Groundwater and Contaminant Transport Modelling at the Sydney Tar Ponds

Mark King, Groundwater Insight Inc., Halifax, NS
Gordon Check, Jacques Whitford Environment Limited; currently with Nova Scotia Department of Environment and Labour, Halifax, NS
Grant Carey, Environmental Institute for Continuing Education, Waterloo, ON
Daron Abbey, Waterloo Hydrogeologic, Waterloo, ON
Fred Baechler, ADI Limited, Sydney, NS

ABSTRACT
The Muggah Creek estuary has accumulated contaminants from 100 years of iron, steel and coke manufacturing in its contributing watershed. The estuary, locally known as the Tar Ponds, contains sediments contaminated with PAHs and PCBs. A program of groundwater modelling was aimed at estimating current contaminant fluxes to the estuary and site streams, via groundwater. The conceptual model developed for the site has attempted to incorporate a complex stratigraphic profile, where groundwater flow and contaminant transport is strongly controlled by shallow fractured bedrock. This paper presents the conceptual model for groundwater flow and contaminant transport at the Sydney Tar Ponds site. Model simulations illustrate the complex flow patterns between bedrock and overburden, and between the bedrock units and surface water bodies. Results indicate that groundwater flow is dominated by discharge to the streams and the estuary.

RÉSUMÉ
L'estuaire de Muggah Creek a amassé des contaminants pendant plus de cent ans de production d'acier et de coke au sein de son bassin versant. L'estuaire, mieux connu sous le nom de Tar Ponds, contient des sédiments contaminés par des HAP et des BPC. Un programme de modélisation des eaux souterraines fut instauré afin d'estimer les flux de contaminants dans l'estuaire et les ruisseaux du site via les eaux souterraines. Le model conceptuel développé pour le site tente d'incorporer un profil stratigraphique complexe où l'écoulement des eaux souterraines et le transport des contaminants sont grandement contrôlés par le socle superficiel fracturé. Cet article présente le modèle conceptuel d'écoulement des eaux souterraines et du transport des contaminants sur le site des Tar Ponds de Sydney. Les simulations du modèle illustrent les patrons complexes d'écoulement entre le socle et les dépôts meubles ainsi qu'entre les unités de socle et les cours d'eau de surface. Les résultats indiquent un écoulement souterrain dominé par une décharge vers les ruisseaux et l'estuaire.

1. INTRODUCTION

The modelling work described herein was undertaken to advance the understanding of groundwater flow in the Muggah Creek Watershed, and was part of a larger Phase II/III assessment (JDAC, 2002). Muggah Creek is a tidal estuary, locally known as the Tar Ponds. It is located in Sydney, Nova Scotia (Figure 1), and has accumulated contaminants from nearby iron, steel and coking industries that operated for 100 years.

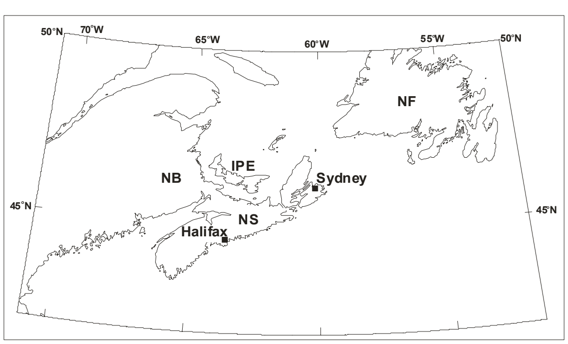

Figure 1. Site location map

The main objectives of the modelling work are to estimate the distribution of recharge and discharge zones throughout the site, and to estimate current contaminant fluxes to local surface water bodies, via groundwater. The work is also intended to provide general insight related to groundwater flow, for future use in evaluating site remediation scenarios.

The primary area of interest for the numerical model was the Coke Ovens Site and associated zones that may receive groundwater flow from the Coke Ovens Site. The approach used herein was consistent with accepted groundwater modelling practices (e.g., ASTM, 1995), whereby a Site Conceptual Model is developed and used as the basis for building a numerical model.

2. SITE CONCEPTUAL MODEL

The Watershed Conceptual Model provided the initial input for development of the numerical model, including the following: 1) the distribution and hydraulic properties of the main hydrostratigraphic units underlying the site, 2) a basis for establishing boundary conditions at the upper surface of the model (infiltration), and the lateral boundaries, and 3) the configuration of surface waterways. The numerical flow model was initially developed according to the understanding of these features, and was then adjusted, as required, through the calibration process.

3. GROUNDWATER FLOW MODEL

3.1 Groundwater Flow Model Code

The model *Visual MODFLOW*, Version 3.0 (Waterloo Hydrogeologic Inc., 2002) was selected for simulation of groundwater flow and contaminant transport. *Visual MODFLOW* is an internationally recognized software that integrates the United States Geological Survey groundwater flow model *MODFLOW* with the contaminant transport model *MT3D99*, and associated add-on packages (e.g. *MODPATH*, *ZONE BUDGET*, *FMBUDGET*). It meets the requirements of the Site Conceptual Model for simulation of the complex three-dimensional flow system at the site.

Groundwater flow was evaluated under steady state conditions. Within Visual *MODFLOW* the Bi-Conjugate Gradient Stabilized (*Bi-CGSTAB*) acceleration routine was used to solve the groundwater flow partial differential equations. Convergence of the matrix solver for the calibrated model was determined with head changes set to 0.01 metres and residual criteria set to 0.001 metres.

In *MODFLOW*, a rectilinear grid pattern is used to divide the modelled domain, both horizontally and vertically, into rectangular blocks or cells. Known or estimated boundary conditions, reflecting water inputs to the model, are assigned to cells for such features as lakes, streams, coastal zones, and precipitation infiltration. The program then numerically calculates groundwater head conditions in each cell of the modelled domain. *MODPATH* allows three-dimensional particle tracking and the determination of capture zones associated with a flow system. Water balance calculations are performed by *ZONE BUDGET*, which allows the determination of flow volumes into and out of user-specified zones.

3.2 Model domain

Figure 2 shows a plan view of the model domain. The domain covers a rectangular area, roughly five by six kilometres that encompasses the Muggah Creek Watershed. The domain extends from South Arm Sydney Harbour/Sydney River in the west, about six kilometres east to a straight line connecting a number of up gradient lakes (i.e., Grand Lake, Power Lake, Gilholmes Lake and Mud Lake). These lateral boundaries were selected to minimize the effect of boundary conditions within the Coke Ovens Site and adjacent zones that may receive groundwater flow from the Coke Ovens Site (known herein as the area of primary interest). The model domain boundary extended approximately 1.5 km to the north of the Coke Ovens Site and about 2.5 km to the south.

The model domain was discretized into a grid of 324 rows and 417 columns. Each layer in the model contains 135,108 grid cells. These cells are approximately 5 by 5 m in the area of primary interest. Outside this area, the grid cells increase in size to a maximum of 100 by 100 m.

3.3 Hydrostratigraphic units

Vertically, the domain is discretized into seven layers of varying thickness. The model domain is approximately 100 m thick and of variable elevation. The thickness or depth, of the domain was intended to minimize the influence of the bottom boundary constraints on groundwater flow in the shallow units (i.e., Fill, Till and Shallow Bedrock) where the majority of contaminant transport occurs. The model layer surfaces were developed through interpretation and interpolation of borehole stratigraphy and surface topography, within a GIS system. In model areas that were outside the bounds of the field investigation, average thicknesses were used for each layer.

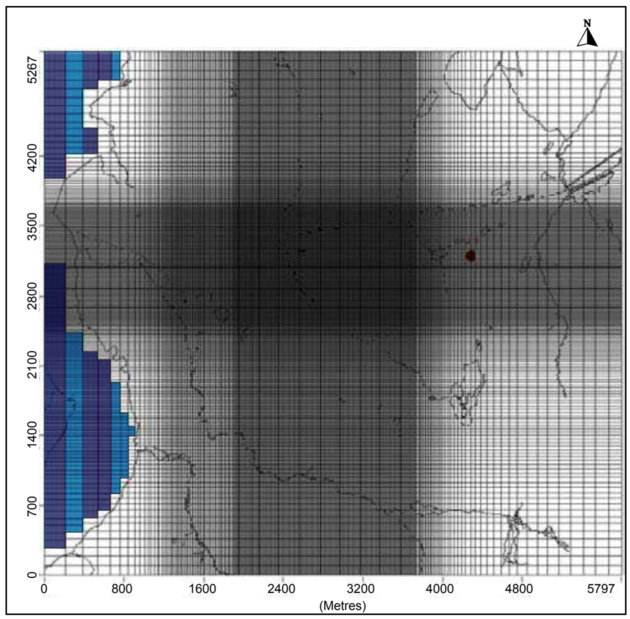

Figure 2. Model domain and Site Grid

Figure 3 illustrates an example model domain cross-section and the variable thicknesses of the model layers. The geologic contact between the two bedrock types at the site (Canso and Morien Groups) was modelled as an eastward sloping discontinuity surface with an approximate 7.5 degree dip. Note that due to vertical exaggeration in Figure 3, the apparent contact dip is greater than the true dip. Model hydraulic conductivities derived during the calibration process are presented in Table 1, and compared with average values calculated from the site data.

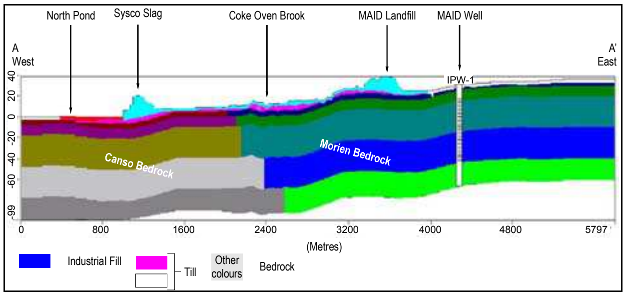

Figure 3. Domain cross-section (see Figure 4 for location)

Figure 4 shows the plan view distribution of the Fill and Till units in the upper model layer. Fill was assumed to be present at the surface throughout the industrialized areas of the model domain. The variable thicknesses shown in Figure 3 are represented in the model, with some approximation due to model cell discretization.

Hydrostratigraphic Unit	Estimate of Mean Hydraulic Conductivity (cm/s)	Model Hydraulic Conductivity (cm/s)
Saturated Fill	2.06×10^{-4}	9.0×10^{-3}
Till	1.65×10^{-4}	2.0×10^{-3}
Shallow Bedrock (Morien)	2.86×10^{-3}	6.0×10^{-3}
Shallow Bedrock (Canso)	1.64×10^{-3}	6.0×10^{-3}
Intermediate Bedrock (Morien)	1.56×10^{-3}	6.0×10^{-3}
Intermediate Bedrock (Canso)	7.7×10^{-4}	5.0×10^{-3}
Deep Bedrock - Morien[1]	1.0×10^{-2}	a) 7.0×10^{-4} b) 5.0×10^{-3} c) 5.0×10^{-3}
Deep Bedrock - Canso[2]	1.60×10^{-5}	a) 7.0×10^{-4} b) 6.0×10^{-4} c) 6.0×10^{-5}

Notes:
1. Morien deep bedrock is subdivided in the model into three layers with variable hydraulic conductivities
2. Canso deep bedrock is subdivided in the model into three layers with variable hydraulic conductivities

Table 1. Hydrostratigraphic Unit Hydraulic Conductivity

A plan view of the distribution of Canso and Morien Shallow Bedrock units in the model is shown in Figure 5. The elevation of the top of bedrock is represented in the model. Within the model, bedrock has been represented by five layers of consistent thickness throughout the domain: a five metre thick Shallow Bedrock layer, a 10 metre thick Intermediate Bedrock layer and three Deep Bedrock layers, each of 30 metres in thickness. Recent Estuary Sediments in Muggah Creek were also included in the model.

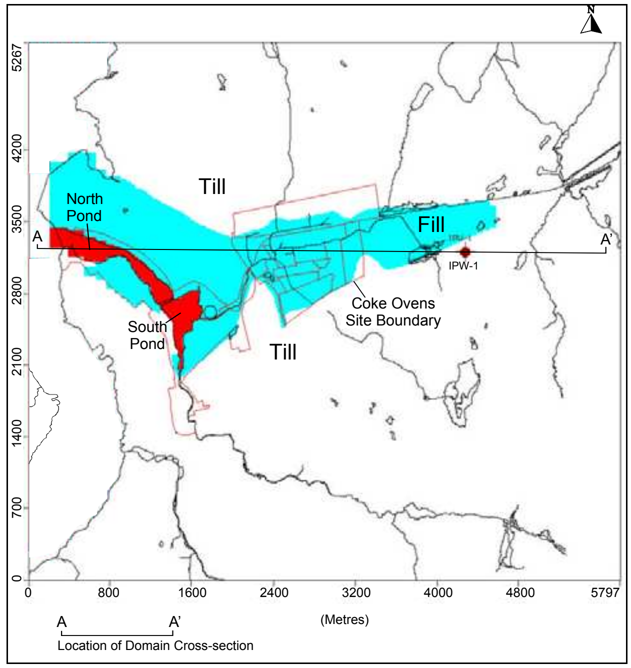

Figure 4. Plan view distribution of the Fill and Till units

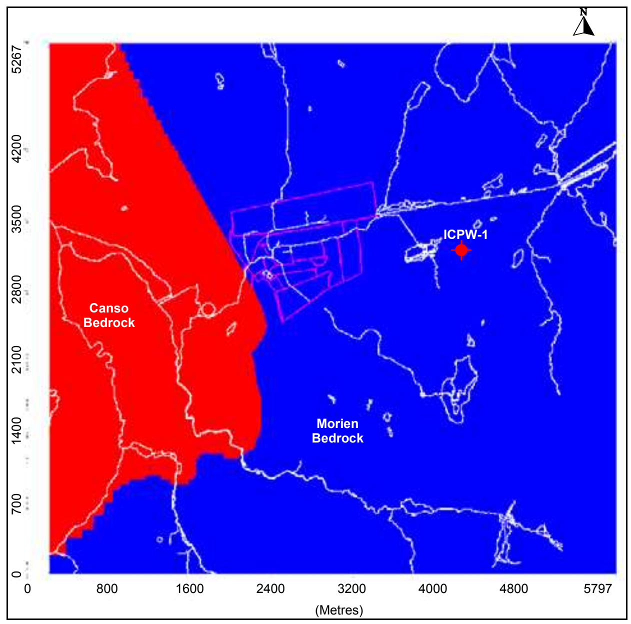

Figure 5. Plan view distribution of the Canso and Morien Shallow Bedrock units

3.4 Boundary conditions

3.4.1 Top boundary - Precipitation

The top boundary of the groundwater model was represented as a specified flux (i.e., precipitation infiltration) surface. Groundwater recharge due to infiltration is dependent on various factors including the soil/fill permeability, surface cover, topography, amount of rainfall (duration and intensity), amount of snowfall and timing of snowmelt. Although no studies have been conducted specifically for recharge in this area, recharge has been evaluated for two other areas in Nova Scotia: Pictou County (Gibb and McMullin, 1980) and Cumberland County (Vaughan and Somers, 1980). These studies estimated annual groundwater recharge between 14-38 % and 13-21 % of average annual precipitation, respectively, based upon data collected over a 10 year period.

Different infiltration zones were used in the model, on the basis that different surface materials affect infiltration rate. The estimated infiltration zones are indicated on Figure 6, where a distinction was made between industrial fill, urbanized areas (buildings and asphalt roads) and woodlands or vegetated areas.

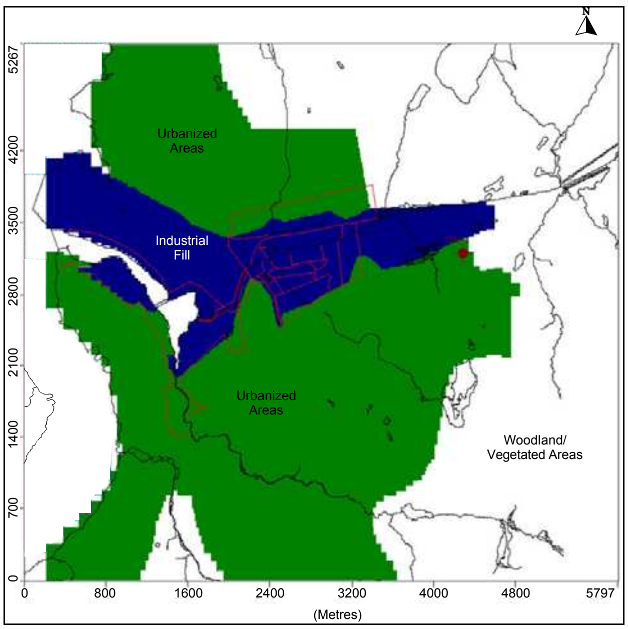

Figure 6. Estimated recharge zones

Average annual precipitation reported for the Sydney area is 1480 mm/yr (JDAC, 2002). Site recharge conditions corresponding to fall conditions were estimated for the three general types of surface materials and refined during the calibration process. The modelled recharge values are 500 mm/year for the Industrial Fill, 200 mm/year for the Urbanized Areas, and 400 mm/year for the Woodland/Vegetated Areas, corresponding to 34%, 14% and 27% of the total annual precipitation, respectively.

3.4.2 Eastern boundary - Specified Head

A plan view showing the model cells assigned as specified heads is shown in Figure 7. Figure 8 shows a cross-section from west to east across the model domain with the vertical boundary conditions shown.

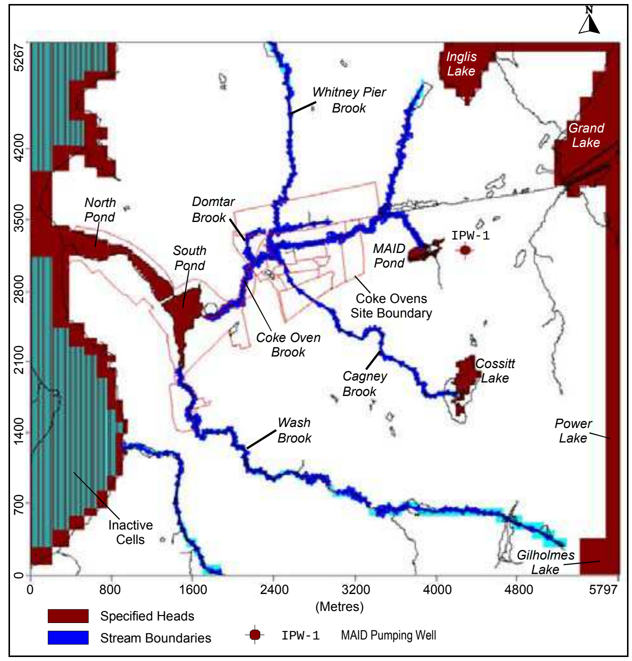

Figure 7. Plan view of Specified Head Boundary conditions

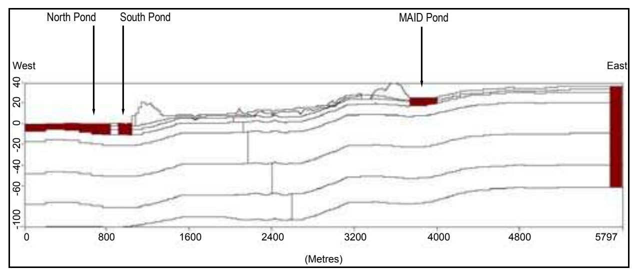

Figure 8. Cross-section of Specified Head Boundary conditions

Specified heads were assigned on the eastern and northeastern boundary of the model domain, along a line connecting Gilholmes, Power, Grand, and Inglis Lakes. Boundary head values were assigned to be consistent with lake elevations determined from topographic survey information. Groundwater piezometric levels between lakes were estimated by straight-line interpolation. These boundary values were assigned to all model layers.

3.4.3 Western Boundary – Specified Head

Specified head of 0 m asl were assigned to areas of South Arm of Sydney Harbour and North Pond of Muggah Creek. South Pond was assigned a slightly higher specified head of 0.8 m asl, due to impoundment by a dam, that is intended to keep the bottom sediments permanently submerged.

For the model boundary with the South Arm of Sydney Harbour, constant head cells extend to a depth of approximately seven metres, which is the estimated depth of the harbour within the model domain. In North Pond, the top three model layers (approximately the top seven metres of the model) were assigned as constant head cells while in South Pond, constant heads were assigned to the top two layers (approximately the top two metres of the model domain).

3.4.4 North, South and Bottom Boundaries – No Flow Conditions

The northern and southern boundaries of the model domain were represented as no flow boundaries, with the assumption that flow in these outlying areas was generally westward and parallel to the boundary, due to recharge in upland areas and discharge to Sydney Harbour/Sydney River.

3.4.5 Brooks/Internal Lakes

Brooks which had measurable stage levels and/or flow during the investigation were included in the model. These brooks included: Coke Oven Brook, Domtar Brook, Cagney Brook, Whitney Pier Brook, Frederick Street Brook, Radar Brook, and Wash Brook. All of these, except Wash Brook, are tributaries to Coke Oven Brook, which flows into Muggah Creek. Stream sections where flow occurs through culverts and underground channels were also included.

Brooks were assigned in the model as stream boundary cells. The stream boundary condition simulates the hydraulic interaction between surface water and groundwater systems, and accounts for the amount of streamflow in cells and individual stream reaches. The degree of flow between stream boundary cells and the adjacent groundwater system is determined in the model by the hydraulic conductivity of the streambed and the modelled hydraulic head difference between the stream boundary cell and aquifer. Unlike *MODFLOW* river boundary cells, stream boundary cells account for the flow that has entered the cell from upstream stream boundary cells as well as adjacent aquifer cells, and uses this as the amount that is available for potential aquifer recharge. The stream boundary was only assigned to the top layer of the model.

The brooks in the watershed were simulated by assigning stream segments or reaches to locations that correspond to stream confluences and surface water monitoring station locations. In the Streamflow-Routing Package, stream segments are additive, allowing cumulative flows along the stream. Stream stage measurements from 2001 survey data were used to assign stage elevations to each reach.

Stream bed conductance is calculated in the model based on specified stream bed hydraulic conductivity, thickness and the width. A thickness of 0.3 m was assigned to all stream beds. Hydraulic conductivity was adjusted during the model calibration to provide the best fit with observed hydraulic head data. The calibrated model stream bed hydraulic conductivities ranged from 0.1-0.2 cm/s for Coke Oven Brook to 0.01-0.001 cm/s for some of the tributaries. Cumulative streamflows were calculated by the addition of flow values from each contiguous stream segment.

Other internal surface water bodies simulated in the model include MAID Pond and Cossitt Lake. These water bodies were assigned specified head values corresponding with water surface elevation measurements. The specified heads for the internal lakes were applied in the top three layers of the model domain.

3.4.6 Pumping Wells

Pumping wells represent groundwater sinks to the model. The only pumping well that affects groundwater flow in the area of primary interest was the CBRM well (IPW-1), shown on Figure 7. The steady state pumping rate assigned to the well in the model was 491 m^3/day (i.e., 75 igpm), on the basis of average use estimated by CBRM. The depth of the open bedrock zone in the well is from 12 to 75 m below ground surface. This zone was assigned as the pumping interval in the groundwater flow model. The pumping rate of the CBRM well is distributed over the length of the open hole interval of the pumping well which intersects multiple model layers. In Visual MODFLOW the user assigns the total pumping rate to the well and this total rate is apportioned by the model to each layer, based on the length of the well screen intersecting the model layer and the horizontal hydraulic conductivity of the model layer.

3.5 Groundwater Flow Model Calibration

The groundwater flow model calibration procedure involves adjusting model parameters so that the simulated results provide an acceptable match to observed conditions, while reasonable parameter values are maintained. The approach used to calibrate the groundwater flow model is divided in three steps which are referred to as Flow Calibration Targets, Flow Model Calibration, and Flow Model Water Balance.

3.5.1 Flow Calibration Targets

The targets used to calibrate the groundwater flow model were based on matching the following types of site data: water levels at individual monitoring wells, measured streamflow during baseflow periods, groundwater flow directions, and vertical gradients between hydrostratigraphic units.

The observed water levels used for comparison to the model were those collected during a November 2001 synoptic water level monitoring event. During this event, groundwater levels were measured at 169 monitoring wells: 30 wells in fill, 20 in till, 85 in shallow bedrock wells, 29 in intermediate bedrock wells and 5 in deep bedrock.

Surface water flows measured when the streamflow was assumed to be solely from groundwater discharge (baseflow) were used as calibration targets on the basis that the brooks and groundwater flow system were in efficient hydraulic connection. The net groundwater discharge to the river cells in the model was directly compared to measured stream flow from November 2001.

Groundwater equipotential contours and flow directions based on measured groundwater levels were used as qualitative calibration targets. Observed contours and associated flow directions were compared with simulated results to achieve a reasonable match. Vertical differences in observed groundwater head between hydrostratigraphic units were also used as qualitative flow targets.

3.5.2 Flow Model Calibration

Various model parameters were refined during the calibration process to achieve a closer match with the observed data, and to develop a calibrated model. Refined parameters include hydraulic conductivity values for all hydrostratigraphic units, recharge infiltration values, and stream bed hydraulic conductivity.

Figure 9 shows a scatter plot of simulated heads from the calibrated model versus observed hydraulic heads for all 169 monitoring wells used at the site. The 1:1 slope line on the plot indicates where the points would plot if the simulated heads were an exact match with the observed results. The plotted points follow the trend of the 1:1 slope, with scatter on both sides.

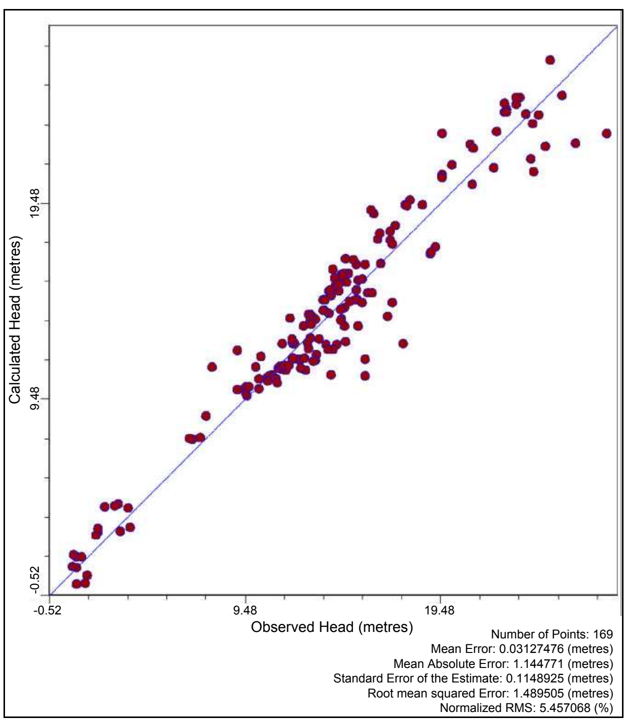

Figure 9. Calculated versus Observed Hydraulic Heads

Statistics on the data scatter provide an estimate of the model calibration error. Statistical errors may be reported by various measures. Five of these measures are reported at the bottom of Figure 9. RMS error is often regarded as one of the best error estimates for modelling (Anderson and Woessner, 1992). , and is the average of the squared differences (i.e., residuals) between observed and simulated heads. When applied to the whole site, the RMS error is divided by the maximum difference in observed head values. The result is called the Normalized RMS error and is expressed as a percentage. A normalized RMS error of <10% is a typical target in evaluating model calibration (ASTM, 1995). The Normalized RMS error of 5.46% for the calibrated model indicates an acceptable calibration.

The net model discharge rates to streams were compared to the observed surface water station measurements. The modelled discharge to Coke Oven Brook was within 20% of the measured baseflow indicating reasonable correlation with Coke Oven Brook and its tributaries.

Modelled equipotential contours for the Fill layer are shown on Figure 10. Qualitative comparison between the modelled and the observed contours indicates that the two sets are reasonably comparable. Both sets show a distinct upstream V along much of Coke Oven Brook, and an approximate match of hydraulic gradients as indicated by the spacing between contour lines of the same value. Similar trends were also noted for Till, Shallow Bedrock and Intermediate Bedrock piezometric contours.

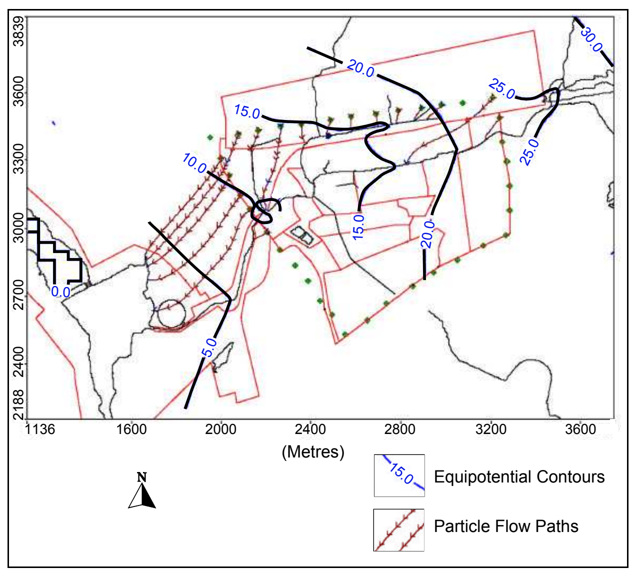

Figure 10. Steady State Particle Tracking, Moderate Flow Conditions, Fill Layer

Vertical gradients were simulated for Shallow Bedrock to Fill and for Intermediate to Shallow Bedrock. The model simulates strong upward gradients from the Shallow Bedrock into the Fill, primarily along Coke Oven Brook and its tributaries. In some areas of the Coke Ovens Site, vertical gradients vary from slightly upward (positive) to slightly downward (negative) between the reference layers.

Based on the quantitative and qualitative comparisons with flow calibration targets, the calibration of the groundwater flow model under steady state conditions was considered appropriate to address the objectives of the modelling work.

3.5.3 Flow Model Water Balance

The results of the modelled water balance components are shown in Table 2. Water balance inputs to the model include recharge from precipitation, constant head cells and stream boundary leakage. Modelled results for these components are qualitatively consistent with the conceptual model developed for the site. The input from constant head cells occurs along the eastern boundary and at the cells used to represent two internal surface water bodies upgradient of the site (MAID Pond and Cossitt Lake). The input at the eastern boundary is consistent with the conceptual model and is indicative of westward groundwater flow into the domain from upgradient areas to the east. Inputs from MAID Pond and Cossitt Lake are generally consistent with measured and/or estimated hydraulic head data.

Water Source	Water Balance	
	IN (m^3/day)	**OUT (m^3/day)**
Recharge	22611	0
Constant heads	27068	22067
Stream boundaries	4314	31438
Pumping wells	0	491
Sum	53993	53997
Notes: Water balance discrepancy between inflows and outflows is 0.01% for the calibrated model		

Table 2. Hydrostratigraphic Unit Hydraulic Conductivity

Outputs from the model include constant head cells, stream boundary leakage and the MAID site pumping well, with the large majority of output due to the first two components. The constant head cells at which groundwater exits the model domain are primarily located along the coast, and discharge of groundwater to the marine environment is consistent with measured hydraulic heads and the conceptual model for the site. Substantial discharge of groundwater to the site streams is also consistent with the conceptual model and measured heads. An acceptable steady state flow water balance discrepancy for the calibrated model of 0.01 % was obtained.

3.6 Flow Model Sensitivity Analysis

A flow model sensitivity analysis was conducted to determine the parameter values that are the least constrained by the calibration data and have the greatest uncertainty. For the sensitivity analysis, quantitative comparisons were made against two of the main calibration targets - the normalized RMS comparison of calculated and observed heads, and the discharge values for Coke Oven Brook. Seven primary parameters were adjusted to determine the effects on these calibration targets. The parameters adjusted were Fill hydraulic conductivity, Till hydraulic conductivity, Shallow Bedrock hydraulic conductivity, Shallow Bedrock vertical hydraulic conductivity, Stream Bottom hydraulic conductivity, Specified Head boundary conditions and Recharge. Parameters were increased and decreased relative to the calibrated value for hydraulic conductivity, recharge and specified heads. For Shallow Bedrock vertical hydraulic conductivity, the value was decreased, to evaluate the potential importance of bedrock anisotropy. Parameter values were varied independently within and beyond the range of acceptable calibration, considered to be <6.0% normalized %RMS.

Figure 11 shows an example of a model sensitivity analysis result. This figure shows a graph comparing changes in the parameters with key calibration targets (normalized %RMS and Coke Oven Brook discharge at COB-4-SW). These sensitivity curves indicate which parameter values are most constrained by the calibration data, or have the least uncertainty.

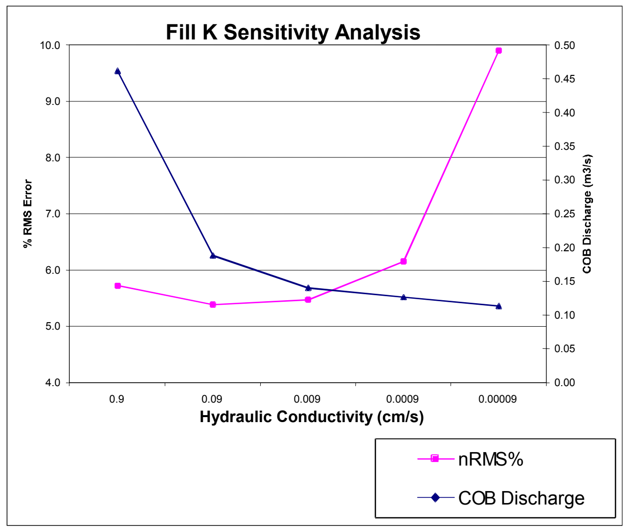

Figure 11. Sensitivity Analysis Example - Fill Conductivity

The sensitivity ranking for the tested parameters, from most sensitive (least uncertainty) to least sensitive (most uncertainty), is as follows: the till hydraulic conductivity, shallow bedrock horizontal hydraulic conductivity, fill hydraulic conductivity, shallow bedrock vertical hydraulic conductivity, stream bottom hydraulic conductivity, specified head boundary conditions, and recharge.

3.7 Flow Simulation Results

Interaction between groundwater and surface water in the vicinity of the Coke Ovens Site was evaluated under three surface water flow scenarios: low, moderate and high. These three scenarios were approximated with the range of flow data from the Surface Water Monitoring Program conducted for Coke Oven Brook and its tributaries from September 2000 to November 2001. These flow conditions were used as an indication of the range of the overall range of flow variability in the watershed; an exact match to each flow data set was not required, for the purposes of the evaluation.

An example of the evaluation results is shown in Figure 10, which represents groundwater in the Fill layer, under moderate flow conditions. This figure illustrates steady state groundwater flowpaths with both equipotential lines (groundwater flow direction is orthogonal and downgradient, relative to the equipotentials) and particle tracks. Particle tracks originate from points placed in selected model locations. They extend downgradient from the placement point, in the direction of groundwater flow, and are therefore indicative of groundwater flowpaths. The termination of the particle tracks occurs where the groundwater flowpath ends due to discharge to surface water (i.e., into Coke Oven Brook and its tributaries, or Muggah Creek). Consequently, the particle tracks provide an effective means of evaluating the interaction between groundwater and surface water in the vicinity of the Coke Ovens Site.

Overall, groundwater flowpaths are qualitatively similar among the upper four model layers, which represent the hydrostratigraphic units containing the great majority of the contaminated groundwater at the site. Flowpaths are also similar among the moderate, high and low flow scenarios. In all cases, the particle tracks indicate substantial discharge of groundwater to Coke Oven Brook and its tributaries, with most flowpaths terminating in streams on the Coke Ovens Site. Groundwater from the northwest edge of the Coke Ovens Site tends to flow westward, discharging to Muggah Creek, under low and moderate flow conditions, but reverses and is captured by Domtar Brook under high flow conditions. The model output indicates that groundwater from the southwest edge of the Coke Ovens Site flows westward off-site, but is captured downstream by Coke Oven Brook. Modelled equipotential lines for all units and all three flow conditions tend to point upstream, which is another indication that groundwater discharge to the brooks is a dominant process across the site.

4. SUMMARY AND CONCLUSIONS

A numerical model of groundwater flow in the vicinity of the Coke Ovens Site was developed to estimate the distribution of recharge and discharge zones throughout the site, and to estimate current contaminant fluxes to local surface water bodies, via groundwater. The work is also intended to provide general insight related to groundwater flow, for future use in evaluating site remediation scenarios.

A detailed sensitivity analysis of model parameters was conducted. Of the parameters evaluated, the relative order from most sensitive to least sensitive was as follows: till hydraulic conductivity, shallow bedrock horizontal hydraulic conductivity, fill hydraulic conductivity, shallow bedrock vertical hydraulic conductivity, stream bottom hydraulic conductivity, specified head boundary conditions and recharge. The K values for the units through which most of the contaminant fluxes are well constrained by the calibration, increasing confidence in the representation of the flow system and predictions made about flux to the brook.

The model shows that groundwater flowpaths are qualitatively similar among the upper four model layers, which represent the hydrostratigraphic units that contain the large majority of the contaminated groundwater at the site. Flowpaths are also similar among the moderate, high and low flow scenarios. In all cases, the particle tracks indicate substantial discharge of groundwater to Coke Oven Brook and its tributaries, with most flowpaths terminating in streams on the Coke Ovens Site. Evaluation of vertical gradients by the model is also consistent with groundwater discharge along most of the length of the brooks, in the vicinity of the site.

Groundwater from the northwest edge of the Coke Ovens Site tends to flow westward, discharging to Muggah Creek, under low and moderate flow conditions, but reverses and is captured by Domtar Brook under high flow conditions. The model output indicates that groundwater from the southwest edge of the Coke Ovens Site flows westward off-site, but is captured downstream by Coke Oven Brook.

5. ACKNOWLEDGEMENTS

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