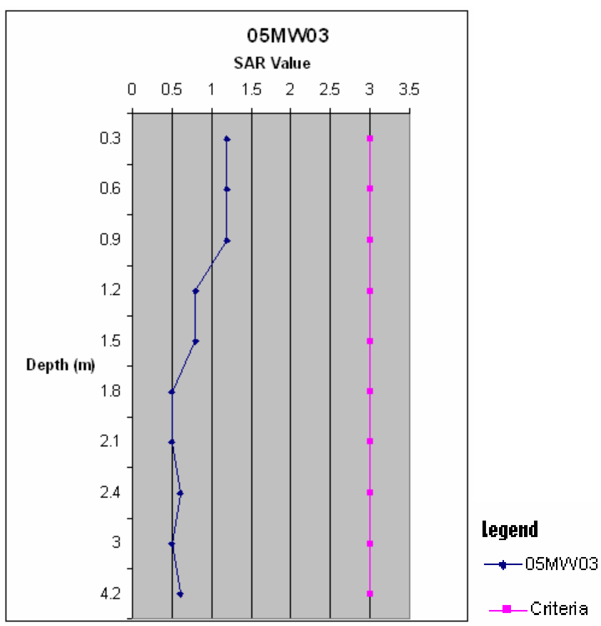

Figure 6 B

Northeast of the Pipeline Break Area

Figure 7A and Figure 7B show the chloride concentrations and SAR values versus depth, respectively in the northeast of the pipeline break area (05MW06/05MW07 nested wells within red purple area shown in 2004 EM 38 map)

The chloride concentrations decreased from 1,936.55 mg/kg at 0.6 m to 51.28 mg/kg at 1.8 m depth. The soil samples collected between 2.1 m to 4.2 m depth exhibited the chloride concentrations ranging between 33.15 mg/kg and 9.45 mg/kg. The SAR values exceeded the criteria at the depth of 0.3 m, 0.6 m, 0.9 m, and 1.2 m and decreased with the depth. SAR exceedances ranged between 4.9 SAR to 9.2 SAR.

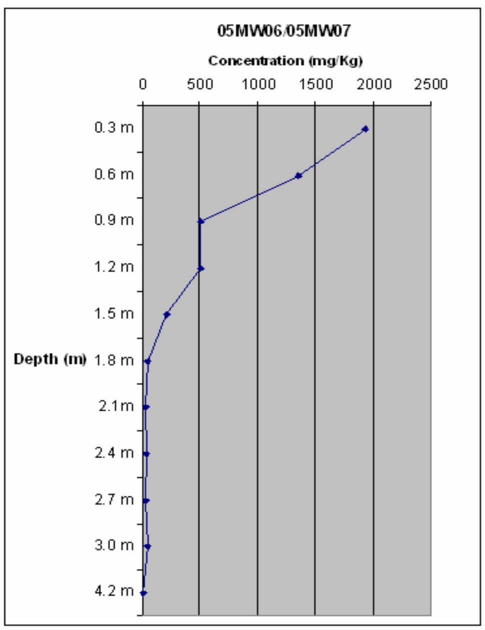

Figure 7A

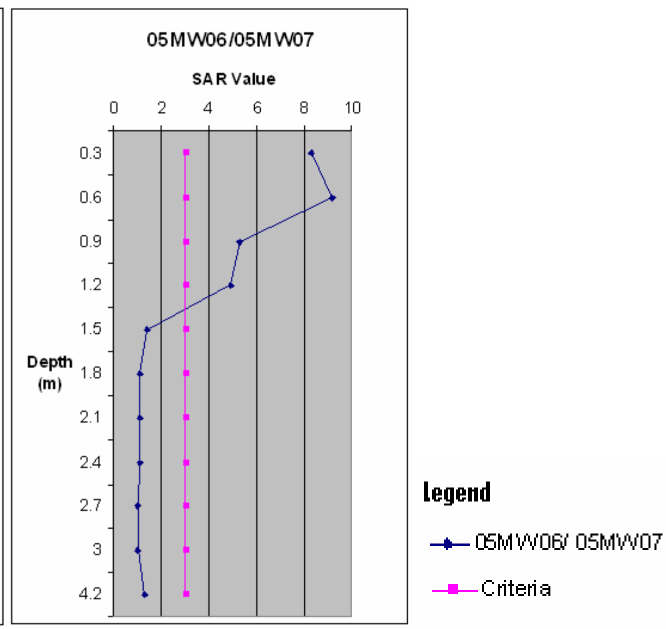

Figure 7B

North of the Pipeline Break Area

A maximum chloride concentration of 195.01 mg/kg was observed at 0.3 m and decreased with depth to 58.34 mg/kg at 1.8 m.

SAR exceeded the governing criteria of 3 SAR units in the soil samples collected from the depths of 0.3 m, 0.6 m, 0.9 m, and 1.5 m and generally decreased with the depth. The exceedances ranged between 3.0 SAR and 5.2 SAR.

Groundwater Flow Direction

The groundwater monitoring data collected from the monitoring wells inferred that the direction of shallow groundwater flow at the site is toward north-northeast (Figure 8). The water levels in few shallow downgradient monitoring wells towards northeast were measured at or above the ground levels (artesian conditions). A deep monitoring well also exhibited an artesian condition with water levels measured above ground.

The average horizontal hydraulic gradient measured was approximately 0.025 m/m.

The vertical hydraulic gradient has been estimated at the nested monitoring well pairs located upgradient (near the vicinity of the pipeline break area) and downgradient (towards northeast of the pipeline break within red purple area). A slight downward vertical gradient of approximately 0.003 m/m was observed at upgradient nested wells; however, an upward hydraulic gradient of approximately 0.35 m/m was observed at downgradient nested wells. The difference at upgradient nested well is less than the elevations typical of surveying and field measurements. In this location, the groundwater flow appears to be essentially horizontal. Discharge groundwater conditions exist at the downgradient nested well location. A groundwater flow net is presented on Figure 9.

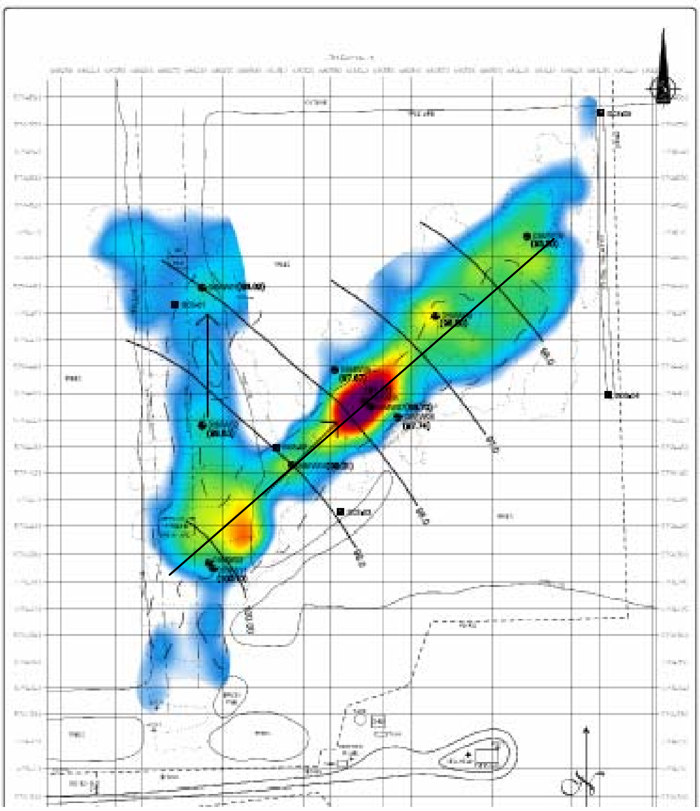

Figure 8: Groundwater Flow Direction

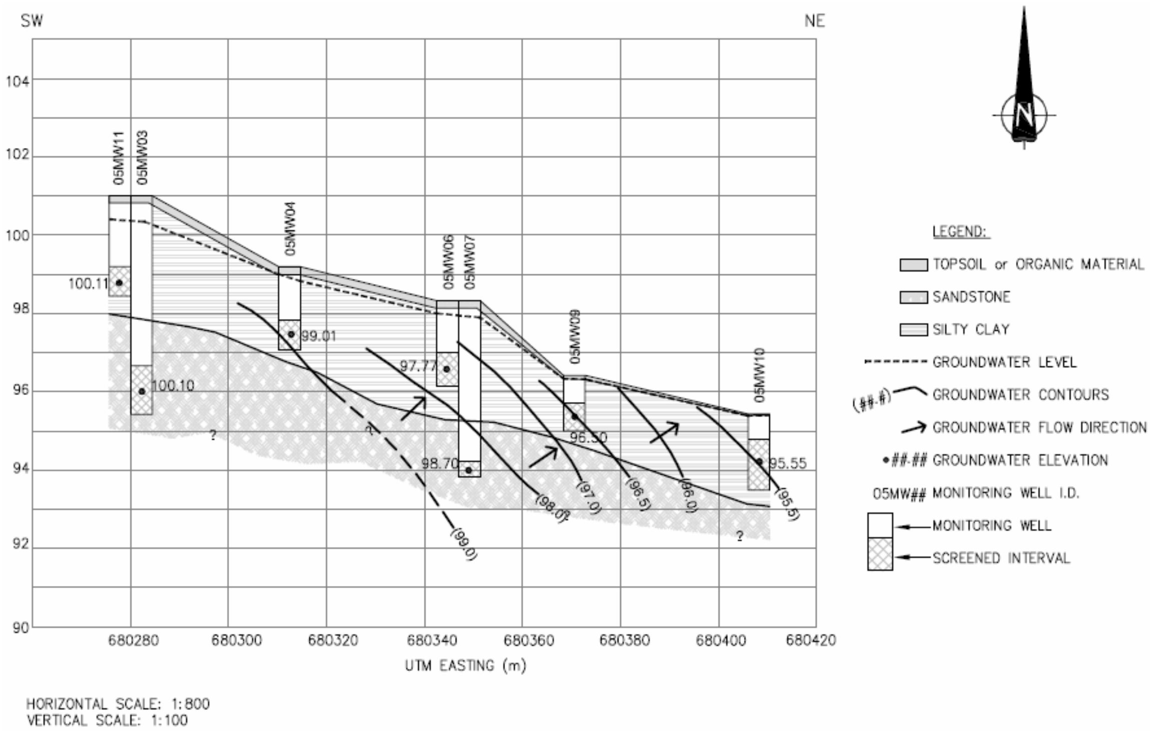

Figure 9: Groundwater Flow Net

Hydraulic conductivity values of 3 x 10^{-7} m/sec and 1 x 10^{-5} m/sec at the upgradient and downgradient shallow wells, respectively, were estimated. The average linear groundwater velocity was estimated as 57 m/year and 45 m/year towards north and northeast of the pipeline break area, respectively.

Groundwater Quality

The groundwater quality in three areas affected by the spill is summarized below.

Vicinity of the Pipeline Break Area (05MW03 and 05MW11)

Groundwater quality in this area is characterized by neutral pH values ranging between 6.9 and 7.2 and total dissolved solid (TDS) concentrations between 408 mg/L and 1,350 mg/L. The maximum concentrations of sulphate and nitrate were detected as 20.7 mg/L and 0.66 mg/L, respectively. Greater concentrations of chloride were detected at shallow groundwater monitoring wells than deep. In the nested pair chloride concentrations were detected as 523 mg/L and 21.7 mg/L in shallow and deep groundwater monitoring wells, respectively.

The results of the laboratory analyses indicate that the concentrations of all routine parameters, BTEX, PHC fractions (F1 and F2) were less than the established criteria.

North of the Pipeline Break Area (05MW01 and 05MW02)

Groundwater quality in this area is characterized by neutral pH values of 7.3, TDS concentrations between 379 mg/L and 934 mg/L. Maximum concentrations of sulphate and nitrate were less than the established criteria

Northeast of the Spill Area

Groundwater quality in this area is characterized by neutral pH values ranging between 7.1 and 7.5 and TDS concentrations between 658 mg/L and 1,670 mg/L. The maximum concentrations of sulphate and nitrate were detected as 87.6 mg/L and 0.14 mg/L, respectively.

Maximum chloride concentrations of 778 mg/L were detected at shallow well drilled in the red purple area shown in 2004 EM survey map. Deep well within red purple area exhibited a chloride concentration of 5.7 mg/L. Trace dissolved metal concentrations were also detected in this area.

BTEX, PHC fractions (F1 and F2) were less than the established criteria in all three areas.

Model Development

The following conclusions were made based on the results of site investigations:

- trees were not killed by the salt spill;
- chloride concentrations were not affecting the water quality within the deep (bedrock) aquifer; and
- the chloride plume was moving and decreasing over time.

A hydrogeologic conceptual model of the site was developed to evaluate the processes causing chloride mass decrease with time (attenuation). The sustainability of the processes (fate and transport of chloride mass) was also assessed by performing predictive modelling.

Conceptual Model

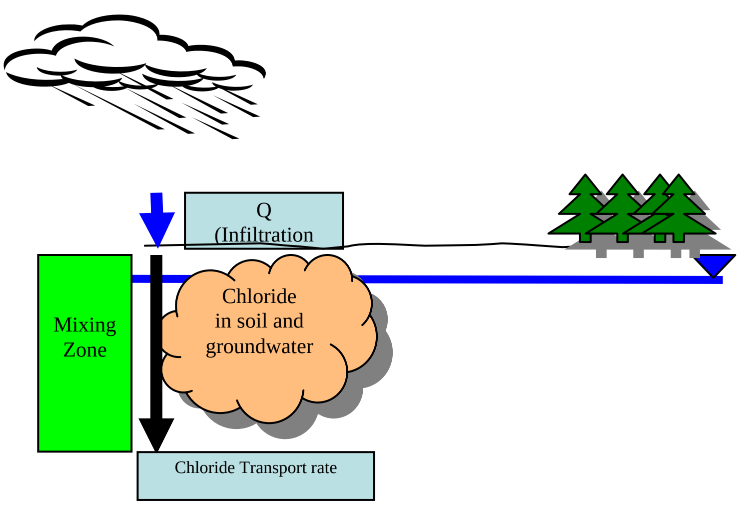

Figure 10: Conceptual Salt Leaching Model

2002 EM survey results showed that the area in the vicinity of the pipeline spill was highly impacted with the greatest EC values (Figure 2). During the initial pipeline spill response (September 2002) chloride concentrations of 39,100 mg/kg was detected in a soil sample collected in this area. Due to the shallow depth to the groundwater, this concentration was considered to be present within the saturated zone and; therefore, affected the groundwater quality. 2003 and 2004 EM38 maps showed a plume (red/purple colour) along the northeast pathway, which had migrated from the spill area to the northeast pathway. Fate and transport of this contamination plume was assessed in the model. The model was based on the mass of chloride in a volume of a cell represented dimensionally by a conventional time length (travel distance) and area comprising of a mixing width and depth during a time step. The mass of chloride is being diluted by the processes of infiltration through recharge, horizontal, and vertical groundwater flow (Figure 11). The mass in the cell during one time step will be the sum of the mass entering to the cell though horizontal groundwater flow, infiltration through recharge and upward groundwater flow as represented by transport model matrix (Figure 12).

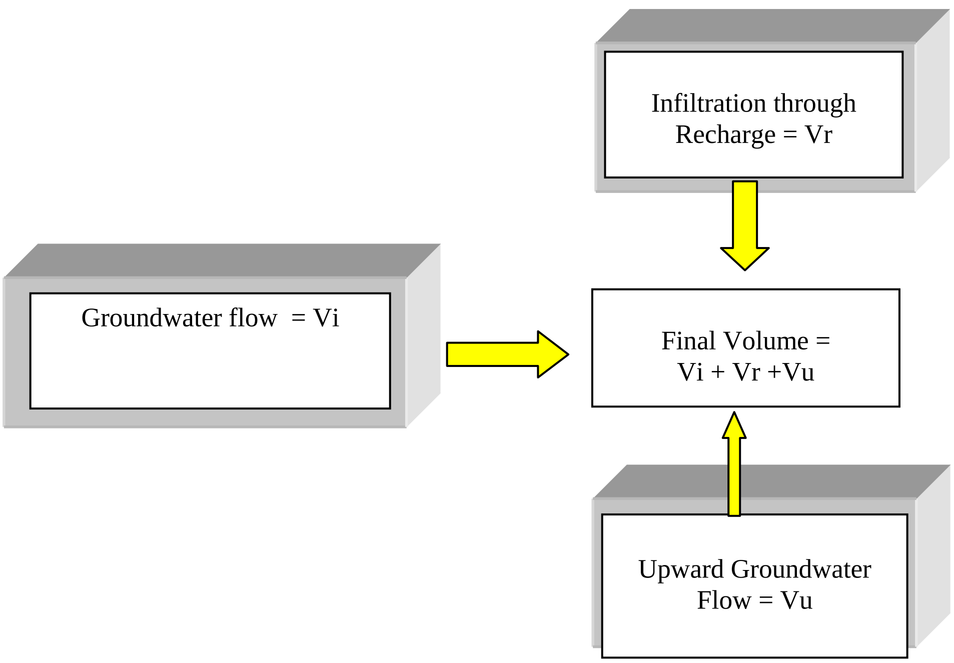

Figure 11: Representative Cell Volume and Dilution Processes

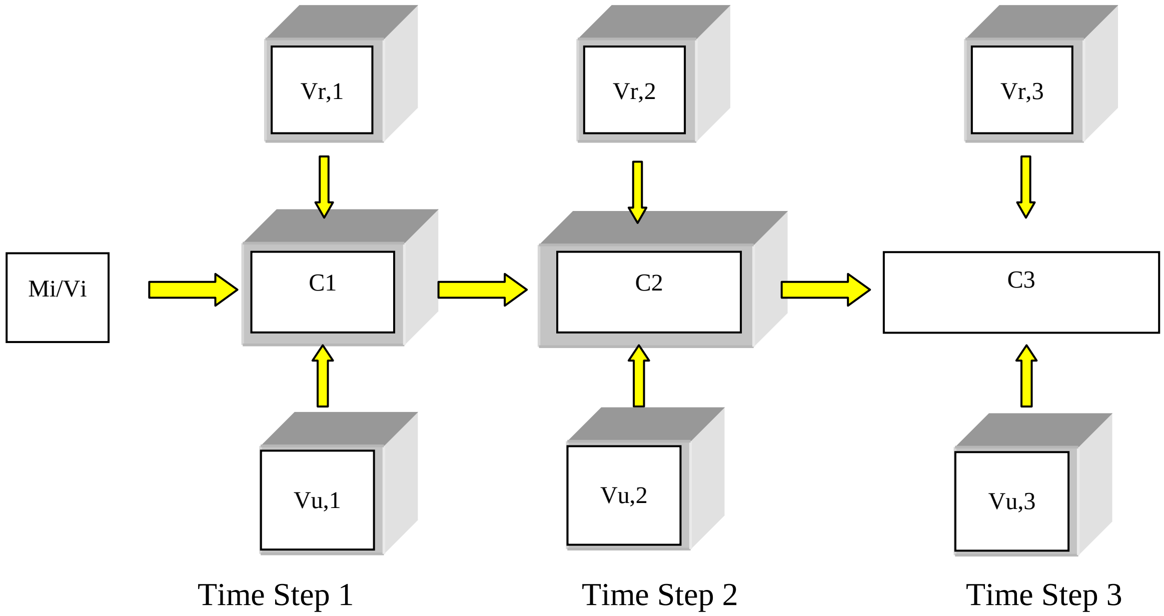

Figure 12: Transport Model Matrix

Model Results

Figure 13 shows the estimated spatial chloride concentrations at different time steps. The results suggest that initial chloride concentration of 39,100 mg/L in 2002 is decreased to the concentrations ranging between 622 mg/L and 936 mg/L at the end of second time step (two years after the spill). The travel distance in two years is approximately 90 m. This concentration corresponds to the measured concentration of 745 mg/L at the monitoring well 05MW06 drilled at approximately 90 m from the pipeline spill in spring 2005. This was a good calibration for the model and validated the estimated dilution rates due to infiltration, horizontal and vertical groundwater flows. The model was also solved for the future time steps and it was observed that chloride concentrations will decrease to less than the governing drinking water criteria with a travel distance of further 45 m in the next time step (Figure 13).

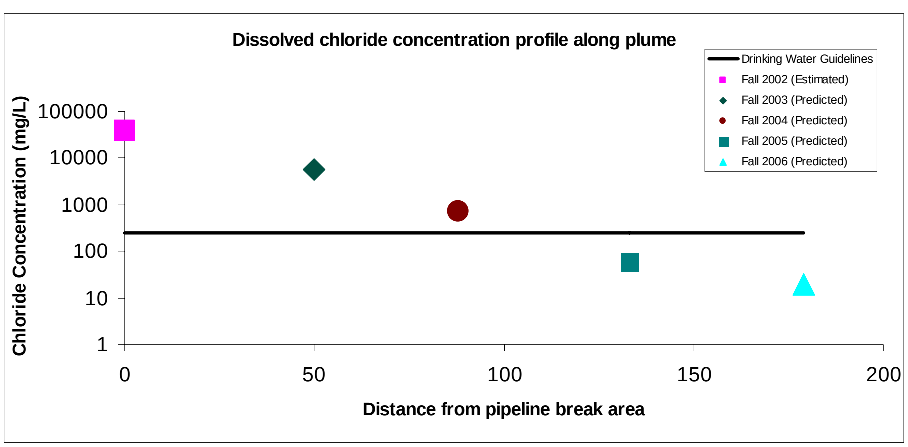

Figure 13: Model calculation results

Model Results Verification

Figure 14 shows the dissolved chloride concentration profile along the plume measured in spring 2005, spring 2006, and fall 2006. Figure 15 shows a comparison of estimated and measured chloride concentrations in different time steps.

The field results suggest that the chloride concentrations have decreased to less than the criteria in spring 2006. The measured chloride concentration in the downgradient well is marginally greater than the predicted chloride concentrations which may be due residual concentrations outside of the conceptualized cell of chloride mass, which will potentially be attenuated with a significantly high dilution rate.

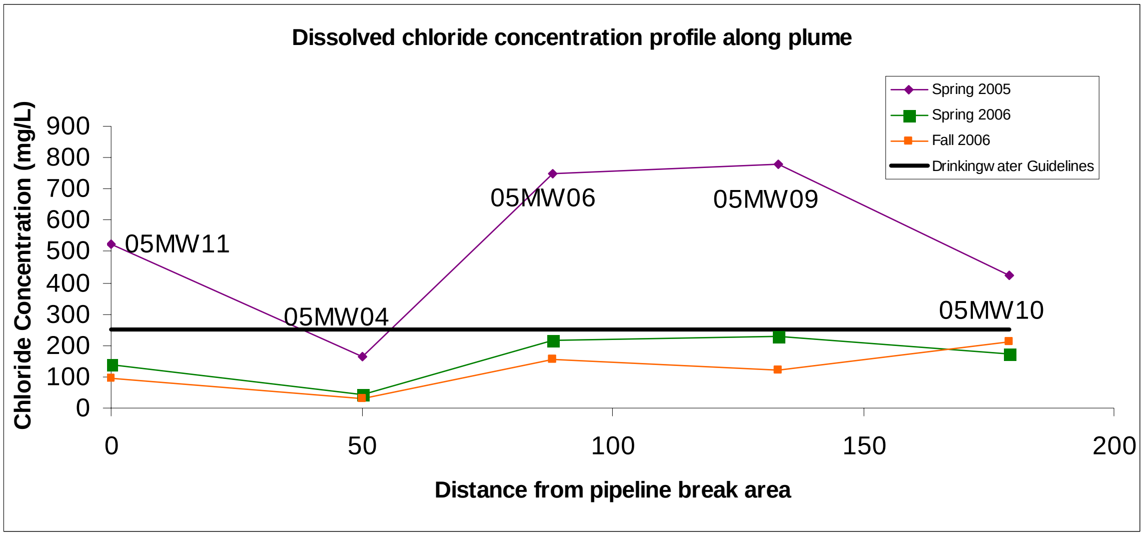

Figure 14: Groundwater Monitoring Data

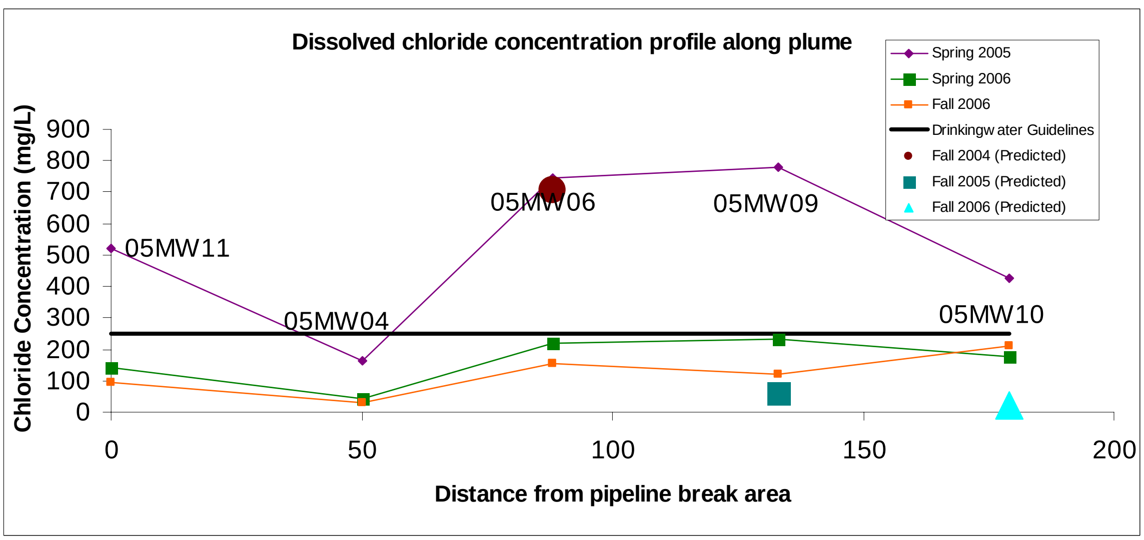

Figure 15: Groundwater Monitoring Data vs. Model Data

Conclusion

Based on the results of the 2005 site investigations, the following conclusions were made:

- Model calculations support the EM survey results and indicate a significant decrease in chloride concentrations with time. The decrease is due to the dilution of chloride concentrations with infiltration, horizontal, and vertical components of groundwater flow. The prevailing dilution rate is sufficient for chloride concentrations to decrease to acceptable levels prior to reaching off-site water resources.

- Some of the key elements of natural attenuation and dilution of salts are:
  - Upward vertical groundwater flow direction (Vu).
    - salts not being transported deeper; and
    - enhances soil flushing.
  - Horizontal flow 45 m/year (Vi).
  - Infiltration rate (Vr).
    - provides groundwater recharge; and
    - enhanced by ponding (drainage course disrupted).

- Mature white spruce trees in the spill area have been dead for greater than five years (before the pipeline spill). Tree mortality is understood to be the result of a rise in the local water table and not due to the contact with the produced water. The rise in the local water levels may have resulted from construction activities carried out along the natural drainage path during 1990s. White spruce regeneration has been impacted by the pipeline spill.

- Cost Saving of $900,000 to $2.3 million Canadian dollars. Remediation complete within four to six year timeframe with a minimal surface disturbance

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