Contaminant Load Balance Study for Mount Morgan Mine, QLD, Australia[1]

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ABSTRACT

The Mount Morgan Mine is a historic mine site located in Central Queensland, Australia which has heavily impacted portions of the adjacent Dee River. As part of overall closure planning a chemical load balance study was performed for the Mt. Morgan mine site. The contaminants of concern (COC) included in this analysis are sulphate (SO4), aluminum (Al), copper (Cu), iron (Fe) and zinc (Zn). The load balance model was developed based on detailed groundwater quality monitoring at the site (since 2003) and used groundwater flow estimates obtained from a 3D groundwater flow model calibrated for the site.

The analysis indicates that seepage from the flooded Open Cut/Sandstone Gully represents the single largest source of contaminants on the site exceeding all other contaminant sources by a wide margin (except for the Lower Mundic Waste, which contributes the highest iron loading). Seepage from the Western Dump and Shepherds Dump represent other dominant sources of contaminant loads, in particular with respect to sulphate, aluminum, and copper.

The load balance further suggests that the Mundic West and Frog Hollow sumps intercept nearly 90% of the contaminant load that is generated by the Open Cut/Sandstone Gully and downstream waste units. Seepage interception is less efficient in the Shepherd's catchment, where the interception system removes only 20-40% of the contaminant load supplied by seepage from the Shepherd's Tailings Dam and the Shepherd's Outer Dump.

The load balance study also identified several data gaps which resulted in the installation of additional monitoring wells on site and along the Dee River. This new monitoring data is currently being used to refine the load balance model for the site and to assess the contaminant loading to the upper Dee River.

Additional Key Words: mine closure, acid rock drainage, groundwater modeling.

INTRODUCTION

The Mount Morgan Mine is a historic mine site, located 40 km SSW of Rockhampton, in Central Queensland, Australia (Figure 1). The mine site is adjacent to the Dee River, which flows between the mine and the township of Mount Morgan, into the Don and Dawson Rivers and thence into the Fitzroy River. Mining commenced at this site in 1882 to recover gold, but considerable quantities of silver and copper were also discovered. During the 108-year life of the mine approximately 262 t of gold, 37 t of silver and

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387,000 t of copper were recovered from underground and open cut operations. The mine closed in 1990 after the re-treatment of 28 Mt of tailings. In 1993, the state of Queensland accepted environmental liability for the site with technical oversight by the Department of Mines and Energy.

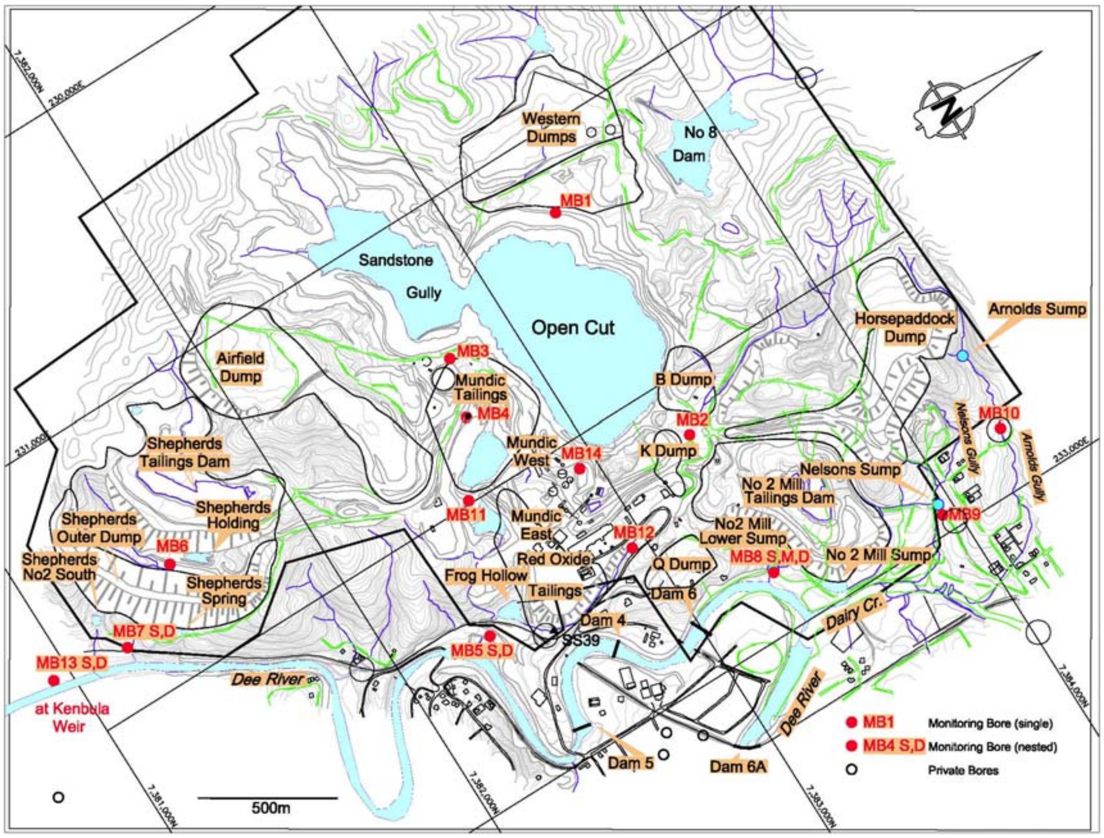

Figure 1. Location map of Mount Morgan mine site

The site is characterized by the environmental problems associated with Acid Rock Drainage (ARD), which impact the site and the Dee River downstream of the mine. Over the years, the mine operators developed a seepage interception system (SIS) to capture acidic seepage and pump it back to the open cut.

A detailed hydrogeological investigation was undertaken in 2003 to identify the key contaminant sources, understand water movement on site and impacts to the Dee River and to develop a range of rehabilitation scenarios (Unger and Laurencont, 2003). As part of this work, a groundwater model was developed to understand the magnitude and fate of ARD seepage on the site (Wels et al., 2006). Results of the groundwater model were subsequently incorporated into a load balance model which has been used to estimate contaminant loads generated by the mine waste and by-passing the SIS. The key results of the load balance model are presented in this paper.

BACKGROUND

Mine Waste Units

Figure 1 shows the various mine waste units, including the open cut pit and sandstone gully (both now flooded), various overburden and waste rock units and historic tailings dams located on the Mount Morgan mine lease. Table 1 lists the estimated tonnage of waste rock and tailings stored in the various mine waste containment units (after Taube 2000). The open cut was excavated into the northern flank of the Mundic drainage. It has a surface area of approximately 34.5 ha and maximum depth of approximately 200 m (relative to the current rim). The open cut was backfilled between 1982 and 1990 with 28 Mt of retreated tailings, the majority of which was removed from Sandstone Gully (Figure 1). After final closure in 1990, the partially backfilled open cut (and Sandstone Gully) were allowed to flood further by natural inflows (surface runoff and groundwater inflow) and by pumping ARD impacted seepage back into the open cut.

The overburden and waste rock was placed in five major containment areas (Figure 1). The bulk of waste rock from the Open Cut is estimated to be acid-forming based on the depth of weathering of the original profile. This material contains up to 10% sulfur with the major sulphide minerals being pyrite, chalcopyrite, and pyrrhotite (EWL Sciences, 2001). Since waste types were not segregated during mine life, it can be presumed that all areas of waste rock on site are potentially acid-generating with very low acid-neutralising capacity.

Table 1. Summary of mine waste units, Mount Morgan Mine

Waste Rock Unit	Estimated Tonnage (Mt)	Tailings Unit	Estimated Tonnage (Mt)
Horsepaddock Dump	15	Reprocessed Tailings (OCSG)[a]	28
Airfield Dump	24	Mundic Red Tailings	0.63
Western Dump	25	Mundic Grey Tailings	0.97
Shepherds Dump	21	No. 2 Mill Tailings	2.1
B&K Dumps (& others)	8.4	Shepherds Tailings	3.9

[a]OCSG = Open Cut & Sandstone Gully

The Mundic tailings were placed into the historic drainage channel of Mundic Creek (between the open cut and Frog Hollow), whereas the other tailings were placed into tailings dams (see Figure 1 for location). Anecdotal evidence suggests that tailings were initially deposited in the Mundic drainage without proper containment.

Seepage Interception System

Acidic seeps have been observed discharging from the various mine waste units for an extended period. Over the years, the mine operators developed a seepage interception system (SIS) to capture acidic seepage and pump it back to the open cut. In 2004, the SIS consisted of 7 active sumps, which collect toe seepage and/or shallow groundwater. Most sumps are located along the eastern edge of the mine waste units, often located within original creek channels, in which mine waste had been placed.

The majority of seepage at Mount Morgan is collected in the Mundic Creek area, i.e. in the sumps referred to as "Mundic West" and "Frog Hollow" (Figure 1). These sumps are located in the Mundic creek valley, originally draining the upper Mundic catchment encompassing the Sandstone Gully and the Open Cut. This valley was historically used for tailings discharge and was subsequently overdumped with as much as ~50 m of waste rock and slag. The majority of seepage intercepted in Mundic West (~7 L/s) and Frog Hollow (~4-6 L/s) is believed to be originating from the partially backfilled and flooded Open Cut/Sandstone Gully.

Seepage By-passing Existing SIS

A groundwater flow model was developed for the Mount Morgan mine site to assess the effectiveness of the seepage interception system (Wels et al, 2006). The flow model indicated that the backfilled (and flooded) Open Cut/Sandstone Gully (OCSG) represents the largest single source of ARD seepage (8.0 L/s) on the site with tailings impoundments representing important secondary sources of seepage. The flow model suggested that the total seepage from the Mount Morgan mine site by-passing the SIS and entering the Dee River and underlying aquifer under baseflow conditions is about 258 m^3/day (3.0 L/s). This seepage rate is orders of magnitude less than streamflow observed during runoff events in the Dee River (typically 300 to 3,000 L/s). However, this seepage can provide a substantial contribution to the Dee River during extended dry spells. During these periods, the Dee River has no "measurable" surface flow; however, some underflow in the very permeable stream sediments below Kenbula weir (Figure 1) undoubtedly occurs.

At the time of model calibration, the SIS collected about 13.8 L/s during baseflow conditions (Greg Bartley, pers. Comm.). Based on the modeled bypass, this would suggest that the SIS intercepted about 82% of all seepage from the site at the time. These estimates of seepage by-pass are generally consistent with initial estimates of seepage by-passing the SIS based on Darcy calculations (Wels et al. 2004).

Groundwater Quality

Groundwater quality has been routinely monitored on the mine site since June 2003. Average values for selected parameters (grouped by reaches) are shown in Table 2 (Robertson GeoConsultants Inc., 2007). Overall, groundwater quality has remained relatively stable over the monitoring period, reflecting mature acid rock drainage (ARD) system. Most groundwater on the Mt. Morgan mine site is heavily impacted by ARD from various sources (Open Cut, waste rock and tailings seepage) resulting in highly elevated TDS relative to background water quality in the area. The dominant ions are sulphate, magnesium, calcium and (if acidic) aluminium. The extent of acidification (and thus metal concentrations) in the local groundwater varies significantly depending on the proximity to ARD sources and/or buffering capacity of the local lithology. Based on the results of the initial water quality survey at Mount Morgan (Robertson GeoConsultants Inc., 2004), the following groundwater types were identified:

Table 2. Average water quality measured at the Mt. Morgan mine site (2003-2006). After Robertson GeoConsultants Inc. (2007).

	pH	Acidity mg/L	SO4 mg/L	Al mg/L	Cu mg/L	Fe mg/L	Zn mg/L
Open Cut - Mundic System							
MB3	3.32	4,953	13,066	806	53.7	279	28.4
MB4	3.59	12,429	36,519	2,294	8.5	2160	136
MB11	3.54	2,051	15,070	285	18.7	116	30.1
MB14	4.33	595	5,938	27	149	0.78	19.6
MB5S	3.09	6,307	13,724	998	132	955	29
MB5D	3.54	3,973	10,432	602	84.3	774	20.9
Linda Gully							
MB2	2.39	5,390	12,172	833	46.5	343	14.1
MB12	4.69	654	6,821	27.3	3.82	59.6	6.2
Shepherds Area							
MB6	3.67	2,860	10,044	548	11.9	1.57	11.2
MB7S	3.14	17,600	33,809	3,660	69.4	10	36.9
MB7D	3.18	22,044	33,722	4,077	74.9	97	34.2
No. 2 Mill Tailings Area							
MB8D	4.49	2,081	9,999	152	3.53	622	10.9
Arnold's and Nelson's Gullies							
MB10	6.36	360	26,220	14.6	0.28	0.94	1.7
MB9	6.99	172	7,250	0.79	0.1	0.78	0.06
Dee River System							
MB13S	4.73	944	4,411	140	11.2	2.29	4.6
MB13D	5.73	256	18,413	11.9	0.38	0.54	8.4
Background Groundwater							
Private Bore 1	7.18	3	47	0.042	0.008	0.153	0.011
Private Bore 2	7.39	7	39	0.036	0.025	0.199	0.019
Private Bore 3	7.28	0	117	0.023	0.023	0.125	0.028

- Type 1: Highly acidic groundwater with low pH (<4.0), very high acidity (>3,000 mg/L CaCO3) and highly elevated concentrations of dissolved metals (in particular Al, Fe, Cd, Cu, Mn and Zn);
- Type 2: Acidic groundwater with low pH (<5.0), moderate to low acidity (<3,000 mg/L CaCO3) and highly variable concentrations of dissolved metals (typically low in Al, Cu and Zn but elevated in Fe and Mn);
- Type 3: Buffered groundwater with elevated pH (>5.0), high to moderate alkalinity (<1,000 mg/L CaCO3) and low concentrations of most dissolved metals (except Mn);
- Type 4: Un-impacted groundwater with high pH (7.0-8.0), moderate to low alkalinity (< 500 mg/L CaCO3) and low TDS (including dissolved metals).

Type 4 groundwater has not been not encountered on the mine lease but is inferred to be present up-gradient of all mine-impacted areas. This water type was defined based on water quality observed in "background" bores located off the mine site, east of the Dee River.

Acid rock drainage (ARD) from the historic Mount Morgan mine site is characterized by highly elevated concentrations of sulphate and magnesium. Dissolved metal concentrations in local groundwater vary greatly depending on the buffering capacity of the local bedrock. In buffered groundwater, the only metal observed at highly elevated concentrations is manganese (100-400 mg/L). In acidic groundwater, the highest concentrations of dissolved metals are observed for Al (up to ~5,000 mg/L), Fe (~3,400 mg/L), Cu (~190 mg/L), Mn (~470 mg/L) and Zn (~140 mg/L). Dissolved concentrations of As, Be, Cr, Cd, Co, Ni and Se are significantly lower but also at levels of environmental concern. High levels of Na and Cl indicate impact from Open Cut seepage while high Cu:Zn ratios indicate impact from waste rock dump seepage. High Fe and Cu concentrations appear to be indicative of seepage from the old oxide tailings (e.g. in No. 2 Mill tailings area and Mundic Valley).

LOAD BALANCE ANALYSIS

Method

A simplified load balance model was developed for the Mt. Morgan mine site using the results from the groundwater model and the routine water quality monitoring program. The load balance model was developed to give a first approximation of the magnitude and distribution of contaminant loading on the mine site. In this way the model could be used to assist in the development of a rehabilitation strategy for the site.

The load balance model is a spreadsheet model that tracks key contaminants of concern (namely SO4, Al, Cu, Fe, Zn) along the flow path, from source areas to discharge points. The key elements incorporated into the load balance model are as follows:

- Contaminant load introduced from the mine waste units (WRD, tailings, OCSG) (Source)
- Contaminant load removed by SIS (Sink)

- Contaminant load added (dissolution) or removed (precipitation/sorption) by “chemical reactions” (Source/Sink)
- Contaminants not removed by the SIS or chemical reactions (By-Pass to Dee River).

Contaminant loads were calculated by multiplying modeled seepage rates by contaminant concentrations measured in the sources and sinks. Table 3 summarizes the concentrations applied to the various sources and sinks in the load balance. Where available, contaminant concentrations for the different sources, sinks and by-passes were taken directly from existing monitoring data (from seeps, sumps and groundwater monitoring bores; see Table 2). In some cases, no water quality data was available for source areas (e.g. Airfield Dump, Shepherds Outer Dump). Here, the groundwater flow model was used to determine what fraction of flow originated from each of the upstream sources, from which the unknown source concentration were back-calculated.

Where possible, the calculated loads were checked against downstream monitoring bores to determine if they were realistic. If large discrepancies were noticed, contaminant load was added or removed from the system by a generic “chemical reaction” term. This component simply closes the load balance and is not based on geochemical modeling.

Results

Table 4 summarizes the estimated total contaminant load contained in seepage from the various mine waste units. Table 5 summarizes the global load balance for the Mt. Morgan site. Seepage from the flooded OCSG represents the single largest source of contaminants on the Mount Morgan mine site exceeding all other contaminant sources by a wide margin (except for Lower Mundic Waste, which produces the highest iron loads). Seepage from the Western Dump is also significant, however the groundwater model indicates that this seepage is completely captured by the OCSG.

In the Mundic area, the combined loading from the OCSG, downstream mine waste units (Upper and Lower Mundic Waste) and Mundic East is substantial (nearly 6,000 t/yr SO_4, 350t/yr Al, 25 t/yr Cu, 257 t/yr Fe and 15 t/yr Zn). However, sumps completed within this reach (i.e. Mundic West and Frog Hollow) recover close to 90% of the contaminant load. In all, less than 25% of the SO4, Al and Zn entering the Dee River aquifer system can be attributed to the Mundic Reach. Copper and iron comprise a larger portion of this bypass load (~50%). Much of the iron is thought to originate from the Lower Mundic Waste (in particular, the oxide tailings).

In contrast to the Mundic area, the combined load from the tailings and Outer Dump in the Shepherds area is significantly lower (2,000 t/yr SO4, 180 t/yr Al, 4 t/yr Cu, 20 t/yr Fe and 2 t/yr Zn). In this reach, the seepage interception system (Shepherd’s Spring, Shepherd’s Holding and Shepherd’s no.2 South) is much less effective, removing only an estimated 20-40% of the contaminant load. As a result, more contaminant load by-passes the SIS and enters the Dee River aquifer system in this reach than in Mundic reach (except for iron). Contaminant loading from the Shepherd’s reach is estimated to represent about 50% of the total SO_4, Cu, and Zn load and nearly 80% of the Al load entering the Dee River system (Table 5). The majority of the contaminant load along this reach is believed to originate from the Shepherds Outer Dump.

Table 3. Source/Sink concentrations used in load balance model.

	SO4 mg/L	Al mg/L	Cu mg/L	Fe mg/L	Zn mg/L	Sampling Period
MINE WASTE SEEPAGE (SOURCE)						
Horsepaddock Dump (Arnold's Reach)	48,628	3,714	87	169	100	2004-2006
Horsepaddock Dump (Nelson & No. 2 Mill Reach)	20,809	768	38	43.8	58	2000-2003
No. 2 Mill Tailings	18,229	1,004	32	1,004	28	2000-2003
B&K Dumps	12,172	833	47	343	14	2003-2006
Western Dump	54,500	4,330	149	230	110	2006
Airfield Dump[1]	3,200	1,400	40	60	7	N/A
Upper Mundic Waste	16,677	1,088	59	340	39	2003-2006
Lower Mundic Waste[1]	4,300	0	160	2,900	30	N/A
Shepherd's Tailings	12,688	346	5.76	192	13	2004-2006
Shepherd's Outer Dump[1]	97,000	12,000	300	500	100	N/A
SEEPAGE INTERCEPTION SYSTEM (SINK)						
Open Cut	13,878	859	49	272	30	2003-2006
No. 2 Mill Sump	30,972	2,461	738	85	61	2000-2003
Mundic West	17,978	1,176	59	388	43	2003-2006
Mundic East	14,105	982	91	969	38	2003-2006
Frog Hollow	14,110	766	81	1,176	42	2003-2006
Shepherd's Holding	12,688	346	6	192	13	2003-2006
Shepherd's Spring	13,778	787	23	38	17	2003-2006
Shepherd's No. 2 South	27,706	1,306	73	310	30	2000-2003

[1]Concentrations back-calculated using the groundwater flow model.

Table 4. Contaminant Load Entering the Groundwater System (by Source Area).

COC	Horsepaddock Dump t/yr	No. 2 Mill Tailings t/yr	BK Dump t/yr	Western Dump t/yr	OCSG t/yr	Upper Mundic Waste t/yr
SO_4	385	193	238	2,016	3,573	1,799
Al	18	10	16	160	221	97
Cu	0.7	2.9	0.9	5.5	13	4.0
Fe	0.9	16	7	9	70	46
Zn	1.0	0.1	0.3	4.1	8	5.0
COC	**Mundic East t/yr**	**Lower Mundic Waste t/yr**	**Airfield Dump t/yr**	**Shepherds Tailings t/yr**	**Shepherds Outer Dump t/yr**	**Total Load Entering GW System t/yr**
SO_4	340	175	139	902	1,241	11,000
Al	24	0	61	25	154	785
Cu	2	6.5	1.7	0.4	3.8	41
Fe	23	118	3	14	6	312
Zn	1	1.2	0.3	0.9	1.3	23

Seepage by-passing the No.2 Mill Sump also represents a significant load entering the Dee River Aquifer. The No.2 Mill sump is fed by the Horsepaddock Dump and the No.2 Mill Tailings. The sump captures ~20% of SO_4 and Zn, 35% of Al and 85% of Cu emanating from the two facilities, however it recovers less than 2% of the iron. The iron load bypassing this sump amounts to 30% of the total iron load entering the Dee River system (Table 5). Most of this iron is thought to originate in the tailings. Note that recent upgrades to the No. 2 Mill SIS are not included in this assessment.

Table 5. Global Load Balance for the Mt. Morgan Mine Site.

COC	Total Load Entering	Total Load Recovered		Total Load By-pass	
	t/yr	t/yr	%	t/yr	%
SO4	11,000	-8,488	77	2,372	22
Al	785	-553	70	197	25
Cu	41	-32	78	8	19
Fe	312	-243	78	54	17
Zn	23	-20	86	3	11

Overall, it can be seen that ~70-80% of the SO_4, Al, Cu and Fe load entering the groundwater system is recovered by the seepage interception system at the Mount Morgan mine site (Table 5). Recovery is slightly higher for zinc (86%), which is known to be naturally attenuated in parts of the groundwater system (i.e. in the Nelson's and Arnold's gully catchment areas).

IMPLICATIONS FOR CLOSURE

Although highly simplified, the load balance model developed for the Mount Morgan mine site is believed to be a reasonable first approximation of actual conditions on the site and is considered a useful tool for initial scoping of closure alternatives. One of the closure alternatives being evaluated for the Mt. Morgan mine site involves partial backfilling of the Open Cut/Sandstone gully with the most problematic mine waste. This loading analysis has identified the Shepherd's Outer Dump as the largest contributor of sulphate, aluminium and copper loads to the Dee River, with the Lower Mundic Waste (oxide tailings) and No. 2 Mill Tailings contributing high iron loads. More characterization work, including a detailed flow and load survey in the Dee River, will need to be undertaken to verify these initial results of the load balance model and to ultimately determine which of these mine waste units will be the best candidate for partial relocation.

Based on the results of this study, several additional monitoring wells were recently installed on site and along the Dee River. This new monitoring data is currently being used to refine the load balance model for the site and to assess the contaminant loading to the upper Dee River.

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