Tailings Deposition Planning Supported by Hydrogeochemical Modelling at Vale Thompson

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Abstract
Sulphide-bearing tailings at Vale Limited's nickel mine in northern Manitoba have been primarily deposited underwater. Earlier in the life of mine, tailings were also deposited above water and are now actively generating acidity and metals. A hydrogeochemical model was used to simulate water quality in the Tailings Management Facility (TMF) to understand controls on water quality, and to assist with water quality management and tailings deposition planning. The model was based on water and mass balance principles with linked multiple water bodies and multiple dissolved constituents with time-varying flows and concentrations or mass loadings. Model predictions fit the observed data well and showed that loadings from the exposed tailings are seasonal. Modelling demonstrated the benefit to the discharge water quality at the end of mining operations by progressively covering exposed tailings during operations. It also predicted a spike in dissolved nickel concentrations above compliance levels when basin water pH reverts to natural levels, caused by dissolution of nickel from the sediments. Multiple scenarios were run to support tailings deposition options and to provide guidance on mitigation strategies during operations. The tailings deposition plan consists of the development of temporarily tailings beaches while mitigating acidity and metal loadings.

Key Words: water quality prediction, nickel, sub-aerial beach

Introduction
Vale Limited's nickel mine in Thompson, Manitoba has been operating since 1960 and is projected to continue to 2039. Figure 1 shows the general location of the mine. Sulphide-bearing tailings are primarily deposited underwater in multiple natural basins by advancing a road on top of tailings with plans to inundate all tailings or covering them prior to closure. Some tailings were also deposited above water earlier in the life of the mine. Historically exposed tailings are actively generating acidity and dissolved metals, with nickel being the primary concern. A hydrogeochemical model was developed in the mid 2000s to simulate the water chemistry in the basin in order to improve the understanding of the controlling factors and to assist with water quality management. This paper presents the site-specific modelling tool and describes the application of the model for tailings deposition planning and basin management.

Background

Site description

The tailings basin or Tailings Management Facility (TMF) consists of five sub-basins, referred to as Areas 1 to 5 as shown on Figure 2. Tailings have been discharged to Areas 1 to 3, which are now near capacity with no further deposition planned except during emergency situations. Tailings are currently being discharged into Area 4 and this is scheduled to continue until the end of mine life. Area 5 acts as a polishing basin and is not scheduled for tailings deposition. The TMF water level is controlled by three dams that were built in the 1970s and are scheduled to be raised in the next few years. Two structures are to be built during this time to allow water level raises in Areas 1 to 3 independent of Area 4. This will allow increased tailings storage. The TMF is contained within a 58.3 km² watershed. The average precipitation in the area is 523 mm, comprised, on average, of 67% rainfall and 33% snow.

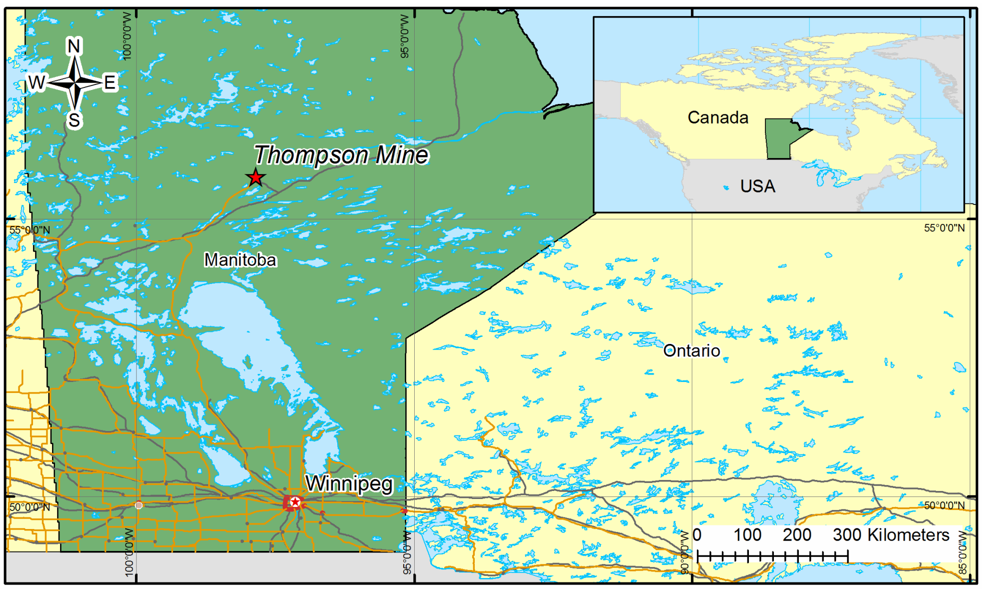

Figure 1. Site location.

Tailings deposition

Tailings are delivered by one of two sets of two stage pumps at the mill and a 22 inch (56 cm OD) High Density Polyethylene (HDPE) pipeline that decreases to a 20 inch (51 cm OD) HDPE pipeline which is over 8 km long. Within the basins, the tailings line is advanced along roads constructed on top of previously deposited tailings. As a result, some of the tailings are temporarily exposed above the water, along with the acid-generating mine rock used as a road base. Earlier in the mine life, some tailings were deposited above water. The largest area is referred to as the South Beach (Figure 2), which contains about 6.4 million tonnes of tailings above the current water level with an exposed surface area of about 1.77 km².

The current annual average tailings production is about 5,700 tonnes per day and this is planned until 2020, followed by lower production values until mining cessation in 2039. As of 2010, 50M tonnes of tailings have been deposited in the TMF. A total of 30.8M tonnes (21.9M m^3) of tailings is to be directed to the tailings basin after January 1, 2011.

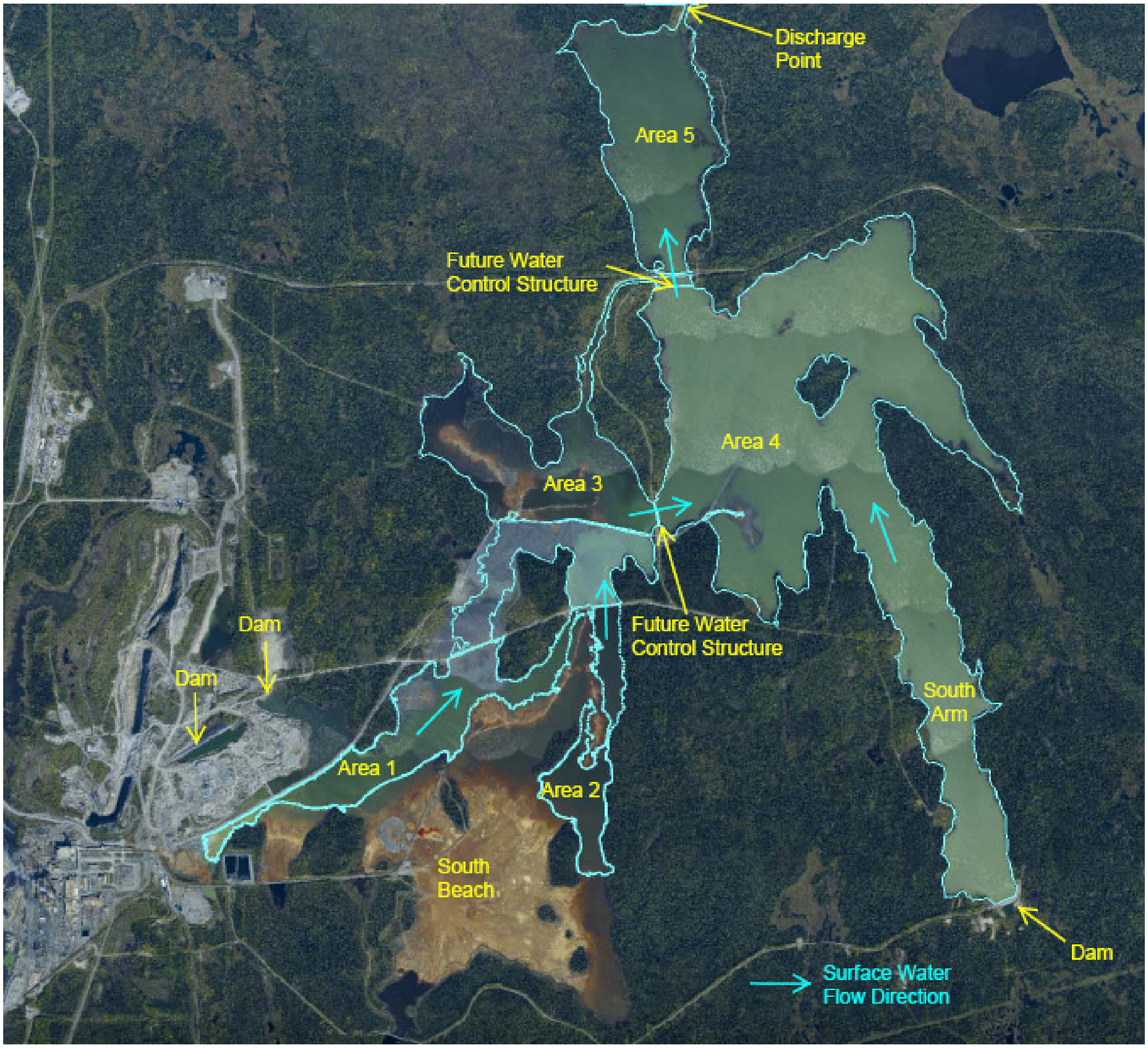

Figure 2. Site plan.

Inputs to tailings basin

In addition to the deposition of tailings, the TMF receives several other input flows (1.1 m and 1.2 m diameter sewers, smelter return, mine water) that deliver variable loadings of several Constituents of Potential Concern (COPC), of which nickel is a focus for compliance in the basin outflow. Flows at the TMF discharge point in Area 5 range from 50,000 to 250,000 m^3/day. Average annual flows and average concentrations for the COPCs for model calibration for each input are shown in Table 1.

The loadings estimates in Table 1 provide an indication of how effective the basin performs in the removal of dissolved nickel from the water. The sum of all the dissolved nickel entering the basin is about 260 tonnes per year. In contrast, only about 15 tonnes of nickel exit the basin at its discharge point annually. This shows that about 245 tonnes of nickel are deposited in the basin as sediment and that the basin is performing as an effective treatment system for nickel, which is made possible by pH control. In comparison, sodium shows only a 20% difference between input and output loads that is within the error expected for mass balance in such a system. Sulphate exhibits only about a 10% difference between inputs and outputs. However, sulphate losses are expected in Area 1 as a result of gypsum ($CaSO_4$*$2H_2O$) formation in the 1.2 m sewer when lime is added there.

Table 1. Summary of flow rates, concentrations and loadings for key constituents

		Concentration (mg/L)					Loading (t/a)				
Input Sources	**Flow (m^3/a)**	**Ni-D**	**Ni-T**	**Mg**	**SO_4**	**Na**	**Ni-D**	**Ni-T**	**Mg**	**SO_4**	**Na**
1.2 m Sewer	4.62E+06	7	25	49	1674	1545	34	118	226	7737	7140
1.1 m Sewer	9.93E+05	4	4	9	55	7	4	4	9	55	7
Mine Water	8.31E+05	17	17	584	5608	1326	6.2	6.2	155	1336	291
Tailings Effluent	2.22E+07	0.08	0.3	14	501	125	2	7	309	11133	2775
Smelter Return	3.13E+06	N/A	N/A	N/A	N/A	N/A	163	N/A	0.04	2	0.3
South Beach (runoff)	N/A	N/A	N/A	N/A	N/A	N/A	44	N/A	316	2082	38
South Beach (seepage)	N/A	N/A	N/A	N/A	N/A	N/A	0.01	N/A	16	92	38
Waste Rock	N/A	N/A	N/A	N/A	N/A	N/A	7	N/A	0	0	13
Total Input Loadings							260	N/A	1030	22436	10303
Output											
Weir Discharge	5.18E+07	0.28	0.3	14.2	389	244	15	N/A	734	20150	12639
Load Difference (Out-In)							-245	N/A	-296	-2286	2336
Percent Load Difference							-1689%	N/A	-40%	-11%	18%

Notes: 1-N/A – Not Applicable; D – Dissolved; T - Total
2 – Smelter Return reports to the tailings but is considered as a separate input to distinguish nickel sources

Discharge water quality

Nickel has a monthly average discharge limit of 0.5 mg/L at the discharge point from Area 5. Control of pH in the basin is achieved by adding lime to two of the input streams (tailings effluent and 1.2 m sewer) as well as at various points in the basin via truck, as required. As shown in Figure 3, nickel concentrations at the TMF discharge point range from about 0.1 to 0.3 mg/L and sometimes between 0.3 and 0.5 mg/L in the late fall and winter months. The pH at the discharge point typically ranges between 8 and 9, with an average of 8.2.

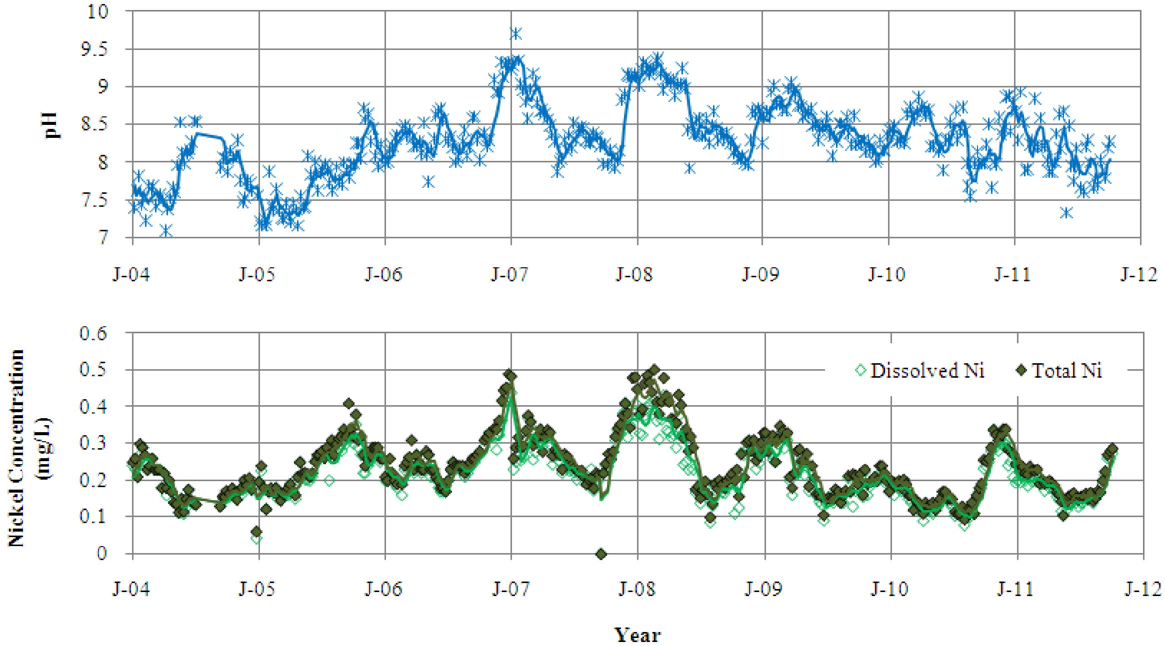

Figure 3. Nickel concentrations and pH at the outlet of the TMF in Area 5, with 4 week moving average.

Hydrogeochemical Model

Model description

The main components of the model are:

- **Areas**: water-bodies that are linked hydrologically and behave as well-mixed reactors.
- **Influents**: different pipes carrying flow from the mill or other parts of the mine to the Areas, such as tailings effluent pipe, 1.2 m sewer, etc.
- **Above-water sources**: beached tailings (such as the South Beach) and the waste rock stockpile that are above water surface and are therefore exposed to the atmosphere and release chemicals.
- **Underwater sources**: sediments and submerged tailings that can release chemicals to the overlying water.

A depiction of the model on the computer screen is presented in Figure 4 showing Areas (blue outline), land-based sources (green outline) and pipes (coloured dots in Areas).

Areas 1 to 5 are connected with flow between them, and the mass balance is maintained in each waterbody. The volumes of Areas are based on bathymetric measurements. The pipe sources can be turned on or off. The input files for pipe sources contain concentrations and flow rates and are user-defined. The above-water sources have inputs in the form of loading rates (mass per time) to the nearest area or water body and are user defined. The underwater sources are embedded into the source code and need not be defined separately. However, if it is intended to control these sources, it can be defined in other files and represented by a mass flux (rate of mass released per unit area) into the overlying waterbody.

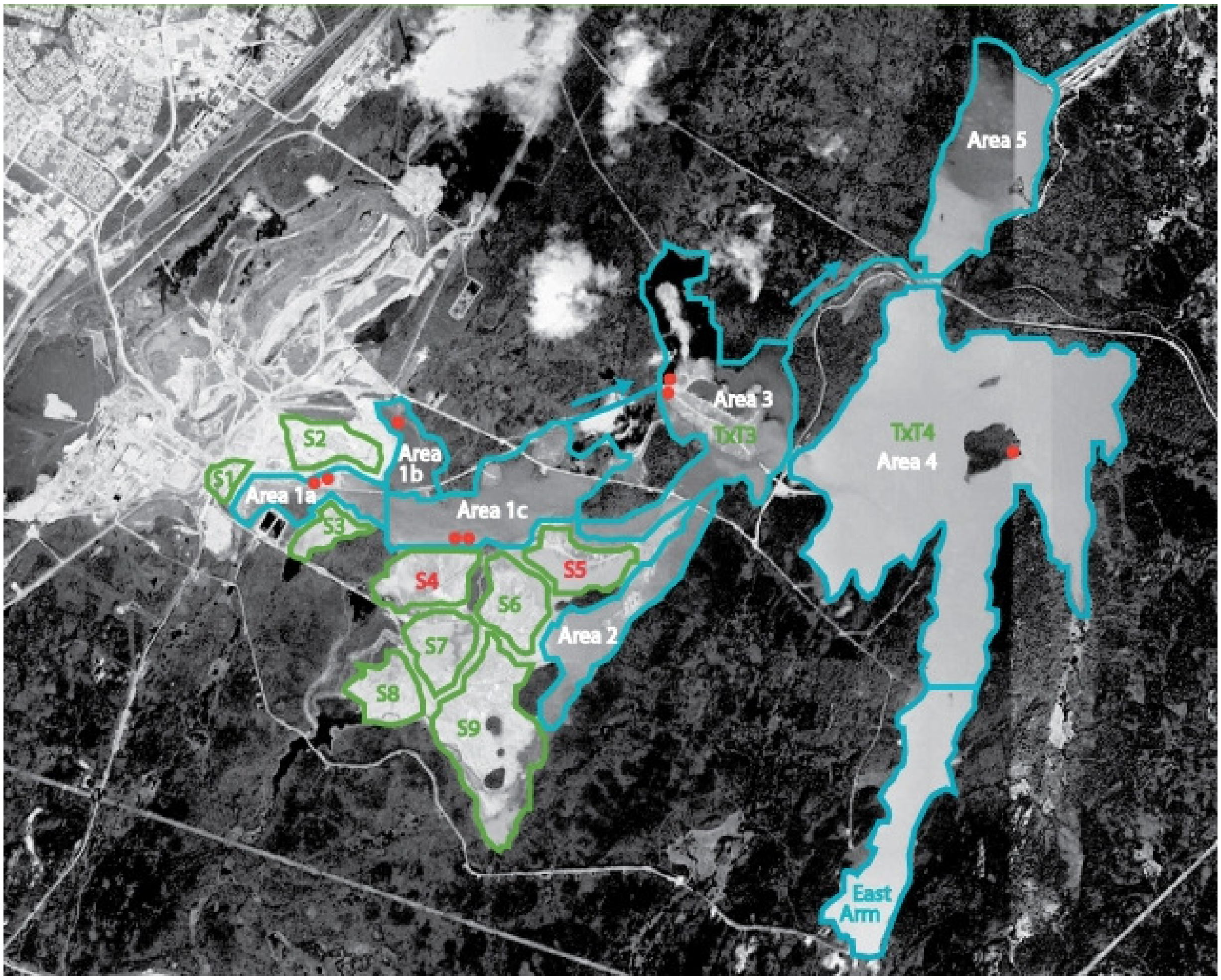

Figure 4. Model user interface showing water Areas 1 to 5 (blue), above-water sources (green) and influent pipes (red).

The input files consist of (1) a scenario file, (2) area files, (3) pipe files, and (4) source files. When a scenario is defined by specifying conditions of flow, source loadings and other inputs, a scenario file is generated and saved. The input files are in Excel spreadsheet format and can define input data as either variable with time or constant. The user can specify such variations as seasonal natural inflow to the basin, providing flexibility to monitor the output of different scenarios. A summary of input area-specific values are shown in Table 2. The output files are in Excel format and can be manipulated and processed, as appropriate.

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Table 2. Summary of area-specific data used in model calibration

Basin Area	Unit → Pipes ↓	Process Effluent (2005-06)	Catchment Area	Fraction of Total Catchment Area	Average Depth	Volume	Average Residence Time
		L/wk	m^2	%	m	m^3	week
1a	1.07m	1.91E+07	2.24E+06	3.85	0.63	1.75E+05	1.42
	1.22m	7.91E+07					
1b	Mine Water (T1)	1.61E+07	2.24E+06	3.85	0.63	1.10E+05	2.71
1c	--	--	4.47E+06	7.70	0.63	4.35E+05	2.06
2	--	--	2.09E+07	35.94	2.63	1.41E+06	6.19
3	Mine Water (1D)	3.57E+05	8.02E+06	13.82	3.49	1.25E+06	2.36
East Arm	--	--	7.79E+06	13.41	2.00	1.72E+06	20.23
4	Tailings Effluent	4.27E+08	7.79E+06	13.41	4.65	2.12E+07	18.83
5	--	--	4.65E+06	8.01	3.85	4.27E+06	4.02

The model considers three key outputs: water concentrations, sediment concentrations, and flow rates. Other parameters involved in determining the model prediction of concentrations are (unit and typical values in parenthesis): diffusion coefficient from water into sediment ($D = 1\times10^{-10}$ m^2/s), water-sediment interface thickness ($h_i = 0.001$ m), active sediment depth ($h = 0.2$ m), sediment porosity ($n = 0.5$ m^3/m^3), and dry bulk density of sediment ($\rho = 1.4$ kg/L). There are also other variables used for the calibration to provide the best fit of the model predictions to measured data. These variables include the total suspended solids (TSS = 5 to 10 mg/L), particle settling rate ($v_s = 5\times10^{-5}$ m/s) and distribution coefficient (K_d) between water and suspended particles (L/kg). A relationship between K_d and pH was developed from laboratory studies and then adjusted through the calibration for each area (K_d suspended particles = 100 to 6500 L/kg; K_d sediment = 100 to 2000 L/kg).

Calibration

The model was calibrated with data from January 2005 to March 2008, which consisted of the following steps:

- set up the known inputs for flows and concentrations in the basin;
- estimate the residence times for each of the areas;
- complete tracer tests in the system by having concentration step-function inputs for selected constituents to each of the areas;
- calibrate the concentrations for magnesium leached from the exposed tailings;
- calibrate the concentrations of other non-conservative constituents;
- evaluate the relationship between pH and the nickel distribution coefficient (K_d) as the dissolved nickel concentration in the model was linked to the basin pH;
- calibrate the normal operating period in 2005-06 to match nickel concentrations to the pH values in Areas 4 and 5;
- refine calibration with sodium concentrations for Areas 1 to 5 (since sodium results are only available for 2007 and 2008);

- conduct a sensitivity analysis on the inclusion of loadings from the South Beach runoff as a source of nickel to the basin; and
- evaluate the shallow flushing of loads from the exposed tailings pore water to runoff and the periodicity of flushing during non-frozen periods by comparing the magnesium concentrations (magnesium is a major leaching component from oxidized tailings).

After all the above steps were completed and all inflows and other input files and data were established, the model calibration was complete. As shown on Figure 5, the calibration resulted in excellent fit for nickel and sodium in Area 5, and reasonable results for sulphate and magnesium. Observed concentrations of sulphate were lower than the modelled values starting in late 2006. This can be attributed to the effects of liming in Area 1, where concentrations of these constituents would be expected to precipitate, a process that is not accounted for in the model.

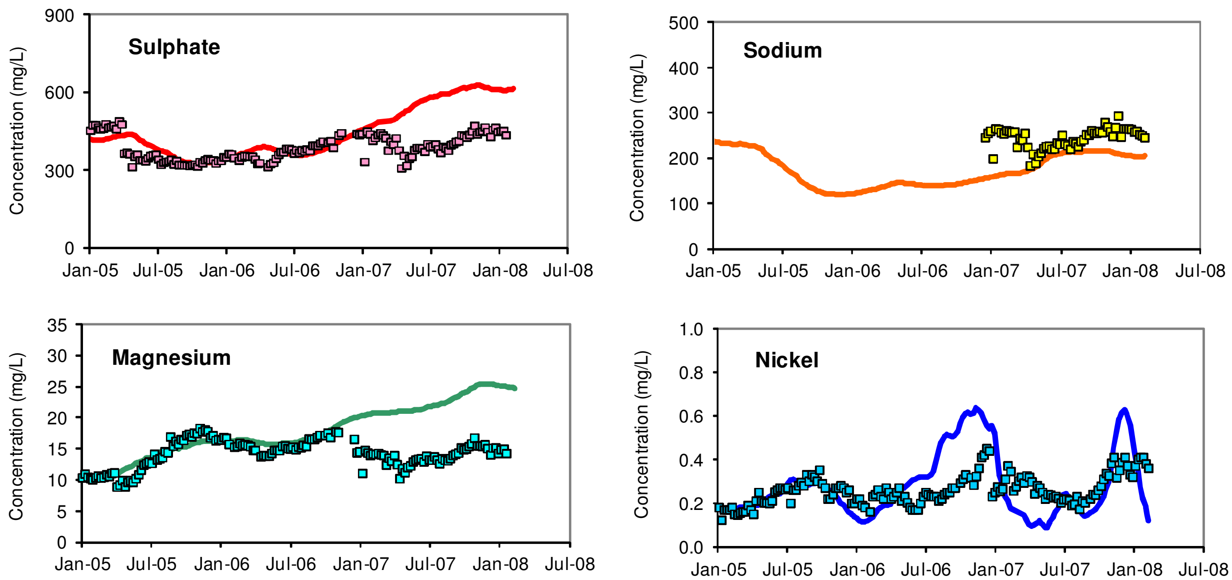

Figure 5. Calibration showing measured and modelled sulphate, sodium, magnesium and nickel concentrations in Area 5 (outlet of tailings basin).

Figure 6 exhibits how the inclusion of seasonal loading from the South Beach improves the prediction of magnesium in Area 4. The magnesium loads were estimated from measured dissolved magnesium in tailings pore water in the topmost 0.3 m of tailing in the South Beach. Without loading from the South Beach, the model significantly under represents the magnesium concentrations in Areas 4 and 5. With constant annual loading the match is improved, but the peaks are offset. With loadings only applied during the non-frozen period (26 weeks from May to October), the model prediction fit the measured data very well. This fit confirms the nature of the loadings from the tailings beach that occur as shallow flushing to runoff during spring melt and rainfall events but not when the ground is frozen.

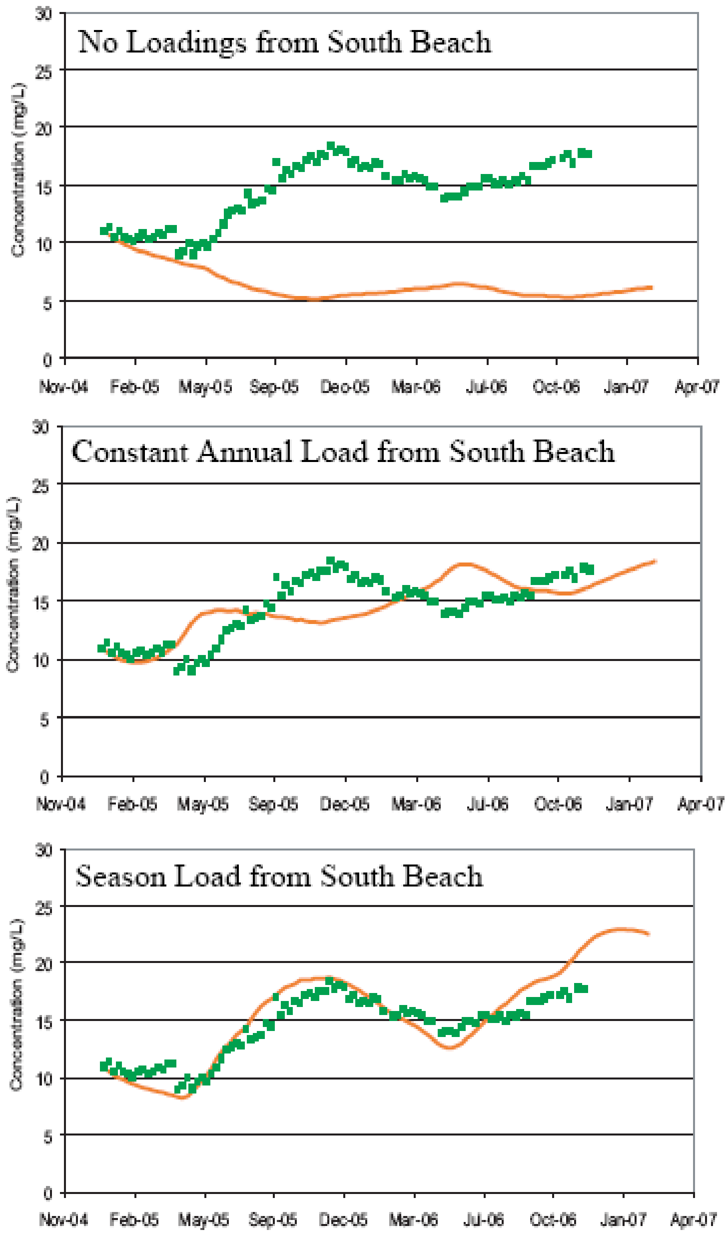

Figure 6. Effects of the inclusion of the magnesium loading from the South Beach on the calibration at the outlet of Area 4 (which is one measuring point upstream of the discharge point from the basin).

Model results

The model has been used to test the effects of mitigating various sources and also to consider changes to the future operation of the basin in the near-term and long-term after mine closure. The results from the beached tailings scenarios are discussed in the context of tailings deposition planning.

South Beach

To demonstrate the effect that South Beach loadings have on the basin water quality after mine closure and the cessation of operations, several scenarios were run with variable loading rates to represent the current loading rate (100%), twice the current loading rate (200%), and 20% of the current loading rate. The reduction of loads to 20% of the current rates was considered to result from mitigation such as by construction of a low permeability cover. It was assumed that pH control continued in the basin during mining operations until closure, which was selected as 2033 in that modelling exercise. Figure 7 shows the results for each scenario, which all show a spike in nickel concentrations at the cessation of mining due to the release of nickel from the sediments as discussed further below. With no mitigation of the South Beach at closure (100%), the maximum nickel concentrations are predicted to be near 0.4 mg/L in the long term after closure. If the South Beach loadings were 200% of current values at closure, the maximum long-term nickel concentrations would be about 0.75 mg/L. A reduction of South Beach loadings to 20% of current values would result in nickel values near 0.1 mg/L over the long term.

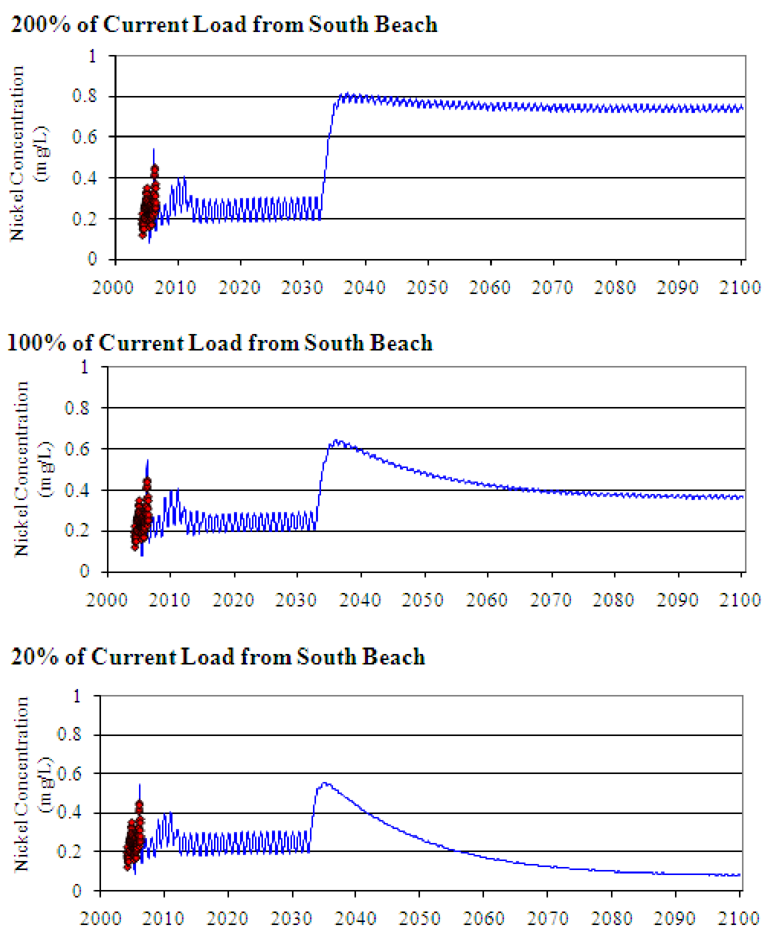

Figure 7. Nickel concentrations at the Area 5 outlet given variable South Beach mitigation scenarios at mine closure.

A progressive reclamation scenario implemented during operation was also considered for the South Beach as presented in Figure 8. It was assumed that the load was reduced from 200% to 20% of current loads in about 20 years while the basin pH was controlled. The concentrations of nickel in the basin during operation decrease continuously to about 0.1 mg/L at the end of operation, followed by an expected increase at closure as the pH reverts to neutral conditions, and then a decline to less than 0.1 mg/L after several decades. It is clear that progressive reclamation by covering the South Beach during operation will have net positive effects on the nickel concentrations at the discharge outlet at closure and in the long term, and could reduce the likelihood of the need for water treatment at the end of operations to prevent an exceedance of the 0.5 mg/L effluent limit.

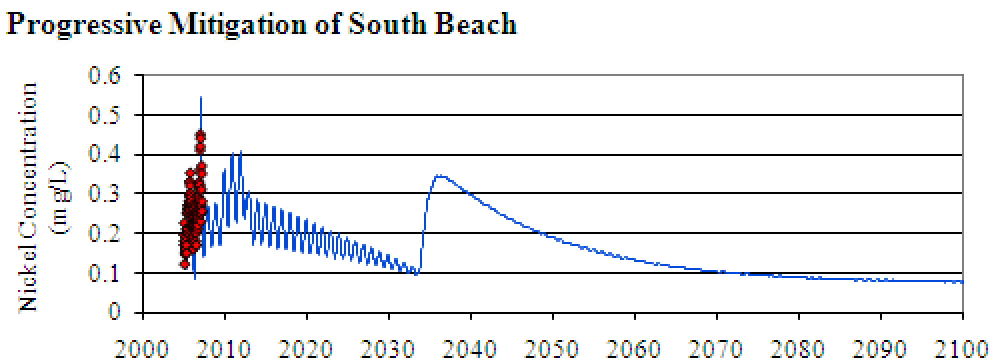

Figure 8. Nickel concentrations at the Area 5 outlet given progressive mitigation of the South Beach loadings to 20% of current values during operations.

Sediments

Another finding from the modelling work is that the sediments in the basin are an important source of nickel at mine closure when pH control in the basin ceases. There is a large inventory of nickel in the sediments throughout the basin due to precipitation as a consequence of pH control. Some of these sediments can readily dissolve when the pH drops below 8. Normal operating pH in the basin ranges from 8 to 9, with some values as low as 7.5. Lower pH values result in higher dissolved nickel concentrations (Figure 3) so lime is then added to lower the nickel concentrations. For the modelling scenarios presented in Figures 7 and 8, the pH in Areas 4 and 5 were assumed to have historical averages of 8.5 and 8.2, respectively during operations, and a value of 7.5 after tailings deposition and basin pH control cease. These results all show a spike in nickel at the end of operations, even with the scenario where South Beach loadings are reduced to 20% of current values. The magnitude of the peak concentration at closure can be reduced further by reducing the formation of nickel treatment solids in the basin prior to closure.

Tailings Planning and Basin Management

The improved understanding of South Beach loading rates was incorporated into the tailings deposition planning and overall management of the tailings basin. Vale's current tailings deposition method consists of advancing a road on top of the previously deposited tailings. Thus, a portion of tailings and waste rock used for the road surface remains above water, which begins to oxidize and becomes a source of acidity and metal loading. Earlier work by Beak (2002) demonstrated that the loadings are substantial within about four years and have reached the peak in about eight years. Given this and the overall storage requirements, the tailings deposition plan developed in 2010 calls for a series of small, stepped water level raises every 3 to

4 years to flood previously exposed tailings and reduce the nickel loadings rates to very low levels.

A new mine plan suggests that even more tailings storage capacity will be required than already planned; therefore, deposition planning is in progress to consider possible modifications. Tailings deposition for the remainder of mine life is scheduled for Area 4 and is currently taking place in the South Arm of Area 4. In order to meet the storage requirements and continue with the current method of tailings deposition, tailings in the South Arm will need to be temporarily beached and the water level raise delayed several more years than planned.

The hydrogeochemical model was applied to estimate the nickel and acidity loads from the South Arm by prorating what has been estimated for the South Beach. Water quality predictions for this scenario suggest that loadings from the South Arm at maturity would contribute an additional 0.15 mg/L nickel at the discharge point. Given the current (2010-2011) range of nickel concentrations of 0.1 to 0.35 mg/L, the incremental increase from the South Arm could result in values very close to the compliance level of 0.5 mg/L. Therefore, consideration is being given to manage these loadings by treating the water at the outlet of the South Arm with a settling area within Area 4. The model will be used to estimate the lime neutralization requirements and then consideration can be given to planning for treatment.

Once the tailings in the South Arm have reached the planned elevation, tailings deposition will continue north in Area 4 without changing the water level for an additional three to four years. It is expected that water treatment at the South Arm outlet will be needed at this time and will continue until sometime after the water level raise to manage dissolved metals and acidity that are expected to flush from the tailings porewater. This approach of planning for temporarily beached tailings while managing the nickel and acidity loadings, increases the basin storage capacity to accommodate the current mine plan with minimal changes to the current operations and method of deposition. Consideration is also being given to depositing the tailings with a floating system in the north zone of Area 4 to further increase the capacity of the basin, if required.

Conclusions

Coupling of the hydrogeochemical tailings basin model with tailings deposition planning allowed adaptive management of changing process inputs and tailings storage requirements in Vale's Thompson TMF. Although there is an obvious limit to the storage requirements, alternate deposition scenarios can be modelled to maximize the available capacity and future water quality predicted for the near and long-term. An iterative approach can be taken to select a deposition plan that meets the operational needs and maintains environmental compliance, with a view to minimizing the likelihood of water treatment at the cessation of mining operations.

References:

Beak. (2002) Development of a Tailings Basin Water Chemistry Model and Management Tool. Report to Inco Limited, September, BEAK Ref. 22587.1