GROUNDWATER MODELING AS A TOOL FOR CLOSURE PLANNING: PREDICTION OF ZINC TRANSPORT FOR ALTERNATIVE COVER SCENARIOS

C. Wels and L. Findlater
Robertson GeoConsultants Inc, Suite 640-580 Hornby Street, Vancouver, Canada V6C 3B6

ABSTRACT

A groundwater flow and transport model has been developed for the Woodcutters lead-zinc mine in Australia. The mine shut down in 1998 after exploiting the deposit through both open cut and underground methods. Historic seepage from two tailings facilities and a waste rock pile had resulted in elevated concentrations of selected trace metals (in particular Zn, Fe and Mn) in the local groundwater system. In 1999, the tailings were backfilled into the open cut to prevent future oxidation and ARD from this source. The waste rock dump, the only remaining potential long-term source of ARD, was to be reclaimed in-situ using a store and release cover.

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 preserve water quality in the creek.

1.0 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 rainshowers 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.

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. The waste rock facility, the only remaining potential long-term source of ARD, was to be reclaimed using a dry cover.

In 2000, Robertson GeoConsultants Inc. was retained to carry out a detailed hydrogeological characterization study to predict water table rebound, to identify existing mining impacts and provide a basis for the development of a closure plan, including the development of a dry cover system for the waste rock dump. This investigation included a detailed field investigation and the development of a 3-D groundwater flow and solute transport model to predict water table rebound and the fate of mine impacted groundwater. This paper focuses on the results of the groundwater flow and transport modeling, and how they were used to design a waste rock cover system that would preserve water quality in the nearby Woodcutters Creek.

2.0 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).

2.1 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 from the WRD was inferred to be still flowing towards the open pit (Figure 1). As of July 2001, the water table in the backfilled pit area was rebounding at a rate of ~9 m y^{-1}.

2.2 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

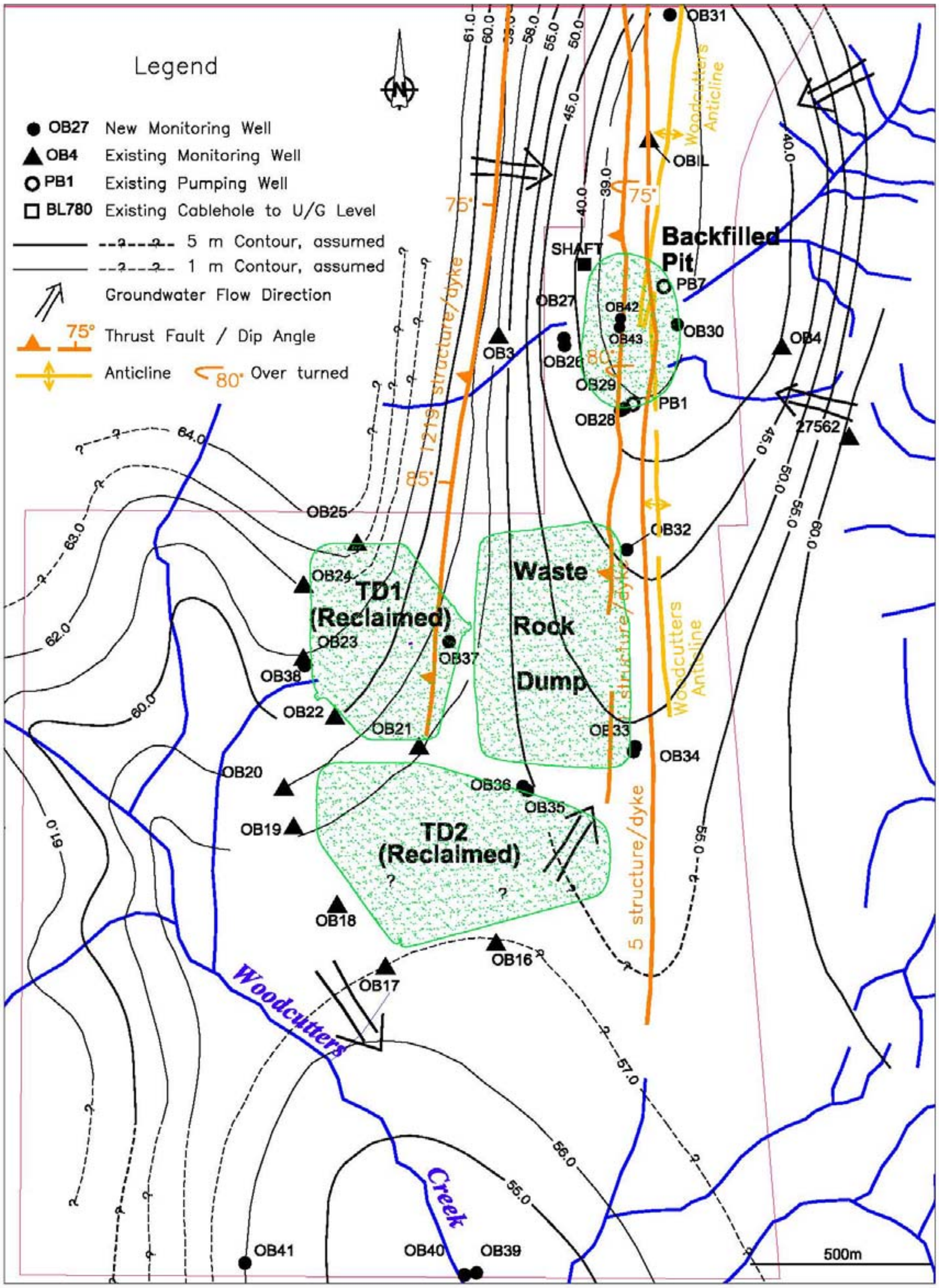

Fig. 1. Observed groundwater levels, February 2001 (m AHD)

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.). The groundwater quality is characteristic of what is referred to as “neutral mine drainage”.

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.

3.0 GROUNDWATER FLOW MODEL

3.1 Purpose

A groundwater flow model had been previously developed for the Woodcutters mine in 1999, prior to cessation of pumping (Aquaterra, 1999). This model did not have the benefit of early recovery data for calibration and therefore significantly under-predicted the rate of groundwater rebound. The rapid reflooding of the underground workings beginning in 1999 prompted the need for an updated groundwater model, which was developed by Robertson GeoConsultants (2002a). This model was used to predict rebound of the groundwater levels in the open pit area and predict general post-closure flow conditions. The results from the flow model in turn formed the basis of a solute transport model (Section 4) which was used to determine the fate of mine-impacted water on the site.

The three-dimensional groundwater flow model was developed using the finite difference groundwater flow code MODFLOW96 (Harbaugh and McDonald 1996) in conjunction with the pre-post processor GMS v. 3.1 (EMRL 2000). The reader is referred to RGC (2002a) for a detailed discussion of the model setup. 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.

3.2 Stages of Mine Life

The Woodcutters mine site had undergone several stages in its mine life at the time of model development. These stages can be summarized as follows:

1. Pre-mine development (prior to December 1984);
2. Dewatering of the open pit (December 1984 – March 1987);
3. Dewatering of the underground workings (March 1987 – December 1998); and
4. Reflooding of the open pit after tailings backfill (November 1999 – June 2001).

Each of these time periods represents a unique hydrogeological environment where different stresses to the system bring various hydrogeological parameters into play. As such, it was necessary to calibrate the model to all four stages of mine life in order to create a credible model. To accomplish this, the four model periods were simulated in sequence using a fixed set of hydraulic parameters. The head solution from the first time period was used as the starting head solution for the second time period and so on.

The pre-mining steady-state model provided an opportunity to calibrate atmospheric input parameters (recharge, evapotranspiration) and hydraulic properties of regions distant from the mine site. Emphasis was placed on calibrating seasonal fluctuations in groundwater levels in the tailings area and base-flow contributing to streamflow in Woodcutters Creek.

Detailed monitoring of groundwater levels occurred during the period of open pit dewatering which allowed for calibration of hydraulic parameters in the vicinity of the open pit in the second calibration phase. The period of underground dewatering (third calibration phase) was not as well documented as the early period of open pit dewatering and proved to be a difficult period to calibrate. Nonetheless, limited pumping data collected during this phase provided an opportunity to calibrate hydraulic parameters in the vicinity of the underground workings.

The period of reflooding of the underground workings and open pit represented the most crucial step in the calibration process for several reasons. Detailed water level monitoring in the open pit during this time provided well-defined calibration targets, which were the most relevant to future water level predictions. In addition, this period also served as a partial verification for the flow model. Sensitivity analyses indicated that the rate of water level recovery in the open pit area was highly sensitive to the assumed specific yield of the bedrock and the backfilled tailings.

3.3 Major Outcomes of the Groundwater Flow Model

A major result from the groundwater flow model was the delineation of the cone of depression caused by mine dewatering. At its largest extent (at the end of underground dewatering), the cone of depression likely 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. While extensive, the cone remained entirely within the watershed of the mine and did not cause trans-basin flow across watersheds. Furthermore, during the furthest extent of the drawdown cone, shallow groundwater in the area of the reclaimed tailings impoundments continued to discharge to Woodcutters Creek which is consistent with evidence of tailings seepage observed in the monitoring wells downstream of TD1 and TD2.

One of the main objectives behind the flow modeling work was to predict the recovery of the water table and predict whether the tailings backfilled into the open cut would be completely reflooded. The model was calibrated to early recovery data collected between 1999 and 2001. 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 overpredicts the magnitude of recovery in the underground workings (due to a datum shift that not known at the time of model calibration), the actual rate of recovery (slope of the graph) was reproduced very well. Water level data collected since completion of the groundwater model has at least partially verified the model predictions (Figure 2). The model predicts that the backfilled tailings will be completely reflooded by 2010-2012 and that the groundwater levels will recover to pre-mining levels likely by 2020-2025. Upon complete reflooding of the tailings, the model predicts that the entire mine site, including the open pit and waste rock dump will drain towards Woodcutters Creek.

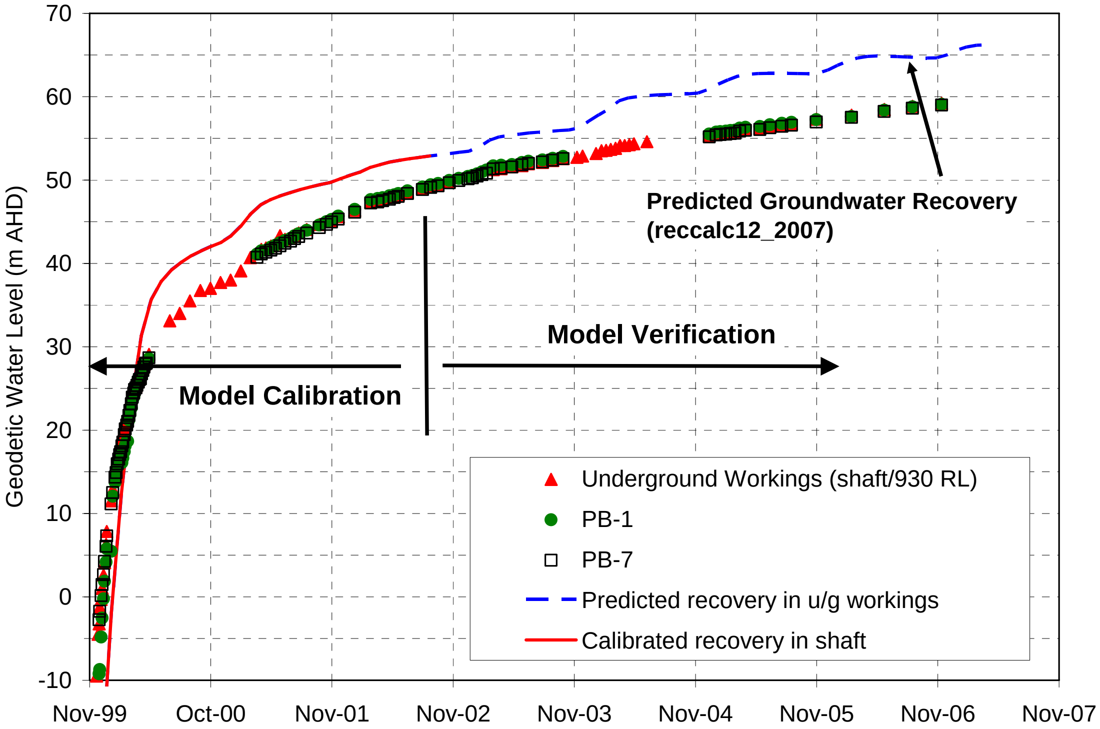

Fig. 2. Simulated and observed water level rebound in the underground workings

4.0 SOLUTE TRANSPORT MODEL

4.1 Purpose

While the timing of groundwater recovery was an important result from the flow model, ultimately the primary focus of the study was to predict the potential impact of shallow groundwater discharging to Woodcutters creek and how that impact could be mitigated by various cover designs for the waste rock dump. This was accomplished through the development of a solute transport model for the site, using zinc as the contaminant of interest. Zinc was chosen as a key contaminant of concern for the site 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.

The transport model was developed using the MT3DMS (version 3.50) code (Zheng and Wang 1999) which was developed for use with MODFLOW96. A detailed discussion of the transport model setup can be found in RGC (2002a). 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).

4.2 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 porewater 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 porewater concentrations.

Removal of the waste rock dump (Scenario 1) was not a realistic option but was included to allow an assessment of the "incremental" impact of seepage from the waste rock pile on groundwater quality and therefore the extent of incremental benefit to be gained by rehabilitation of the waste rock pile.

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"

4.3 Predicted Post-Closure Water Quality

For each scenario, zinc breakthrough curves were computed at six observation points located along the flow path (see Figure 1 for observation point locations). Figure 3 shows the simulated breakthrough curves at these 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.

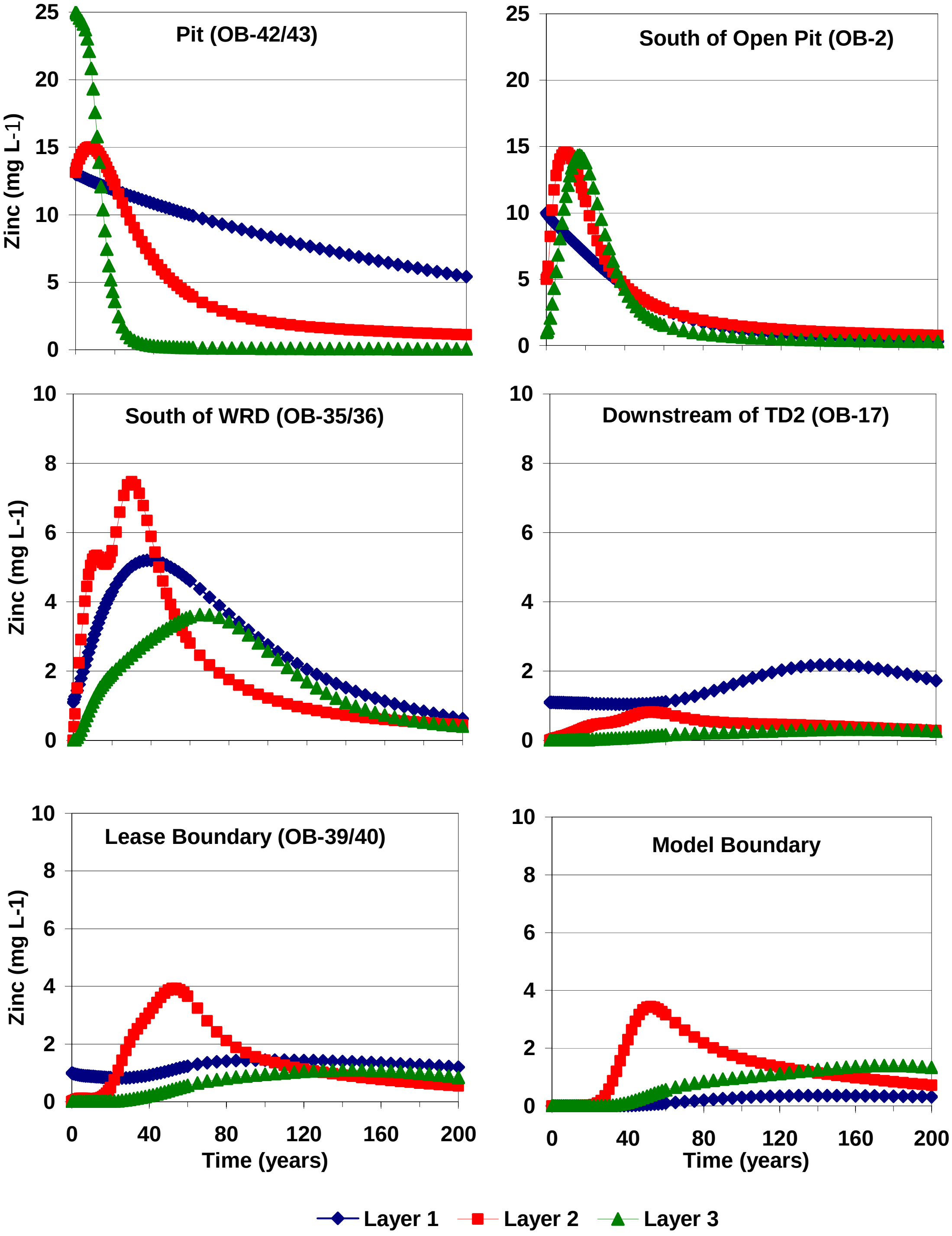

Fig. 3. Simulated zinc concentrations (mg L^{-1}) for Scenario 1 (waste rock dump removed; WRD seepage = 0% MAP, Zn=0 mg L^{-1})

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), implying that the zinc load released from a high quality cover is small relative to the zinc currently stored in the aquifer system.

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. 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.

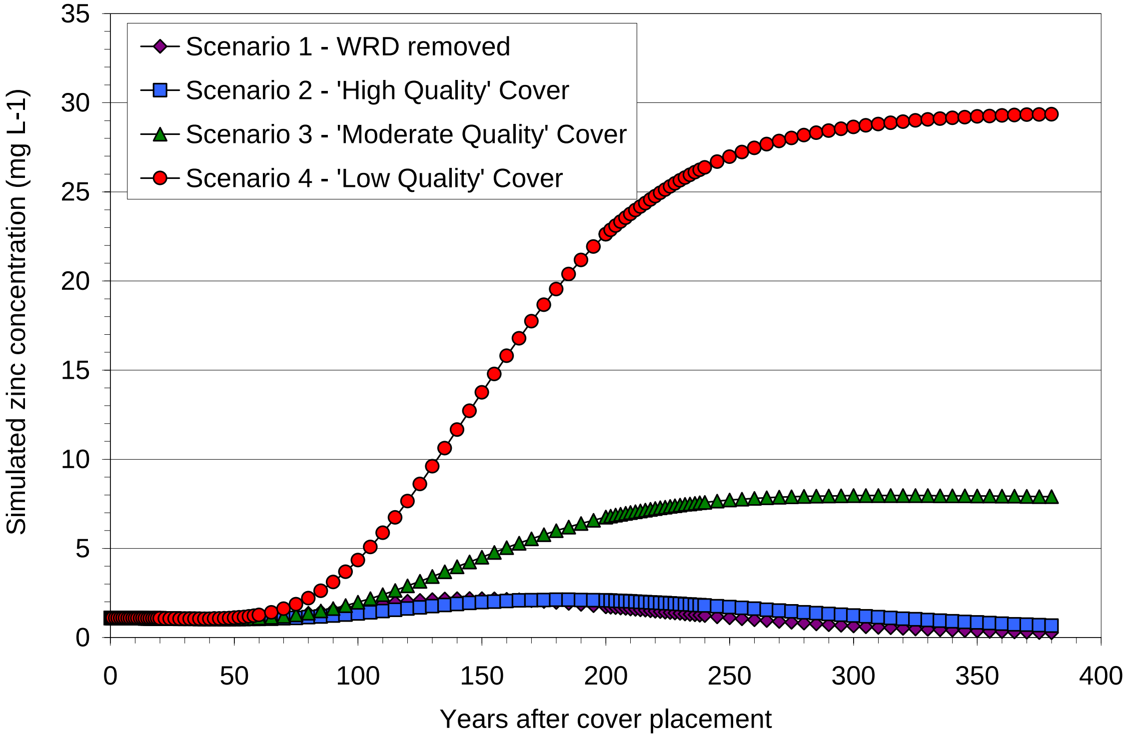

Fig. 4. **Simulated zinc concentrations (mg L^{-1}) at OB17 (shallow groundwater)**

5.0 ECOLOGICAL RISK ON WOODCUTTERS CREEK

The major outcome of the transport model was the ability to predict the timing and magnitude of peak zinc concentrations in the shallow groundwater discharging into Woodcutters Creek for various closure scenarios. While this was an important result in itself, the primary focus of the study was to determine the resultant stream water quality and the potential impacts to stream ecology.

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 diluted by non-impacted groundwater originating from elsewhere in the watershed.

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

As can bee seen from Table 2, 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).

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;
- 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); and
- future water quality in both Woodcutters Creek and Coomalie Creek are likely such that fishes, mussels and other aquatic biota may be eaten (in the absence of other impacts not related to the Woodcutters Mine).

6.0 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. This cover was then constructed in 2003/2004.

Routine water quality monitoring has been undertaken at the Woodcutters site since 2001. No significant changes in groundwater quality have yet been observed at the site (including the reclaimed tailings area) illustrating the slow response of the groundwater system in response to various closure activities. Longer-term groundwater quality monitoring (10-20 years) will be required to evaluate the validity of the solute transport modeling predictions and the success of closure in general.

7.0 CONCLUSIONS AND LESSONS LEARNED

A groundwater flow model was developed for the Woodcutters mine site to predict groundwater rebound post-closure. Extensive monitoring of water levels and pumping rates during active mining plus extensive water level monitoring upon cessation of pumping allowed for a robust calibration of the groundwater model. It was found that prediction of the water table rebound was very sensitive to aquifer parameters (hydraulic conductivity and specific yield/storage) thus emphasizing the importance of good calibration data (pre-mining water levels, dewatering rates, and in particular early recovery data). The model predicted that the tailings backfilled into the open pit would completely submerged by 2010-2012, upon which the entire mine site, including the open pit and waste rock dump, would drain towards Woodcutters creek. Ongoing water level monitoring on the site has demonstrated that the recovery rates predicted by the model are very reasonable.

A solute transport model was developed in order to evaluate different closure options for the waste rock dump and determine their impact on zinc concentrations of shallow groundwater discharging to Woodcutters Creek. The transport model indicated that even if the waste rock dump were removed, the site could expect to see contaminant concentrations increase near the creek due to the reversal of the flow field through time. The results of the transport modeling, coupled with an ecological risk assessment were ultimately used to design and implement a waste rock dump cover that would be sufficient to mitigate negative impacts on aquatic biota in Woodcutters Creek. Validation of the transport model will require long-term (15-20 year) water quality monitoring. Both the groundwater flow and solute transport models should be updated as new monitoring data becomes 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.

8.0 ACKNOWLEDGEMENTS

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