Developing and Implementing an Environmental Remedial Action Plan at a Mercury-Contaminated Industrial Site

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ABSTRACT Redevelopment of former industrial properties often involves environmental assessment and remediation before the site can be returned to productive use. URS Vancouver has been involved with the assessment and remediation of a former mercury cell chlor-alkali site located in a complex and sensitive marine environment for over five years. Planning and implementation of the remediation action plan for the site involved a broad range of technical disciplines, including geochemistry, hydrogeology, remediation engineering and geotechnical engineering. This paper provides an overview of the key environmental problems faced by the project team and how the team was able to implement solutions that were cost effective and protective of the environment.

The main contaminant of concern at the site is mercury. Detailed site investigations lead to a comprehensive soil and groundwater remediation program tailored to site conditions. The team developed a soil remediation approach that satisfied the requirements of BC Water, Land and Air Protection while considering the technical limitations of equipment, air quality, schedule and geotechnical constraints. Groundwater impacts were managed through the design and implementation of a control and containment system. This task was extremely complex owing to the fate and transport of the contaminant, the strong tidal influence and the presence of a semi-confining layer. A multi-disciplinary, multi-consultant team approach with strong organization and frequent communication was key in the successful implementation of the remedial action plan.

Project Overview

Large industrial properties often contain multiple environmental concerns that require assessment and remediation prior to redevelopment. URS Vancouver has been involved with the assessment and remediation of a former mercury cell chlor-alkali site located in a complex and sensitive marine environment for over five years. This paper describes the process of environmental assessment and remediation of the 19-hectare industrial property.

Planning and implementation of the remedial action plan for the site involved a broad range of technical disciplines, including geochemistry, hydrogeology, remediation engineering and geotechnical engineering. Successfully completing the assessment and remediation process required these disciplines work together to reach common goals.

This paper provides an overview of the key environmental problems faced by the project team and how the team was able to implement solutions that were cost effective and protective of the environment. Ultimately, the basis of the site remedial action plan was soil remediation, groundwater control, and risk assessment.

Historical Site Development

The subject site is located in an ecologically sensitive environment. Historically, the site was a tidal marsh located near the mouth of a river. The majority of the site was developed in the early 1960's through the placement of dredged sand (hydraulic fill) to raise the ground elevation up to 4 metres. The site was mainly unpaved with portions utilized for plant infrastructure, process wastes ponds, and paved access roads.

A mercury cell chlor-alkali plant was constructed and operated on the site from 1965 to 1991. In the mercury cell chlor-alkali process used at the plant, brine composed primarily of dissolved sodium and chloride ions was passed between fixed graphite or coated titanium anodes and a flowing liquid mercury cathode within each process cell. Through the application of an electrical current, chloride ions were oxidized to chlorine gas at the anodes and sodium ions were reduced to form an amalgam or solution with the liquid mercury cathode as shown below:

[1] $Na^+ + 2Cl^- + Hg + \text{electricity} \rightarrow Na\text{-}Hg + Cl_2$

The chlorine gas was collected, dried, purified and compressed, mainly for use in the pulp and paper industry. The sodium-mercury amalgam was then drained into a second portion of the cell, the decomposer, where it was contacted with water to form caustic soda and hydrogen gas:

[2] $Na\text{-}Hg + H_2O \rightarrow NaOH + \frac{1}{2} H_2 + Hg$

The sodium hydroxide was collected and purified for use as caustic in a variety of industries. Approximately 10-15% of the salt in the brine solution was electrolysed while passing through the cells. The spent brine from the cells was dechlorinated and recycled to the brine saturation tank where it was mixed with imported raw salt and municipal water to form raw feed brine. The spent brine contained residual mercury.

The use of liquid mercury in the process was the main source of contamination, although other process-related contaminants, such as trace metals and chlorinated hydrocarbons, were also present. Process wastes, including wastewater and sludge, as well as spills of liquid mercury, brine and caustic, all contributed to the accumulation of potential sources of contamination at the site. Mercury cell technology has since been replaced by diaphragm filter technology that poses significantly less risk to the environment.

Regulatory Requirements

A number of regulatory mechanisms can be applied to the remediation of a contaminated site. The most common mechanisms provided under the *Waste Management Act* and its regulations, include assessment and remediation orders, the issuance of permits, and the provisions under the *Contaminated Sites Regulation* (CSR, 1997, last amended 2002).

Orders are effective and direct mechanisms used to establish minimum requirements for assessment and remediation. Normally, they are issued in cases where immediate action is required to protect the environment.

Permits are authorizations for the discharge of waste materials to the environment. In site remediation cases, permits are often issued to address disposal of soils or effluents at authorized locations.

The BC Ministry of Water, Land and Air Protection (BCMWLAP) has established standards for evaluating contamination and associated remediation requirements in the *Contaminated Sites Regulation* (CSR, 1997). Under the CSR, there are three types of commonly used remediation standards. The Generic Numerical Standards refer to concentrations of given substances in soil or water for a particular land use. Matrix Numerical Standards are applied for some substances in soil, taking into account various site-specific factors such as proximity to receiving waters, likelihood of human ingestion, and use of land for livestock rearing. Risk-based Standards involve the generation of a standard for a specific site, based on human health and ecological risk assessment protocols outlined by BCMWLAP.

Soil standards are classified into five levels, based on the type of land use. Sites that contain analytical parameters at concentrations greater than the standard for the specific land use are considered to be contaminated. Similarly, water standards are classified into four levels, based on the use of the water. Sites at which parameters exceed the specific standard for the type of water use at the property are considered contaminated.

In cases where hazardous constituents are present at a contaminated site, the *Special Waste Regulation* (SWR, 1988) will apply in addition to the previously mentioned legislation. The SWR classifies substances as Special Wastes if they contain leachable contaminants at concentrations in excess of a specified maximum. The Special Waste Extraction Procedure (SWEP) test outlined in the SWR is employed to assess contaminant leachability. Special Wastes may also be defined by their total content of certain substances. Soil or groundwater contaminated in excess of the Special Waste standard (SW) must be handled and disposed of as Special Wastes in accordance with the SWR.

The key regulatory mechanism used on this project was a remediation order. The order specified the nature and timing of the site investigations and stipulated the content and schedule for submission to BCMWLAP of a comprehensive remediation plan. The order also established timelines for the completion of remediation over a three year timeframe. In addition, the site already held permits for the discharge of treated effluent which proved to be a valuable asset in the implementation of the remedial plan.

Detailed Site Investigation

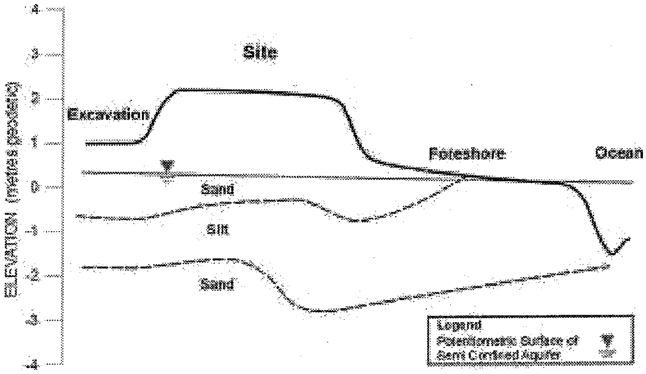
A Detailed Site Investigation (DSI) is defined in the CSR as providing information on the environmental status of a site in sufficient detail to permit the development of a remedial action plan or risk assessment. A DSI is normally conducted as a follow-up to preliminary assessments of historical land use and of soil and groundwater conditions.

For the subject property, the DSI consisted of a comprehensive evaluation of site conditions. The investigative techniques included 65 test pits, 105 direct push and auger soil borings, and the installation and sampling of 125 new and existing groundwater monitoring wells. Each of these locations produced samples which were analyzed for potential contaminants of concern (PCOCs). For the size of the property and complexity of environmental conditions, the DSI was considered to be an acceptable starting point for remedial planning.

The DSI identified impacted soils and process wastes located each of the three stratigraphic layers (Figure 1, below). The majority of impacts were found in the sand fill in the upper stratigraphic layer. Initial estimates of the volume of impacted soils and process wastes was 45,000 to 55,000 cubic metres of material, excluding clean overburden.

Impacted groundwater was identified in the all three stratigraphic layers, including the semi-confined sand and gravel aquifer approximately 5 metres below grade. The hydrogeologic studies conducted as part of the DSI determined an average groundwater gradient at the site, and in conjunction with concentration data from monitoring wells, a mass loading or mercury flux to the environment was estimated.

Fig. 1. General Site Stratigraphy Determined by DSI



Remedial Action Plan

On the basis of the DSI findings, the project team proceeded with the development of a comprehensive remedial action plan to address soil impacts, process wastes and groundwater impacts.

The preparation of an effective plan requires a broad-based understanding of the regulatory requirements, and applicable remedial techniques. An effective plan will demonstrate an awareness of environmental risks and impacts posed by the identified contaminants of concern relative to site-specific site geology and hydrogeology. An effective plan also has an achievable project scope, budget and schedule. For a complex remediation project, a multi-disciplinary project team consisting of hydrogeologists, remediation engineers, geotechnical engineers, risk assessment specialists and project managers should be assembled. Strong project management skills and frequent communication between all parties is vital. Working cooperatively, this team should identify potential project pitfalls well in advance and develop an effective remedial action plan.

Fundamental to the development of a remedial action plan is the establishment of remediation objectives. For simple sites, these objectives may be as simple as stating that the CSR numerical standards will be achieved for the intended land use. For more complicated projects involving soil and groundwater remediation and/or involving ecological and human health risk assessment, the remediation objectives may be risk-based and take into account the fate and behaviour of the contaminants in the environment. Overall, the remediation objectives must be achievable, affordable, and have permanence.

Other components of a CSR-compliant remedial action plan include clear delineation of the contaminant distribution, consideration of remediation alternatives, a statement of the preferred remediation methods, a management plan for any impacted material remaining in place, and where risk assessment is utilized, an overview of the risk assessment methodology and calculations. In the event that a Certificate of Compliance is sought from BCMWLAP, confirmatory sampling procedures consistent with BCMWLAP guidance documents must be defined and implemented. Sampling density and analytical parameters that do not adequately reflect the site conditions or guidance documents will be viewed as inadequate, potentially causing additional confirmatory assessment to be necessary after project completion.

For the subject project, in accordance with the order requirements, the DSI and remedial action plan was submitted for regulatory review and comment. The remediation objective for the site was to ultimately receive a Certificate of Compliance for portions of the site that achieved the CSR numerical standards, and a Conditional Certificate of Compliance for portions of the site where contamination was left in place and risk assessment was utilized.

The finalized remedial action plan was authorized by an amendment to the order. In more typical projects, authorization is provided by a document issued by BCMWLAP known as an Approval in Principal.

Mercury Fate and Behaviour

Mercury is the main contaminant of concern at the site. The characteristics of this contaminant make it unique relative to most contaminants encountered at contaminated properties. Its fate and behaviour in the environment is also unique. With a specific gravity of 13.6, mercury is an extremely dense liquid metal. It has a high surface tension, is hydrophobic and yet it is volatile (produces a vapour under ambient conditions). In liquid form, mercury acts as a dense, non-aqueous phase liquid (DNAPL), meaning it will persist as a separate phase and sink through the water column.

In soils at all depths beneath the site, elemental mercury (Hg^0) is the primary form of mercury. Mercuric sulphide (HgS) is present in site soils at all depths. Mercury is strongly partitioned towards the solid phase in site soils. Mercury is transported via groundwater both as elemental and as soluble complexes. Mercuric hydroxide complex ($Hg(OH)_2$) as the primary dissolved form of mercury in the upper, freshwater environment, and mercuric disulphide complex (HgS_2^{-2}) is the primary dissolved mercury species in the deeper salt water environment.

Precipitation, and hence immobilization, of dissolved mercury is caused by the reducing conditions in the semi-confined aquifer. pH is a factor in determining the mobility of mercury. Elevated pH in groundwater in some portions of the site enhances the solubility of mercury, thereby increasing its mobility with groundwater flow. In salt water near the receiving environment, it is believed that the mercury makes other complexes, particularly with natural organic colloids present in the third layer sediments.

Understanding the fate and behaviour of a contaminant of concern significantly improves the ability to manage the risk posed by the contaminant through the development and implementation of an effective remedial action plan. Avoiding unnecessary or ineffective remedial measures is important to control project costs.

Soil Management Plan

With respect to remedial planning for soils, sludge and sediments, a soil management plan is typically prepared to address all aspects of the remedial program. For the subject site, a three-year soil management plan was designed to access an on-site rail spur for off-site shipping of wastes, and use the existing on-site water treatment, offices, analytical laboratory and related infrastructure.

The project was broken down into campaigns, each approximately nine months in duration. Tangible project milestones were established to guide the overall remedial action plan. Each year new campaign milestones were established. This proved to be a very effective approach as it permitted the team time to evaluate successes and difficulties from the previous campaign in preparation for the following year's challenges.

Various key aspects of the soil management plan prepared for the subject site are described in the following sections.

Establishing a Site Grid

One of the most important first steps in the design of a soil management plan is the establishment of the site grid. While this may appear to be a simple and obvious step, it is often not considered properly due to site-specific constraints. A permanent, reproducible site grid allows the in-situ location of impacted soils to be properly identified in three dimensions. This identification is carried through the entire project, linking the DSI data to the excavation plan and on through the confirmatory sampling process. Used properly, the site grid establishes where impacted materials were initially present and excavated, and prevents mixing of clean and impacted soils. It is our experience that a grid is a more effective tool than contaminant isopleth (contour) drawings whose boundaries are often arbitrarily defined and not necessarily representative of actual conditions. Bulk soil excavation according to a fixed grid is more conducive to the ability of the excavator to selectively remove impacted soils and of the management of soils post-excavation.

BCMWLAP's *Guidance Document #1, Site Characterization and Confirmation Testing* specifies the sampling density (also known as the support volume) for various classifications of land use for both in-situ sampling and for bulk stockpile sampling. For example, soils considered to be special waste trigger a confirmatory sample area of 5 metres by 5 metres, or 25 square metres equivalent. In simple excavations of special waste, this would be the typical grid size.

At the subject site, the size of the excavator relative to the bearing capacity of the site soils and sludge needed to be considered. Portions of the excavation required that both excavator and truck traffic cross a basin of settled clarifier solids (sludge). Purpose-built 'swamp mats' floatation pads constructed from 0.3 x 0.3 m timbers approximately 1.5 m wide and 3 m long allowed equipment to access the sludge by spreading the equipment load. These rigid pads had to be repositioned continually during excavation to maintain a stable working surface and haul road.

The sludge had low bearing capacity, particularly when subjected to equipment vibration, so only a moderate sized excavator could be utilized. Meeting this constraint, the selected tracked excavators (John Deere 690 series) had a maximum reach of 5 metres at the design excavation depth of up to 6 metres.

As the site was tidally influenced, minimizing management of excavation water and preventing heave, as discussed below, was imperative. Daily production schedule had to correspond with the tidal cycle.

The best solution to meet all these constraints was the establishment of a 5 by 17 metre grid. This grid size permitted the excavation of a manageable volume of material and subsequent backfilling in a single day. On the basis of this grid size, the number of final excavation surface confirmatory samples was determined. Also, other components of the project influenced by the excavation production rate then were incorporated into the plan.

Avoiding Excavation Heave

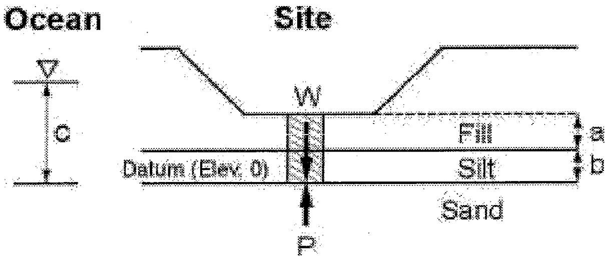
At sites where groundwater is in connection with tidally influenced waters, the affect of tidal fluctuations is apparent for many metres inland. In these cases, high tides cause an increase in groundwater pressure (measured as hydraulic or elevation head) in the affected area. The highest pressure occurs at high tide. Where groundwater pressures exceed the static load of the soils resisting the upward pressure, liquefaction or heave of the soil will occur. Visually, this is apparent as "quick-sand", or as a "boil" where water surfaces from underground.

In excavations of clean sites, this would be controlled by a well point system and the clean water discharged to the environment. Dewatering was not available at this site due to the inability to adequately control inflow to the excavation at a reasonable cost and the difficulty in treating large volumes of contaminated water.

In order to reach all impacted materials on this project, it was required to excavate to elevations where heave would possibly occur while excavating at depth. Allowing heave, even after removal of contaminated materials, could not be permitted, as the entire excavation would be compromised, potentially mixing sludge with clean material. Therefore, an analysis of site conditions was completed and an excavation schedule was developed that minimized heave by working in sequence with tidal fluctuations.

For each cell in the site grid, the potential for heave was determined based on the target depth of excavation, the thickness of the semi-confining layer subjected to upward hydrostatic pressure, and the high tide elevations that day. An equation was developed to predict the heave potential for any given cell relative to the anticipated tide elevations during excavation each day (Figure 2).

Fig. 2. Illustration of Determination of Heave Potential



Where:

[3] W = downward force per unit area
= height soil x soil density = $(a \times \rho a) + (b \times \rho b)$

[4] P = upward force per unit area
= tide height x water density = $c \times \rho water$

Combining the two expressions above, it is possible to calculate heave potential where $P > W$ at any point in the tide cycle relative to excavation depth. In conjunction with tide charts, it is then possible to estimate the schedule (tide window) for excavation at various depths.

To prevent heave, the elevation of the bottom of the excavation at any time was off-set by approximately +1 metre from the tidal elevation. Excavation to depth and collection of confirmatory samples was conducted on the falling or slack tide, and the cell backfilled during the rising tide. Maintaining this off-set at all times virtually eliminated the occurrence of heave. This technique provided a daily 4 to 6 hour window for excavation and backfill of a cell to depths between 3 and 5 metres.

The data for all the cells were entered into a spreadsheet. As a digital file, the heave calculation for any given cell could be updated instantly by entering a new date. This allowed the excavation supervisor to tailor the excavation against the risk of heave in the establishment of the weekly production schedule.

Excavation Water Management

Although the soil management plan was designed to minimize the inflow of groundwater to the excavation, the excavation intercepted perched groundwater in the upper stratigraphic layer. The team also anticipated that potential accumulations of excavation water from precipitation would have to be managed. Potentially elevated concentrations of mercury and suspended solids precluded a direct discharge of this water to the environment.

The water management system implemented for the site utilized an initial stage cone bottom settling tank prior to feeding into the existing site water treatment plant. With a treatment capacity of approximately 275 litres per minute and limited on-site tank storage capacity, excavation water control was important to maintain the excavation integrity. Hence, work was suspended during conditions of heavy rain.

Dust and Vapour Management

Best engineering practice was used to control dust emissions during remediation activities. The goal was to maintain dust concentrations well below the MOE air quality objective of 0.05 mg/m^3 (PM_{10}) at the boundary of each worksite. If this target was not being met, more aggressive dust control measures were implemented. Visual and real-time instrumentation was used to demonstrate effectiveness of dust control measures. Dust control techniques included water sprays using on-site fire hoses, roadway sprinkling using a truck mounted watering system and minimisation of area of exposed sludge both at the excavation and interim storage facility.

As it was impractical to enclose the excavation to collect and treat impacted ambient air, source control methods were utilized. Best engineering practices were also used to minimize mercury emissions during remediation activities. Workers were protected where necessary by wearing mercury-specific respiratory protection. This included excavating areas with high vapour potential during the cooler months, when vapour evolution would be less. The goal was to maintain mercury concentrations at pre-determined off-site locations at less than 150 ng/m^3 as a 2-week average. If monitoring data indicated that this target was not being met, more aggressive vapour control methods would be implemented.

In addition to site-perimeter and off-site vapour monitoring, mercury vapour of site personnel was monitored using dosimeter badges. These are colorimetric indicators of elevated mercury vapour. A Jerome instrument was also utilized as a roaming air quality monitor. This instrument takes spot measurements representing 7-second average concentrations. It has a useful measurement range from 0.003 to 0.99 mg/m^3.

Ultimately, the engineering practices were sufficient to control both on-site and off-site vapour concentrations to within acceptable concentrations.

Stockpile Management

Remdiation of contaminated property typically involves the management of various "classes" of soil, including clean overburden, industrial grade soils and potentially special waste soils. The cost to treat or dispose of these soils is directly related to the concentration or class. In-situ sampling data indicates the general location and volume of impacted material to be removed, but the density of sampling is usually insufficient for classification of all excavated material. Therefore, to minimize costs associated with soil management, segregation and ex-situ sampling of impacted materials is often necessary. Guidance for this procedure is provided by BCMWLAP's *Guidance Document #1, Site Characterization and Confirmation Testing.*

Segregation can be based on physical characteristics, such as soil versus rock (riprap), or by contaminant type and disposal method, such as metals versus petroleum hydrocarbons. The remedial planning process should consider these factors in order to optimize excavation, material handling and ultimately disposal or treatment costs. On sites with limited space for soil management, careful consideration of stockpile locations and material flow around the site is critical.

The standard approach to segregation is to classify a cell on the basis of in-situ sample data obtained from that cell or inferred from adjacent cells or depths. Cells classified with actual in-situ data typically are managed according to that classification. Suspect materials are routed to suspect stockpiles for ex-situ testing. The support volume specified in the guidance document and the sensitivity to the disposal cost limits the size of the suspect stockpiles. Once classified, the stockpiles can be moved, either as backfill if the classification is suitable for the intended site use, or to treatment or off-site disposal.

Off-site disposal of soils at the subject property utilized both truck and rail car transportation. Bulk shipment by rail is significantly more cost effective than trucking in most cases, but is contingent upon rail access for both the loading and unloading facilities. Multiple handling of materials, for example removal of material from a rail car for reloading into a truck, or other double handling, is normally not cost effective. Soils and sludge shipped by rail were enclosed in a polyethylene liner to minimize loss of material and vapour during transport. All soils and waste material volumes shipped off-site were recorded in a material handling database.

Groundwater Control

A groundwater control and containment system was designed and installed to control the discharge of mercury via groundwater into the marine receiving environment. This involved intercepting contaminated groundwater using extraction wells placed near the shoreline. The following sections describe how various engineering tools were used to design, install, operate, service, and monitor the extraction system.

Conceptual Groundwater Model

A 3-dimensional numerical groundwater flow model was developed using Visual MODFLOW to simulate average hydrogeological conditions in the semi-confined, tidally influenced aquifer. Once calibrated, the model was used to predict the extent of capture achieved by various pumping arrangements of the extraction system.

Various field studies were carried out to measure key hydrogeological parameters that were entered into the model. The first was a 72-hour tidal survey, wherein groundwater elevations were continuously monitored using pressure transducers over a 72-hour period. These elevations were averaged using the Serfes (1991) method to filter out the tidal signal and calculate the mean hydraulic gradient. Accurate field measurements were imperative during this study owing to the relatively low hydraulic gradient (on the order of 0.001). Next, a 72-hour pumping test was carried out to determine the storage and transmissivity of the aquifer. A single extraction well was pumped at 365 litres per minute, and aquifer response was recorded by pressure transducers installed in surrounding monitoring wells.

The above parameters were entered into the groundwater flow model, which was calibrated against the field-measured head distribution determined before and during pumping. Particle tracking was used to evaluate the size of capture zone achieved by various pumping scenarios. That scenario which provided sufficient capture of contaminated groundwater and minimal interception of 'clean' groundwater was selected.

Implementing a Containment System

The optimal extraction system design consisted of three 15 cm diameter extraction wells installed to depths of approximately fifteen metres. Screen length and slot size were selected to achieve the desired flow rate, filter out formation material, and maintain reasonable entrance velocities. Furthermore, PVC well screens and casings were selected because of the potentially corrosive conditions induced by saltwater intrusion into the aquifer.

Each well was equipped with a submersible Grundfos pump and digital flow meter, which in turn were linked to the process control system of the water treatment plant (WTP). All extracted groundwater was pumped to the WTP, where dissolved mercury was removed from solution by flocculation using ferric chloride.

As part of the process design, a hazard and operability study (Haz-Op) was conducted. A Haz-Op evaluates all potential normal and upset operational conditions in order to evaluate suitability of the design. Of particular concern to any Haz-Op is the safety of workers in the vicinity of the system and potential for environmental impact from system failures, spills or releases.

Maintaining Groundwater Capture

With any groundwater containment system utilizing extraction wells, it is critical to maintain the performance of the well. This is a component of system operation that is very often overlooked at the design stage, resulting in difficult and costly operation and maintenance requirements later on. Fouling and scale accumulation are very common in groundwater wells at contaminated properties. Groundwater often exists under reducing conditions as a result of lack of oxygen and elevated chemical and biological oxygen demand. During pumping, oxidizing conditions are created, resulting in precipitation of metals and the formation of scale on the extraction well screen. Biological slime can also form in certain cases. Unchecked, these chemical and biological processes can virtually disable an extraction well.

At the subject site, diminished well performance was observed at the extraction wells within several months of full-scale start-up of the extraction system. This was indicated by increased drawdowns at the wells and an inability to achieve target flow rates at low tide. A variety of measures were used to rehabilitate the wells, including injection of an acid/biocide solution to remove potential bacteria/mineral encrustations, high pressure jetting along the well screens, and surging and bailing using a cable tool rig (i.e., well redevelopment). Of these, well redevelopment proved to be the most effective solution. In order to prevent and mitigate future rehabilitative efforts, the monitoring program was modified to include regular specific capacity tests at each extraction well.

Pumping rates are established on the basis of groundwater flow rates and the flux of contaminants to the environment. For systems currently in operation in BC, rates vary from as low as 22 litres per minute to over several hundred litres per minute. At the subject site, a total extraction rate from three wells of 240 litres per minute was required to provide containment. The ability and cost to treat the volume of collected groundwater determines if a groundwater pump and treat system will be technically feasible and cost-effective.

Monitoring Program

A critical component of a remedial program is assessing the effectiveness of the contaminant source removal and groundwater control systems. In the case of the subject site, BCMWLAP's remediation order required the implementation of a field-based monitoring program to demonstrate the effectiveness of the extraction system in maintaining hydraulic capture of mercury-contaminated groundwater. An additional 72-hour transducer study was carried out in the vicinity of the extraction system to assess the configuration of the effective capture zone under all tidal stages. Additional monitoring wells were installed and sampled regularly to track mercury concentrations in groundwater. Furthermore, mercury concentrations in the individual and combined extraction well discharge streams were measured to track the mass of mercury removed from the ground by the system.

Groundwater monitoring activities were initiated in the intertidal foreshore downgradient of the extraction system, in closer proximity to the receiving ecosystem. Sand boil discharges and near-bottom water were sampled during low tide (when predominantly made up of groundwater) at various times of year. Permanent drive-points were installed in the foreshore to track temporal changes in groundwater quality; and vertical profiling was conducted using a direct push tool to define the off-site configuration of the mercury plume.

The results of the above monitoring activities indicated a substantial reduction in the discharge of mercury in groundwater, both on-site and in the foreshore, during the first six months of operation of the extraction system. Typical of most sites with pump and treat systems, the challenge now is to persuade the regulatory agencies that source removal activities were sufficient and permanent so that continued operation of the extraction and treatment systems do not provide significant environmental benefit and can be discontinued. While monitoring of groundwater may indicate that an acceptable level of remediation has achieved, obtaining permission to permanently shut-off a groundwater control and containment system has, in most cases, been proven to be more difficult. In the mean time, continued operation of pump and treat systems results in potentially high annual operation, monitoring and maintenance costs and can prevent productive redevelopment of a site.

Risk Assessment

Where contamination is present above the standards prescribed by the CSR, a risk assessment process can be utilized in conjunction with, or instead of, a source removal program to the numerical standards. In BC, both ecological risk assessment and human health risk assessments must be conducted if is necessary to leave impacted soil and/or groundwater in place.

In general terms, risk assessments are a formal approach to the evaluation of the contaminants of concern, the receptors that may be at risk, and the pathways by which the receptors can be exposed to the contaminant. Risk assessment guidance was initially developed in the United States but BCMWLAP recently adopted a prescriptive methodology for risk assessments. BCMWLAP's *Guidance and Checklist for Tier 1 Ecological Risk Assessment of Contaminated Sites in British Columbia* is the guidance document for ecological risk assessments. Human health risk assessments are prescribed by BCMWLAP's *Quantitative Human Health Risk Assessment: Phase 1 – Review of Methods and Framework Recommendations.*

Where a risk assessment finds that there are unacceptable risks to human health or the environment, the risk must be mitigated through the application of risk management techniques. Depending on the site, risk management will remove the contaminant and/or control the exposure pathway. Pump and treat systems, barrier walls, and site caps are all examples of risk management techniques.

Site Closure

The ultimate goal for the owners of former industrial properties is redevelopment to some useful purpose. Under the requirements of the CSR, sites found to be contaminated must receive a Certificate of Compliance or Conditional Certificate of Compliance from BCMWLAP. As the legislation is currently structured, the necessary re-zoning, demolition, building and occupancy permits required by municipalities can not be issued until a Certificate is issued, or until an Approval in Principal of a remedial action plan is issued.

The issuance of a Certificate is significant, in that it indicates to interested parties that the site has been remedated to meet the standards for the intended land use, or has been risk assessed and any unacceptable risks mitigated. Currently, the issuance of a Certificate is intended to extinguish on-going liability for the site, however this has yet to be proven through a legal challenge.

In conclusion, remedial planning and implementation is an exercise where it is critical to proceed with the end in mind. While determining the end use of a site while only initiating a project can be difficult, discussions between the client and consultant to determine the ultimate remedial goals and objectives is time and effort well spent if the project is to be completed efficiently. Proper remedial planning requires knowledge of all the technical and regulatory processes so intelligent project choices can be made. Soliciting and accepting the advice of a competent, multi-disciplinary project team is an owners best strategy for certain resolution of their contaminated site issues.

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