CHARACTERIZATION AND REMEDIATION OF A CHLORIDE-IMPACTED AQUIFER IN NORTHWESTERN ALBERTA

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ABSTRACT

As part of a property acquisition, Devon Canada Corporation inherited a site with subsurface impacts related to the release of produced water at an upstream oil battery in northwestern Alberta. Site characterization and delineation of the groundwater impacts indicates that there are off-site impacts of chloride greater than 50,000 mg/L. The stratigraphy of the site consists of sand overlying fractured clay, with the water table encountered close to the undulating sand-clay interface. Pumping test results suggest that groundwater recovery will be limited and augmentation of the current remediation system is required.

RÉSUMÉ

Lors d'une acquisition de proprieté, Devon Canada Corporation a herité un site avec des impactes souterraines liée au dégagement d'eau saline à une batterie de pétrole située au nord-ouest de l'Alberta. La caractérisation du site et la délimitation des impacts à l'eau souterraine indique que des concentrations de chloride au-delà du site sont plus que 50,000 mg/L. La stratigraphie du site consiste de sable sus-jacent de l'argile fracturée et la nappe phréatique se trouve proche de l'interface ondulée du sable et l'argile. Les résultats des essai de perméabilités suggere que l'extraction d'eau sera limitée et que l'amélioration du system de remise en état pour l'eau souterraine est necessaire.

1. INTRODUCTION

Environmental concerns exist in the vicinity of oil production wells in oilfields of northwestern Alberta. These concerns largely revolve around the release of waste fluids (oil and produced water) at production facilities. Produced water is very saline formation water, which is high in dissolved salts, particularly sodium and chloride.

Devon Canada Corporation (Devon) inherited this site as part of a corporate acquisition package. At that time, the site had been decommissioned and remediation had been initiated by installing a tile drainage system. Matrix Solutions (Matrix) became involved with the project in 2000 when Devon realized that the remediation system was inadequate for the size of the problem.

This paper details the work conducted since Matrix began work on the site including characterizing the soil and groundwater regime, assessing the environmental impacts and developing a remediation strategy.

1.1 Site Description

The subject site is located approximately 150 km northeast of Grande Prairie in northwestern Alberta (Figure 1). The topography is relatively flat but regionally it slopes to the north-northeast towards a tributary of the Smoky River (located approximately 0.7 km north of the site). The area is poorly drained as evidenced by numerous small marshy areas in close proximity to the site.

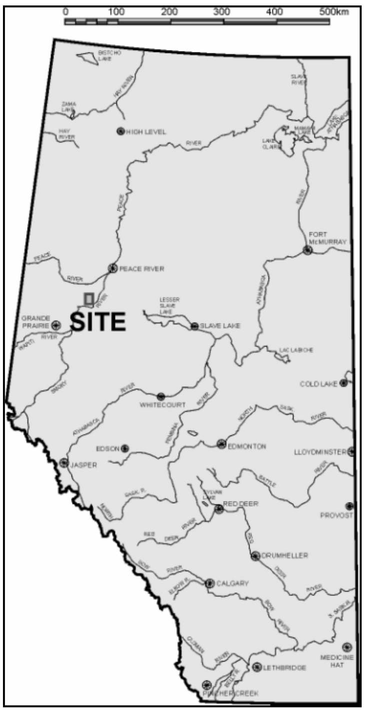

Figure 1: Site Location in northwestern Alberta.

The site was constructed in the late 1950s and was operated for 25 years as an oil battery (where oil was extracted from the ground and primary separation of produced water and gas from the oil occurred). As shown in Figure 2, the site measures approximately 200m x 100m. The site is split by a north-south grid road and is bordered to the north by an east-west grid road. The oil and produced water were stored in a tank farm at the north end of the site. Waste fluids were typically disposed of in unlined earthen pits. When the site was reclaimed the flare pit was obliterated, equipment was removed from the site and the site was covered over by topsoil.

A tile drainage system was installed (by others) in 1996 to capture groundwater in the central part of the site. In 2000 Matrix modified the tile drainage system and identified the need for further remediation.

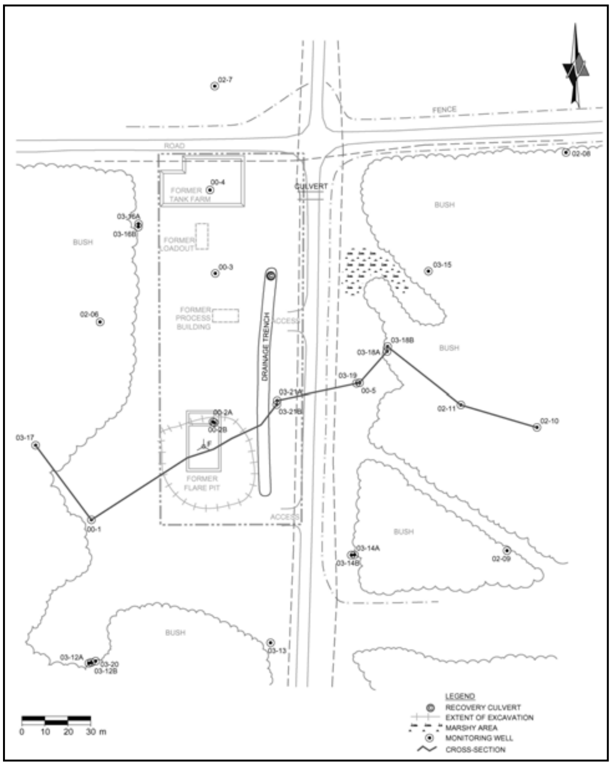

Figure 2: Site Plan

2. METHODOLOGY

Based on the concentration of chlorides in the water extracted from the tile drainage system, a phased approach was implemented for characterizing the site. These phases included multiple drilling programs to delineate the soil and groundwater impacts, semi-annual groundwater sampling programs, and geophysics. A pumping test was conducted to determine which remediation strategies would be effective in reducing the chlorides in the groundwater at the site.

2.1 Site Assessment

2.1.1 Borehole Drilling and Monitoring Well Installation

Borehole drilling and soil sampling was conducted to characterize the soils and collect soil samples for laboratory analyses. In 2000, a total of 16 boreholes were drilled and 6 monitoring wells were installed, including one nested pair.

In 2002, twenty boreholes were drilled to delineate the extent of the flare pit as it had been determined to be the main source of the chloride and hydrocarbon impact. The results were used to estimate the initial volume of soil required to be excavated. Six additional monitoring wells were installed to delineate the extent of the dissolved chloride plume. The results of this investigation indicated that the impact was larger than initially thought and a third drilling program was implemented.

In 2003, 15 additional monitoring wells, including 5 nested wells which comprised either 2 or 3 wells each, were installed.

Both solid and hollow stem auger drill rigs were used to drill the boreholes and install the monitoring wells. The nested wells were installed in separate boreholes with the screened interval placed at various depths. The maximum depth of investigation was 14.8 m below ground surface (bgs). The monitoring wells cover an area of approximately 230m x 260 m.

2.1.2 Geophysics

In 2003, Essis Ltd (Essis) was contracted to conduct an environmental imaging investigation to delineate the potential ionic contamination using the Geonics EM31/38 and Geoprobe SC400 instruments. Using a direct drive Geoprobe 6600 drill, the soil was logged and samples collected. The analytical results of the soil samples were used to provide ground truthing of the geophysical responses.

2.1.3 Excavation of the Flare Pit

Based on the soil and groundwater sampling results and supported by the geophysics, the source of the high chlorides in the subsurface was identified as the former flare pit. Hydrocarbons were also identified as contaminants of concern (including some polycyclic aromatic hydrocarbons related to burning of the waste hydrocarbons). It is likely that the degradation rate of the hydrocarbons was impeded due to the high chloride concentration of the soil reducing bacteria growth.

In 2003, the flare pit was excavated. Initially it was thought that the flare pit covered an area of 15m x 25m, however upon excavation, it was discovered to be a much larger problem. During reclamation (by others) before Devon inherited the site, the soft sludge at the base of the pit was ‘squeezed’ into trenches that had been excavated in a radial pattern from the flare pit to the west. This had the effect of spreading the contaminant in the subsurface. The trenches were up to 4.5 m deep and the maximum depth of excavation within the former flare pit was 5.7 m bgs, although most of the excavation was approximately 2.7 m bgs. The trenches were removed during the excavation. The extent of the excavation was based on confirmatory samples collected from the walls and floor of the excavation for hydrocarbon and electrical conductivity. A total of 5,300 tonnes of soil was disposed of off-site. The pair of monitoring wells in the former flare pit was decommissioned beyond the depth of the excavation.

2.1.4 Groundwater Sampling

The groundwater monitoring wells have been sampled on a semi-annual basis since installation. Samples have been collected using dedicated bailers and have been analyzed for routine water chemistry, dissolved metals and/or hydrocarbon compounds.

2.2 Remedial Design

The results of the site assessments indicated that this is a large site with very high concentrations of chlorides which are mobile in the subsurface. To mitigate the risk associated with this site, Devon decided to upgrade the current remediation system to hasten the rate of remediation relative to the migration of the contaminant plume.

Given that chloride is a conservative ion that tends to migrate at a similar rate to the groundwater flow velocity, capture of the impacted groundwater would be dependant upon the hydrodynamics of the saturated zone. Therefore, the initial stage of designing the remedial system was to conduct a pumping test using the existing infrastructure.

2.2.1 Pumping Test

In May 2004, a pumping test was conducted using the existing tile drainage system which extends over the area of the former process building south to the northern edge of the excavation. The tiles extend in an east-west direction and are understood to extend approximately 30 m west of the trench. The tiles drain into the trench which is a gravel-filled ditch that is sloped to a culvert at the north end. The pump was installed into the culvert.

The pumping test was conducted as a constant rate test with the effluent pumped into a 63 m^3 above ground tank. The flow rate was approximately 42 m^3/day (8 USGPM). Six pressure transducers were used to monitor water level changes during the test and the remaining 20 wells were monitored manually. The test continued for almost 24 hours before being shut down due to insufficient water in the culvert.

3. RESULTS

3.1 Hydrostratigraphy

Very little information is published on the regional hydrogeology of this area and there are few domestic water wells. However, according to Henderson (1960) and Hamilton et al. (1999), the surficial deposits consist primarily of dune sands overlying bedrock. The bedrock consists of a silty shale of the Puskwaskau Formation.

A domestic water well is located at a distance of 6.5 km from the site and is completed at a depth of 8.8 m bgs. Therefore the shallow surficial sands must be considered a potentially potable aquifer.

The soil beneath the site consists primarily of sand overlying fractured clay deposits. The sand unit ranges between 0.8 and 4.5 m thick and is found everywhere beneath the site. The thickest sand deposits are found in the central portion of the site and off-site to the west and southwest. The sand is described as brown to grey, mottled and varying in silt content. It tends to be very fluid, particularly east of the grid road as witnessed during installation of the monitoring well 03-19. The upper surface of the clay is highly variable with channels eroded into it as illustrated on the cross-section (Figure 3). The fractures in the clay unit are sometimes open but are also sand-filled in places. The fractures were larger and/or were more frequent in the upper 5 m of the unit. The clay is described as brown to grey, mottled, firm to stiff with medium to high plasticity. Discontinuous sand lenses within the clay (between 0.1 and 0.3 m thick) were noted between 5.7 and 13.5 m in borehole 03-18a on the eastern part of the site. The thickness of the clay is not known as bedrock was not encountered during drilling. The maximum depth of drilling was 14.8 m bgs.

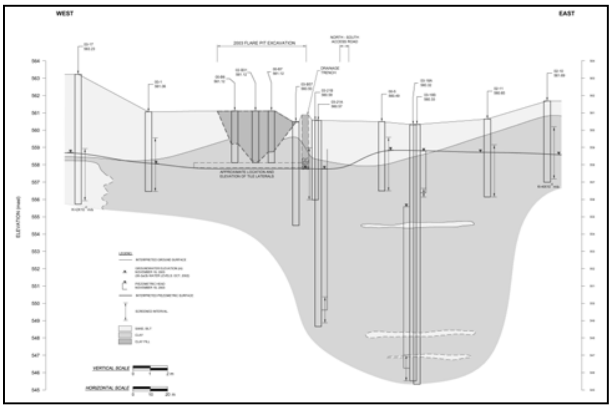

Figure 3: Hydrogeological Cross-Section across the Site.

The water table is as shallow as 0.9 m bgs with seasonal fluctuations of 0.6 m. The water table is fairly flat beneath the site, although minor differences in elevation are evident in the centre part of the site, due to delayed recovery following extraction of water from the culvert. The culvert is currently pumped only during the snow-free months when access to the site is possible. At the time of monitoring, the maximum difference in elevation of the water table is approximately 1 m with the lowest point in the area of the drainage tile, trench and culvert. This is illustrated in Figure 4.

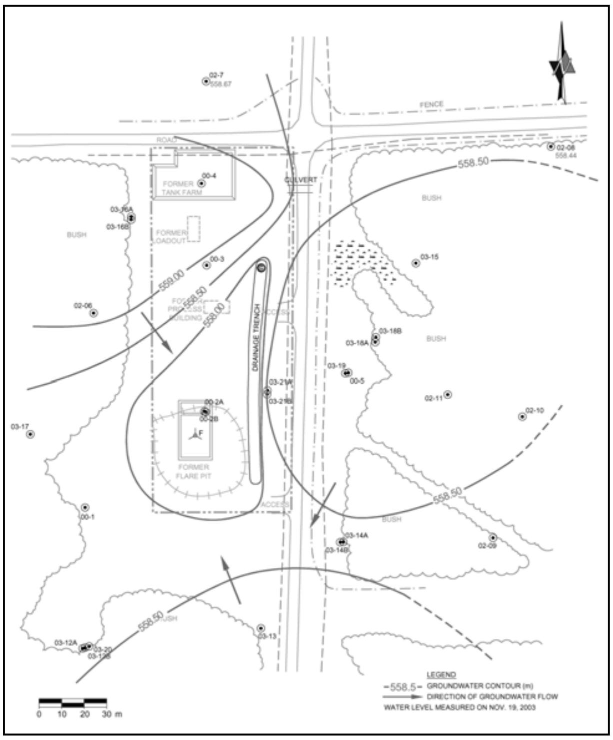

Figure 4: Groundwater Flow beneath the Site.

On the eastern part of the site, the upper clay surface rises and acts as a natural hydraulic barrier to groundwater flow in this direction. Given that the water table is near the interface between the sand and the clay, seasonal fluctuations in the water table have had an influence on the lateral migration of the chloride plume.

The vertical flow gradient is strongly downward (as much as 0.34 m/m) to weakly upward (up to 0.09 m/m). It is unknown whether pumping from the culvert has influenced this measurement although it was noted that the water level declined in the deep well during the pumping test.

Based on the results of hydraulic response tests and analyses of the pumping test data, the hydraulic conductivity of the sand unit varies between 6 x 10^{-8} and 2 x 10^{-6} m/s, whereas the clay varies between 1 x 10^{-8} and 7 x 10^{-6} m/s, largely reflective of the influence of the fractures and sand lenses within the clay.

The average linear groundwater flow velocity for the sand is estimated to less than 5 m/year based on a horizontal gradient of 0.03 m/m, and an assumed effective porosity of 40%. The migration of chlorides in the groundwater is highly dependant upon the position of the water table relative to the sand/clay interface. On the eastern side of the site, the upper surface of the clay rises and the sand is unsaturated. The chloride concentrations in the groundwater wells (decreasing to background concentration) reflect the effectiveness of this natural hydraulic barrier. However, in the centre of the site near the former flare pit, chlorides were found at depth in the fractured clay where the vertical gradient, and likely the concentration gradient has driven the chlorides downward.

3.2 EM Surveys

3.2.1 Horizontal Conductivity

The horizontal EM survey indicates that two "hot spots" are present. Interpretation of this data suggests that these anomalies were originally one large anomaly and that pumping of the water from the culvert and trench has resulted in a cleaning up of the central zone thereby splitting the plume in two. This interpretation is supported by the absence of a possible source of impact east of the grid road.

3.2.2 Vertical Conductivity Profile

The results of the alternating current injection profile beneath the site show a low conductivity zone underlain by a higher conductivity zone beneath it. Based on the soil chemistry results, this low conductivity zone in the shallow soil profile is related to the lower conductivity of the sand unit relative to the clay unit, as well as the degree of saturation. The vertical conductivity profile also suggests a cleaning-up of the groundwater in the vicinity of the trench is possible.

3.3 Chemistry

3.3.1 Soil chemistry

The contaminants of concern on this site consist of soil salinity and hydrocarbons. Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC) are used as indicator parameters of salinity. In the vicinity of the former flare pit, prior to excavation, the maximum EC value was 114 dS/m (compared to the guideline of 3 dS/m for "good" subsoil) and the maximum SAR was 63.8 compared to a guideline of 4.

A black tar-like substance was found in the trench emanating from the flare pit. This material contained benzene (B; 42.3 mg/kg), toluene (T; 23.2 mg/kg), ethylbenzene (E; 12.3 mg/kg), xylenes (X; 68.9 mg/kg), fractions 1 to fraction 4 petroleum hydrocarbons and some PAHs which exceeded the guidelines. This material was identified as weathered crude oil. The guidelines for the BTEX compounds are 0.048 mg/kg, 0.16 mg/kg, 0.36 mg/kg and 14 mg/kg, respectively.

Based on the presence of the black sludge and the high salinity of the soil, it is unlikely that natural biological degradation would reduce the concentrations in the near future. Therefore, it was necessary to remove the source of hydrocarbon-impacted soil for off-site disposal.

3.3.2 Groundwater Chemistry

Chloride impacts were detected in 22 of the 24 groundwater monitoring wells, located both on the site and off the site to the east. Concentrations of chloride are presented on Figure 5 with the maximum concentration detected in well 00-5 of 51,900 mg/L. The concentration in this well increased from 25,000 to 51,900 mg/L in less than 8 months, prompting remedial measures to be increased.

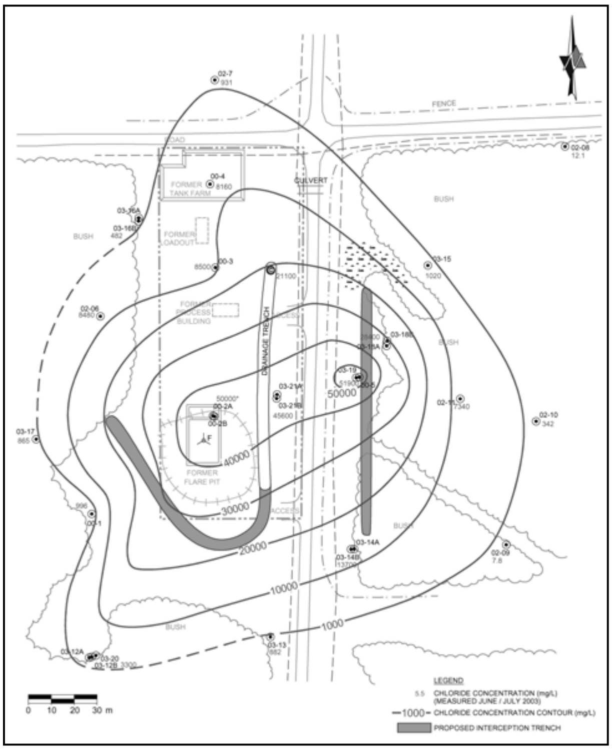

Figure 5: Concentration of Chloride in Groundwater and the Proposed Extension of the Groundwater Recovery System.

Produced water impacts to soil and groundwater are widespread. The likely source of the impacts was the former flare pit and the produced water likely migrated from the flare pit through the sand unit during periods of high precipitation. Groundwater impacts appear to attenuate with distance from the source but are observed at radial distances of at least 75m to 130 m from the source. The estimated area of impact is in excess of 54,000 m2. Groundwater impacts attenuate with depth but are observed to depths of at least 14.8 m off lease to the east with a concentration of chloride of 9,260 mg/L in monitoring well 03-18a east of the road.

3.4 Remedial Action

3.4.1 Excavation

Excavation of the flare pit material resulted in removal of the source of hydrocarbon and some of the soil with high concentrations of chlorides. However, it was recognized at that time that residual chlorides remained in the soil and further remediation would be required to deal with the salts.

3.4.2 Groundwater Recovery

During the summer of 2003, a total of 581 m^3 of water was recovered from the groundwater recovery system. This equates to 12 tonnes of chloride removed from the subsurface via groundwater recovery. Based on the concentration of chloride in the groundwater (using 2003 data) and the spatial distribution of the chloride, it is estimated that there is 1,300 tonnes of chloride in the groundwater.

3.4.3 Groundwater Flow Modelling

Following evaluation of the site characteristics and the results of the pumping test, the factors that control the groundwater flow beneath the site were evaluated using a groundwater flow model. The model was developed to assist in determining the best configuration of a remedial system. The results of this model indicate that the hydraulic conductivity of the clay is heterogeneous and that fractures play a role in the migration of groundwater. Preliminary results indicate that hydraulic conductivity of the clay is less than or equal to 7×10^{-6} m/s. Remediation of groundwater using only the existing system is insufficient to reduce the chloride concentrations in the groundwater in less than 140 years (assuming one pore volume is sufficient to reduce the chloride concentration to a concentration where risk management would be acceptable).

3.4.4 Conceptual Remediation Strategy

It is expected that although desirable, it is unlikely that this site will ever be cleaned up to background conditions. However, an assessment of the potential receptors indicates that no sensitive receptors exist in the near vicinity and the natural hydraulics beneath the site has restricted migration of the contaminant plume. As part of a risk management plan, it is anticipated that the concentrations of chlorides can be markedly reduced with the following actions.

It is proposed that the existing recovery trench would be augmented with additional recovery trenches as shown in Figure 5. The trenches would be excavated to approximately 4.5 m depth and would be filled with gravel. They would be installed with automatic pumps that would empty to an onsite tank, which would be emptied as needed. This system is currently designed for summer-only operation; however it may be augmented to operate year-round. It is estimated that significant decreases in the chloride concentration within the 10,000 mg/L contour line would be reduced within 30 years based on one pore volume recovery.

Although some chloride impacted soil has been removed from the flare pit area, soil with EC concentrations exceeding 20 dS/m (up to 50 dS/m) remain in the ground. Therefore, further excavation of these chloride hot spots would be beneficial in reducing the total amount of chloride in the subsurface. Given the excavation required to install the recovery trench, this is a viable option for hastening the remediation rate. It is proposed to excavate a further 9,400 tonnes of soil from the area near the former flare pit as well as 2,200 tonnes in the area east of the grid road. This material would either be disposed of off-site or would undergo a soil washing which would enable its reuse as fill on the site.

The cost of installing this remedial system and operating it for 10 years is $2M – $2.5M.

4.0 References

Hamilton, W.N., Price, M.C., and Langenberg, C.W., 1999. "Geological Map of Alberta." Alberta Energy and Utilities Board and Alberta Geological Survey, Map No. 236, scale 1:1,000,000.

Henderson, E.P., 1960. "Surficial Geology of Sturgeon Lake, W5M." Geological Survey of Canada Memoir 303.

Matrix Solutions Inc., 2004. Soil and Groundwater Delineation Program (confidential site), file 0285-503 prepared for Devon Canada Corporation.