Groundwater Modeling as a Tool for Closure Planning: Prediction of Zinc Transport for Alternative Cover Scenarios[1]

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ABSTRACT

Groundwater modeling was used to assists in the design of a soil cover for an acid-generating waste rock pile at the Woodcutters lead-zinc mine near Darwin, N.T., Australia. A three-dimensional groundwater flow (MODFLOW) and solute transport model (MT3D) was developed for the site to predict the timing and magnitude of peak zinc concentrations (the primary metal of concern) in shallow groundwater discharging to the nearest stream for different cover scenarios: (1) removal of the waste rock dump (no cover required); (2) use of a “high quality” cover (allowing net infiltration of 1% of MAP); (3) use of a “lower quality” cover (10% of MAP); and (4) use of a “low quality” cover (20% of MAP).

The predicted times for a “breakthrough” of peak zinc concentrations in a nearby creek ranged from ~150 years for Scenario 1, to ~400 years for Scenario 4. While the lowest peak zinc concentrations were predicted for Scenarios 1 and 2 (~1.2 mg L^{-1}), all scenarios produced peak zinc concentrations that exceeded the low risk trigger value (0.008 mg L^{-1}) for protection of 95% of aquatic biota in the creek. An ecological risk assessment ensued which found that cover scenario 3 (10% of MAP) would be sufficient to protect the ecology in the nearby creek.

In 2003/2004, the waste rock pile was reshaped and a high quality cover was placed. Detailed groundwater monitoring is ongoing at the site to assess the performance of all site closure measures, including cover placement. Monitoring over the last five years indicates that the groundwater flow system is recovering as predicted whereas contaminant concentrations (e.g. sulphate, zinc) in the local groundwater and the Woodcutters Creek are lower than predicted.

Additional Key Words: closure planning, cover design, solute transport, groundwater contamination, neutral mine drainage, groundwater impact analysis

INTRODUCTION

The Woodcutters Mine is a lead-zinc mine, located approximately 80 km south of Darwin, N.T. in Australia. The mine area experiences a tropical savannah climate, where 90% of the annual rainfall (~1,600 mm) is delivered in heavy rain showers during the wet season (November to March) and drought conditions are often encountered during the dry-season (April to October). The mine area slopes gently to the southwest and drains toward the ephemeral Woodcutters Creek, which in turn drains into the left branch of the Coomalie Creek.

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The Woodcutters deposit consisted primarily of coarse-grained sulphides (including sphalerite, galena and pyrite) hosted in a carbonaceous, dolomitic mudstone-shale and siltstone unit (Whites Formation). The rocks in the mine area have been complexly folded and faulted and there are strong structural controls on mineralization and groundwater flow.

Ore was first mined from a 100 m deep open cut between 1985 and 1987, after which underground mining continued until 1998, producing 750 m deep underground workings centered beneath the open cut. Significant dewatering (up to 350 L s^{-1}) was required during mining. Pre-concentration of the mill feed produced tailings with a high mineralization content (Pb 3%, Zn 3%, As 1%, Sb 0.3%, Cd 0.2% plus high levels of sulphide) which were stored in two above-ground tailings facilities “TD1” and “TD2” (Figure 1). A waste rock dump (WRD) was constructed during the open cut phase of mining and received overburden that was classified as either clean waste rock or as sulphide bearing waste rock. High pyrite material was placed in the southern half of the dump in a “High Sulphide Cell”.

Mine decommissioning started in 1999. The underground workings were allowed to reflood commencing in April 1999 and were completely reflooded by the third quarter of 1999. All tailings from TD1 and TD2 and minor amounts of waste rock were relocated to the open pit in the 1999-2000 dry season in order to minimize the potential for long-term acid generation and metal contamination. After tailings relocation, the waste rock facility was the only remaining potential long-term source of ARD.

The final closure plan for the site called for placement of a dry cover on the waste rock facility to minimize future seepage and associated metal loading (including zinc) to the local groundwater and near-by Woodcutters Creek. A groundwater model was developed to predict the potential transport of contaminants of concern (COC) in the groundwater towards Woodcutters Creek for different cover scenarios. This paper describes the results of this modeling study and implications for the cover design and implementation.

SITE CHARACTERIZATION

A detailed site characterization was carried out in 2000/2001 to evaluate current impacts and to provide a basis for the impact analysis. The following sections briefly summarize the key findings. For more details the reader is referred to Robertson GeoConsultants (2001, 2002a, 2002b).

Groundwater Flow

Drilling and subsequent water level surveys indicated that dewatering of the open pit and underground workings over the previous ~16 years had resulted in an extensive cone of depression centered on the open cut and aligned north-south along a steeply dipping fracture system associated with the Woodcutters anticline (Figure 1). The water levels in the central part of the cone of depression showed very little variation (at 38.5 m AHD) suggesting good hydraulic connection in the underground workings, shafts and drill holes. The central area of the cone extended more than 1 km north of the open pit likely due to the presence of faults/fractures and the underground workings. In 2001, the footprint of the waste rock pile was located within the cone of depression thus seepage

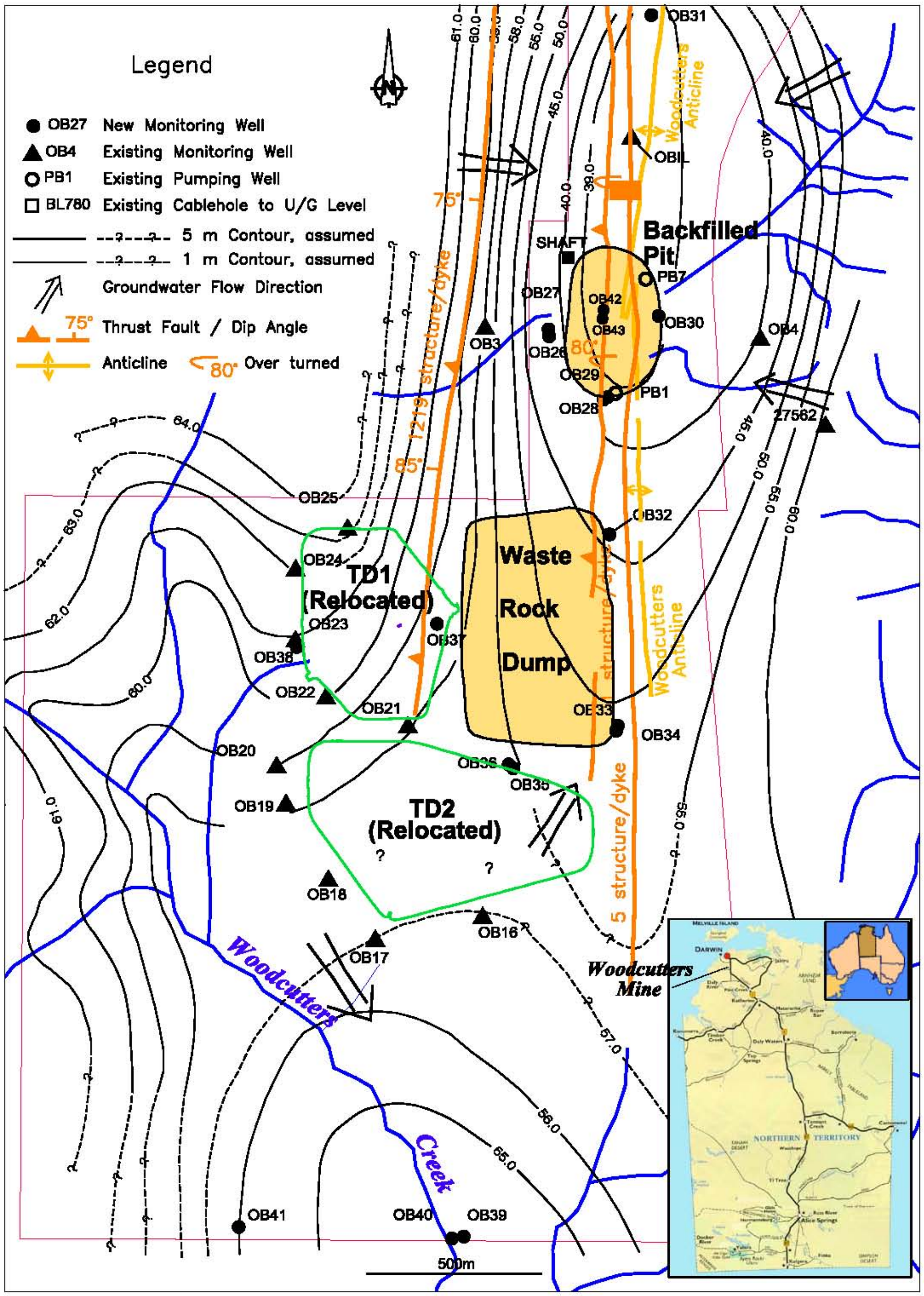

Figure 1. Observed groundwater levels, February 2001 (m AHD)

from the WRD was inferred to be still flowing towards the open pit (Figure 1). At the time of this initial study (July 2001), the water table in the backfilled pit area was rebounding at a rate of ~9 m y^{-1}. The rate of groundwater rebound has gradually declined over the last 7 years (see figure 3).

Groundwater Quality

The historic and recent water quality monitoring data suggest that past mining activities at the site have had a significant impact on the groundwater quality on the lease property. The most significant impact has been an increase in the concentrations of major cations (Ca and Mg) and major anions (sulphate) as a result of sulphide oxidation and subsequent acid neutralization reactions. Elevated concentrations of metals (primarily Zn, Mn and Ni) were only observed in close proximity to the mine units (i.e. open pit, WRD, TD1 and TD2 etc.).

Typical water quality in the pit area has pH below 6.0, sulphate greater than 1,000 mg L^{-1} and Zn and Mn greater than 1 mg L^{-1}. Monitoring wells located east, south and west of the WRD showed much lower concentrations of sulphate, zinc and manganese than were observed in the open pit area and in ARD seepage from the WRD itself (Robertson GeoConsultants 2001). These observations are consistent with the 2001 water level measurements, which suggested that WRD seepage was still flowing in a northerly direction towards the open pit (Figure 1).

Overall, impacted water quality across the site is not uniform suggesting important geochemical controls (e.g. local differences in buffering, sorption and/or precipitation) and/or multiple sources of ARD (WRD and reclaimed tailings area). Monitoring wells located along the southern (downstream) lease boundary indicate that mine-impacted groundwater has not reached the lease boundary and/or is sufficiently diluted.

GROUNDWATER FLOW MODEL

A groundwater flow model was developed for the site to predict (i) the time required for complete groundwater rebound and (ii) the post-closure groundwater flow field. The groundwater flow model was calibrated using early drawdown data and (initial) groundwater recovery data. The calibrated flow model provided the basis for the prediction of post-closure zinc transport towards the Woodcutters Creek.

Key features of the model included explicit representation of Woodcutters Creek, backfilled tailings in the open cut, and seepage (recharge) “source areas” in the footprint areas of the tailings dams and waste rock dump. All stages of mine life, from pre-mining, open pit and underground mining through to reflooding, were simulated with the groundwater model. For more details on numerical methods the reader is referred to Robertson Geoconsultants Inc. (2002a).

The calibrated groundwater model indicated that the cone of depression caused by mine dewatering was aerially extensive. At the end of mine dewatering, the cone of depression extended ~2.3 km in the east-west direction and ~6.5 km in the north-south direction, encompassing a surface area of ~10.7 km^2.

Figure 2 shows the simulated recovery in hydraulic heads in the underground workings. The observed water levels in the shaft and two deep pumping wells are shown for comparison. While the model slightly overpredicted the magnitude of recovery in the underground workings (due to a datum shift that was not known at the time of model calibration), the observed rate of recovery was reproduced very well. Water level data collected since completion of the groundwater model (in 2002) generally agree with the predicted groundwater rebound providing at least partial verification of the flow model (Figure 2).

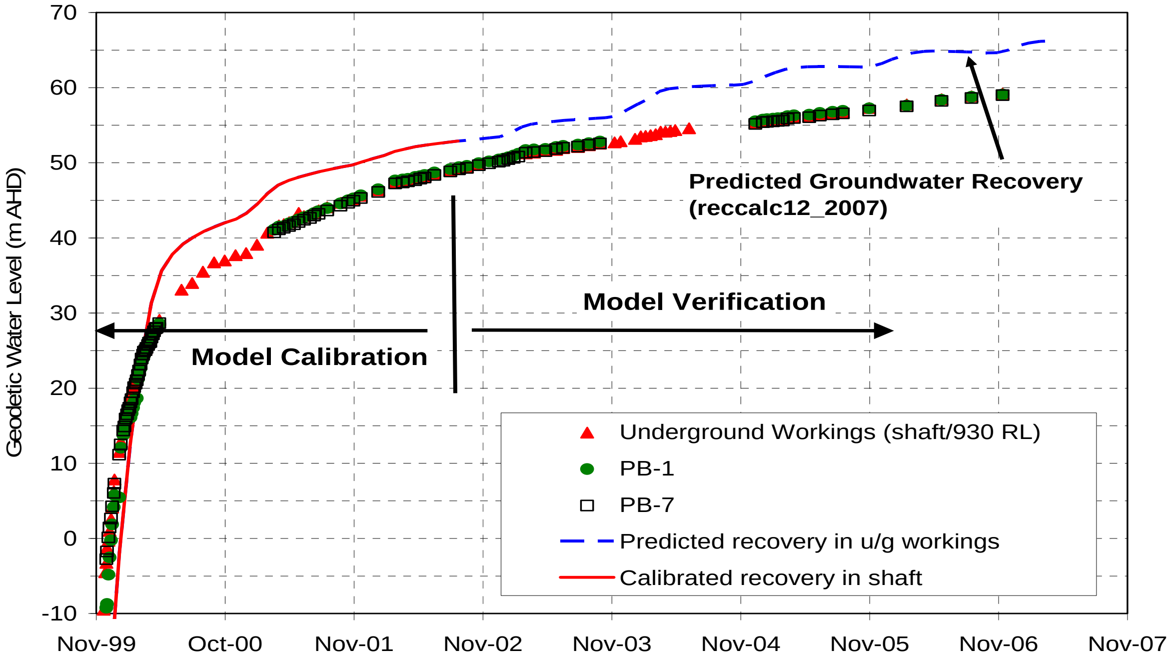

Figure 2. Simulated and observed water level rebound in the underground workings.

The model further predicted that after groundwater rebound hydraulic gradients within the backfilled pit area and the foot print area of the waste rock facility would gradually reverse and impacted groundwater from these impacted areas would move in a southwesterly direction towards Woodcutters Creek. Recent groundwater level monitoring are consistent with these earlier flow predictions (Robertson GeoConsultants Inc, 2008).

SOLUTE TRANSPORT MODEL

A solute transport model was used to simulate the potential impact of waste rock seepage on Woodcutters Creek. Zinc was selected for solute transport because (i) it occurs in high concentration in the WRD seepage (up to 400 mg L^{-1}); (ii) it is mobile in circum-neutral groundwater and (iii) it is potentially toxic to aquatic organisms. In addition, soluble zinc has a relatively low affinity for aquifer materials, thereby making it a ‘worst case’ indicator of potential environmental impact.

Unlike the groundwater flow model, the solute transport model could not be calibrated because historic water quality data was unavailable. Accordingly, current conditions (concentrations) were assumed based on recent water quality monitoring and the model was then run forward into the future (200-380 years depending on the cover scenario simulated). For details on the numerical methods the reader is referred to Robertson Geoconsultants Inc. (2002a).

Modeled Cover Scenarios

A total of four cover scenarios were selected for further impact analysis. The assumed seepage rates, initial (current) zinc concentrations and "future" zinc concentrations in waste rock pore water are summarized in Table 1 for each scenario. Note that current zinc pore water concentrations in the waste rock dump were determined using a geochemical equilibrium model (MINTEQA2) (OKC-RGC, 2002). Geochemical modeling was also used to determine future zinc pore water concentrations.

Removal of the waste rock dump (Scenario 1) was not a realistic closure option but was included to illustrate the impact of other zinc sources (e.g. current zinc plume, seepage from backfilled tailings) on zinc transport towards Woodcutters Creek.

Predicted Post-Closure Water Quality

Figure 3 shows the simulated breakthrough curves at six observation points for Scenario 1, i.e. where the waste rock dump is removed entirely. This hypothetical scenario illustrates that zinc concentrations in the aquifer will remain significantly above background for many decades, even if there was no future release of zinc into the system (i.e. no future seepage from the waste rock pile). This is a result of the large amount of zinc believed to be stored in the groundwater system, both in dissolved form in the groundwater itself and sorbed onto the aquifer material. Note that zinc concentrations downstream of the waste rock pile (at OB35/36) are predicted to initially increase (from ~1.1 mg L^{-1} currently observed to as high as 5-7 mg L^{-1}) due the anticipated reversal of groundwater flow, which will allow migration of contaminated groundwater from the open pit and underground workings towards Woodcutters Creek.

Table 1. Cover scenarios evaluated with solute transport model

Cover Scenario	Cover Quality	Cover Design	Seepage Rate[A]	Assumed WRD Seepage Water Quality (mg L^{-1})	
				Initial Zn	Future Zn
1	WRD removed	No cover required	0% of MAP (no WRD)	10	0
2	High	2m growth medium over 0.5m compacted, active clay	1% of MAP	10	10
3	Moderate	1m growth medium over 0.5m compacted, active clay	10% of MAP	10	50
4	Low	1m growth medium over 0.5m compacted, stable clay	20% of MAP	10	100

[A] Expressed in terms of Mean Annual Precipitation "MAP"

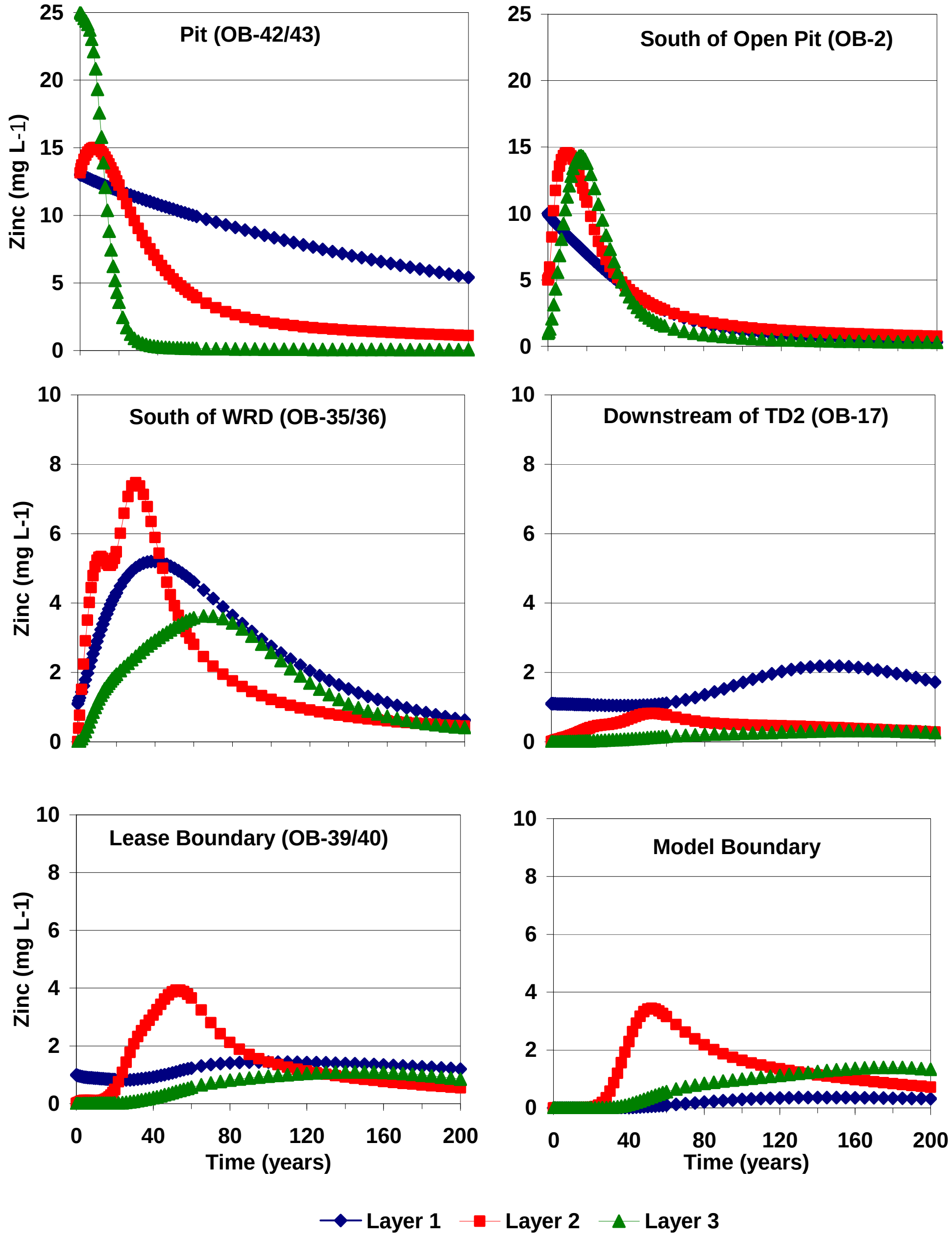

Figure 3. Simulated zinc concentrations (mg L^{-1}) for Scenario 1 (waste rock dump removed; WRD seepage = 0% MAP, Zn=0 mg L^{-1})

To compare the impact of various cover scenarios on shallow groundwater entering Woodcutters Creek, Zn breakthrough curves were computed for a nearby monitoring bore (OB17) and are shown in Figure 4. The predicted times for a “breakthrough” of peak zinc concentrations at the stream range from ~150 years for Scenario 1 (removal of waste rock dump), to ~400 years for Scenario 4 (low quality cover). Note that even in Scenario 1 (waste rock storage facility removed) zinc concentrations are predicted to increase slightly before diminishing due to “flushing” of zinc currently stored in the local aquifer system.

As expected, the highest zinc concentrations in groundwater discharging to the stream were predicted for Scenario 4, which represents the scenario with the highest zinc load from the waste rock pile to the aquifer system. Note that the predicted peak zinc concentrations in shallow groundwater discharging into the stream are very similar for Scenarios 1 and 2 (Figure 4), indicating that the zinc load released from a high quality cover is small relative to the zinc currently stored in the aquifer system.

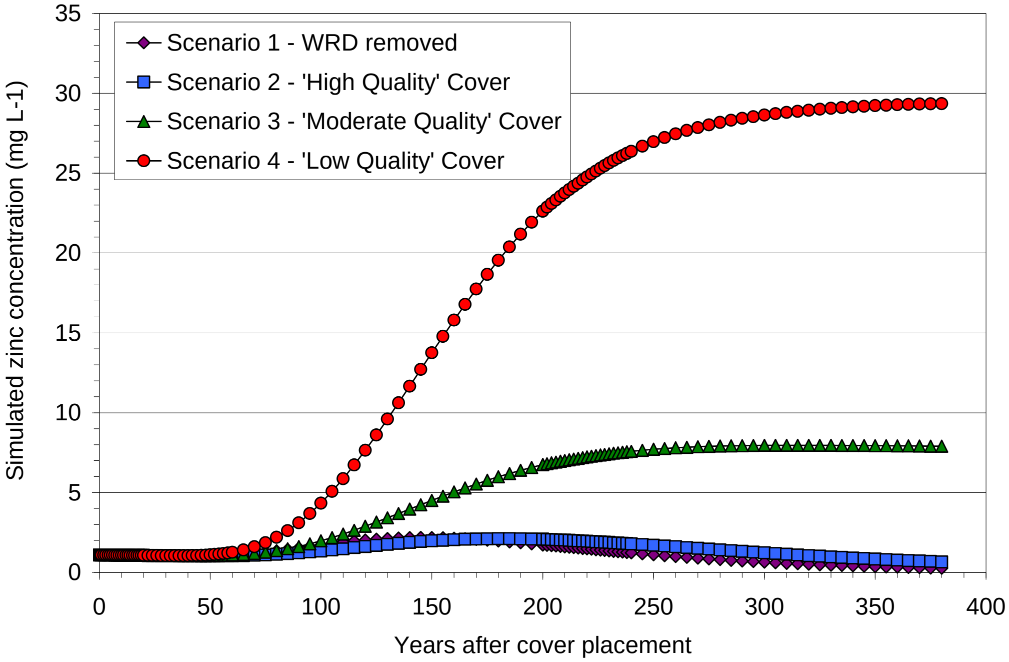

Figure 4. Simulated zinc concentrations (mg L^{-1}) at OB17 (shallow groundwater)

It should be noted that the confidence that can be placed on specific numbers predicted by the transport model is limited because the transport model could not be calibrated. Calibration of the transport model would require longer-term (at least 10-20 years) monitoring of zinc transport in the aquifer. Nevertheless, the modeling results are believed to provide a reasonable framework for a qualitative, if not semi-quantitative comparison of different cover options and their likely impact on the water quality of Woodcutters Creek.

ECOLOGICAL RISK ON WOODCUTTERS CREEK

Table 2 summarizes the predicted peak zinc concentrations in shallow groundwater discharging along three sections of Woodcutters Creek. This shallow groundwater (baseflow) consists of mine impacted groundwater originating from the eastern portion of the watershed (see Figure 4) diluted by non-impacted groundwater originating from elsewhere in the watershed. The predicted peak zinc concentrations for all cover scenarios exceed 0.008 mg L^{-1}, which is considered to be the “low risk” trigger value for the protection of 95% of aquatic biota (ANZECC 2000). As a result, an ecological risk analysis was initiated to evaluate the risk of elevated zinc concentrations to downstream aquatic receptors (EWL 2003).

Table 2. Summary of predicted zinc concentrations in baseflow to Woodcutters Creek at time of peak breakthrough

Stream Segment	Cover Scenario 1	Cover Scenario 2	Cover Scenario 3	Cover Scenario 4
Time of peak zinc concentrations (years)				
	150	200	380	380
Simulated Average Zinc Concentrations in Shallow Groundwater Near Woodcutters Creek (mg L^{-1})				
1 (upper mine reach)	0.2	0.1	0.3	1.2
2 (lower mine reach)	1.2	1.2	3.9	13.3
3 (downstream of mine lease)	0.3	0.3	0.9	3.1

The concentrations in Table 2 were combined with baseflow estimates and available surface water flows to estimate the likely peak zinc concentrations in Woodcutters and Coomalie Creeks. The computed zinc concentrations were then compared to applicable guidelines to evaluate the impact on the stream ecology and beneficial uses of the aquatic resources (see EWL, 2003 for details). Based on this analysis, EWL Sciences concluded that:

- peak zinc concentrations in Woodcutters Creek are likely to exceed the ANZECC 80% aquatic ecosystem protection guideline value as well as background concentrations for all cover scenarios; and
- future impacts to Coomalie Creek are likely to be negligible, provided that seepage rates from the waste rock pile are below 10% of MAP (i.e. Cover Scenarios 1, 2 or 3).

COVER CONSTRUCTION AND MODEL VALIDATION

The transport modeling and the ecological risk assessment suggested that a “moderate quality cover” (Scenario 3) would be sufficient to meet the closure criteria developed for the site. However, allowing for inevitable changes in cover performance through time, the site owner decided to adopt a more conservative design figure of 5% mean annual precipitation for final cover design and construction (in 2003/2004).

Routine water quality monitoring has been undertaken at the Woodcutters site since 2001. In general, contaminant concentrations (e.g. sulphate, zinc) in the local groundwater and the Woodcutters Creek are lower than predicted. This is believed to be a result of a smaller inventory of contaminants stored in the groundwater system (from past mine waste seepage) than originally assumed in the model. Thus far, the reversal of hydraulic gradients (towards Woodcutters Creek) has not negatively impacted groundwater quality, suggesting that the cover system is working as intended. However, longer-term groundwater quality monitoring (10-20 years) will be required to further evaluate the validity of the zinc transport predictions and the success of closure in general.

CONCLUSIONS

A groundwater flow and solute transport model was used to evaluate different closure options for a waste rock facility. The transport modeling and the ecological risk assessment suggested that a “moderate quality cover” with a seepage rate equal to 10% of mean annual precipitation would be sufficient to meet the closure criteria developed for the site. For final design and construction, a more conservative design figure of 5% mean annual precipitation was adopted.

On-going groundwater level monitoring (since 2001) has confirmed model predictions about the rate of groundwater rebound and the reversal of groundwater flow (towards Woodcutters Creek). Initial groundwater quality monitoring has not shown any significant changes in zinc concentrations in the local aquifer (as predicted). However, validation of the transport model will require longer-term (10-20 year) water quality monitoring. Both the groundwater flow and solute transport models should be updated as new monitoring data become available.

The groundwater flow and solute transport model developed for the Woodcutter site proved to be a very useful tool for closure planning. Not only did the model create an awareness of potential deterioration of water quality and contaminant loading to the creek, it also assisted in setting more realistic expectations of the time horizon for lease relinquishment. The models also assisted in communications with the local stakeholders and helped develop closure criteria for the site.

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