Mt Morgan Mine – A Case Study of ARD Impacted Groundwater

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Abstract

The Mount Morgan Mine is a historic mine site located in Central Queensland, Australia. The mine closed in 1990 after more than 100 years of mining, the latter 10 years involved re-treatment of 28 Mt of tailings, which were placed into the open cut pit. Historic mining at Mount Morgan has resulted in the exposure of sulphide-bearing mine waste at surface which produces acid rock drainage (ARD) and has heavily impacted portions of the Dee River flowing adjacent to the mine. While a seepage interception and pump-back system (SIS) is currently in place, the amount of ARD entering the groundwater system and ultimately reaching the Dee River may be substantial and needs to be quantified.

This paper summarizes the results of a detailed hydrogeological study of the Mt Morgan minesite, which included the installation of 19 monitoring wells, hydraulic testing, water level and water quality monitoring and groundwater modeling. In the upland reaches, groundwater flow typically occurs in the unconsolidated material (saprolite and/or colluvium) and upper, fractured bedrock (typically within 15m below natural ground surface); no significant quantities of groundwater were encountered in "deep" wells drilled into tight (unfractured) bedrock (up to ~40m depth). Alluvial deposits in the Dee River valley and the underlying fractured bedrock have a relatively high hydraulic conductivity ($4*10^{-6}$ to $1*10^{-5}$ m/s) and are capable of transmitting significant quantities of groundwater.

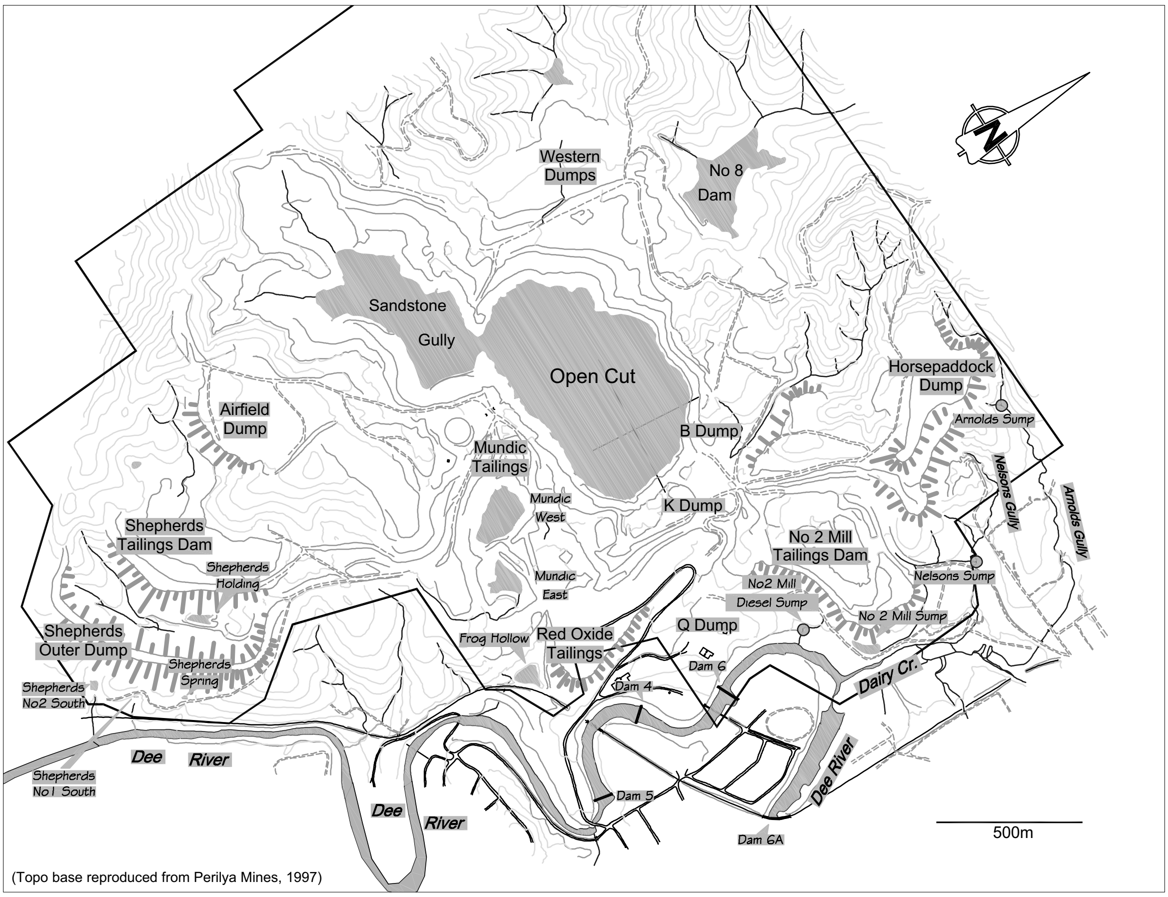
The groundwater draining the minesite is highly impacted by ARD with low pH (2.5-3.5) and highly elevated concentrations of magnesium (1,000-3,000 mg/L), sulphate (7,000-40,000 mg/L), aluminium (100-4,000 mg/L), iron (20-4,000 mg/L), copper (20-100 mg/L), zinc (10-140 mg/L) and various trace metals (Cd, Cr, Co and Ni). Historic stream channels draining the mine site (often filled-in with tailings, slag and/or waste rock) and associated structures in the underlying bedrock appear to represent a preferred pathway for mine-impacted groundwater into the Dee River. The total amount of groundwater seepage entering the Dee River system (Dee River and underlying aquifer) has been estimated to be about 1.8 L/s. This seepage rate is significantly smaller than the amount of seepage currently intercepted during baseflow conditions (13.8 L/s) suggesting a very high efficiency of the existing SIS.

1 Introduction

The Mount Morgan Mine is a historic minesite, located 40 km SSW of Rockhampton, in Central Queensland, Australia (Fig. 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 262t of gold, 37t of silver and 387,000t of copper were mined from Mount Morgan from underground and open cut operations. The mine closed in 1990 after the re-treatment of 28 Mt of tailings.

The site is characterised by the environmental problems associated with Acid Rock Drainage (ARD), which impact the site and the Dee River downstream of the mine. In January 2000 the Department of Mines & Energy (now NRM&E) proposed a 10-year conceptual plan for rehabilitating the site and embarked on a 2-3 year program of studies to identify the key contaminant sources, understand water movement on-site and impacts on the Dee River, and to develop a range of rehabilitation scenarios (Unger and Laurencont 2003).

As part of this program, a detailed hydrogeological investigation was initiated in 2003. The primary objectives of this study were (i) to quantify the amount of seepage by-passing the existing seepage interception system and entering the Dee River and (ii) to provide guidance in the overall site rehabilitation strategy. This paper summarizes the results of the initial field investigation.



(Topo base reproduced from Perilya Mines, 1997)

Fig. 1. Site plan for Mt Morgan mine site.

2 Background

2.1 Climate and Hydrology

The climate at the site is seasonal, with average maximum daily temperatures ranging from 32°C in January to 23°C in July (OKC, 2002). The long-term average annual rainfall is approximately 740 mm with a large amount of the annual rainfall occurring during the wet summer months (November – May). The long-term average annual PET is estimated to be about 1840 mm.

The Mount Morgan minesite is located in the Dee River catchment. The areas disturbed by mining lie on the west side of the Dee River for a distance of approximately three kilometers downstream from its junction with Dairy Creek (Fig. 1). The total minesite catchment area contributing runoff to the river is estimated to be 3.5 km^2 (EWL Sciences 2001).

The streamflow in the Dee River is highly seasonal with short duration runoff events (i.e. a few days of peak flows ranging from 25 to >250 ML/day) typically during the wet season and extended periods of no, or near-zero, surface flow during the remainder of the year (EWL Sciences, 2001).

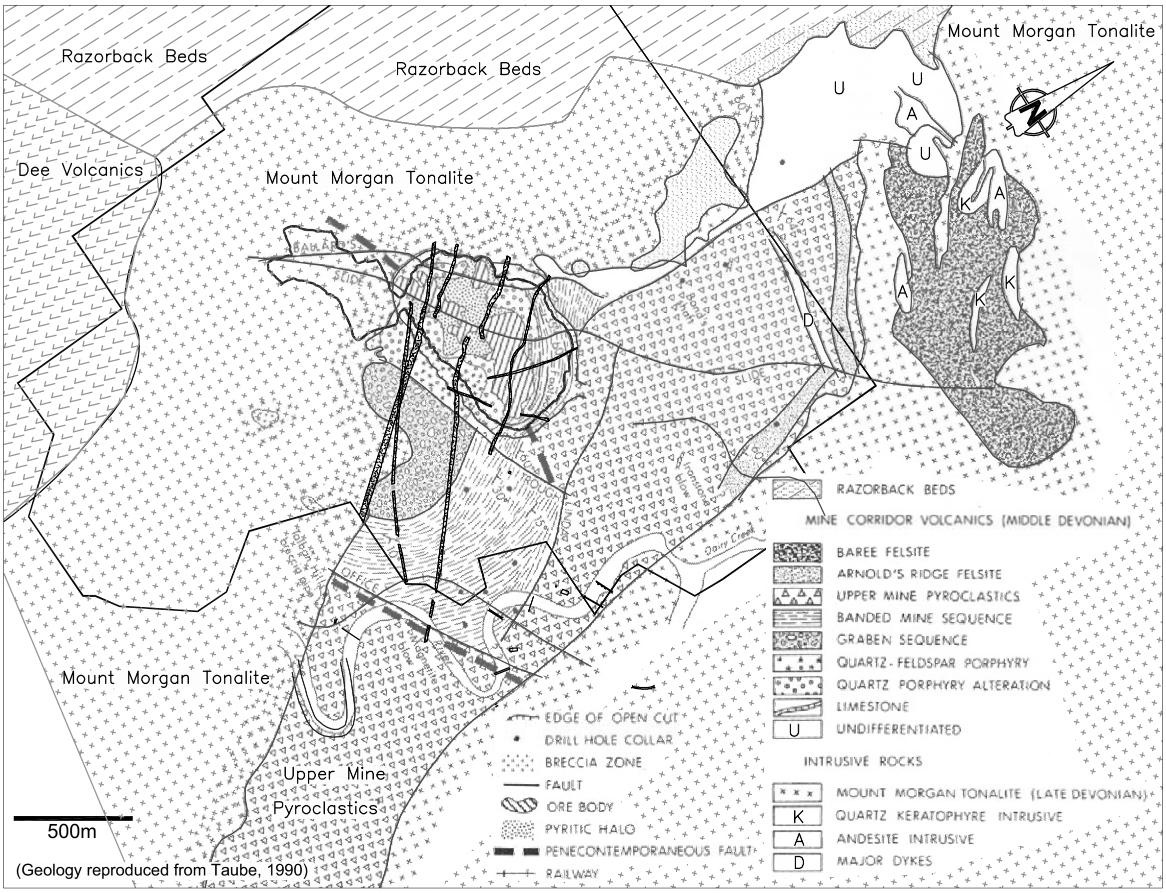
2.2 Geology

The geology of the Mount Morgan gold-copper deposit has been described in detail by Taube (1990, 2000). The Mount Morgan deposit is situated in the Calliope Block, which occurs along the eastern margin of Australia from Rockhampton to Warwick. Figure 2 shows the geology of the mine corridor in immediate vicinity of the Mount Morgan minesite (after Taube 2000). The Mount Morgan orebody occurs at and below the level of the banded mine sequence, extending well down into the lower mine pyroclastics.

The banded mine sequence (BMS) is a well-bedded series of quartz-feldspar crystal tuff, siliceous ash tuff, derived sediments, chert and jasper. The rocks of the upper mine pyroclastics (UMS) are similar to the unaltered lower mine pyroclastics, but they also contain fragments of jasperiod, limestone and rarely sulphide (Taube 2000). The mine corridor volcanics were intruded extensively by the Mount Morgan tonalite (At+) and other intrusives and dykes (Fig. 2).

All of the country rock formations are considered to have no primary permeability and any secondary permeability is believed to be controlled by structure (fractures and/or faults). Additionally, the area is also cut by a series of north-west and north-east trending dykes that serve to compartmentalize the area and further inhibit deeper groundwater discharge from the minesite (Forbes 1990 quoted in Water Studies 2001).

Figure 2 also shows the alignment of several structural faults in the immediate vicinity of the Mount Morgan minesite, which are briefly described below (Forbes 1990 quoted in Water Studies 2001). No information was available on the hydrogeological properties of these structures and/or associated fractures.



(Geology reproduced from Taube, 1990)

Fig. 2. Generalized geology at Mt Morgan.

2.3 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. 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 200m (relative to the current rim). The open cut was backfilled between 1982 and 1990 with 28Mt of retreated tailings the majority of which was removed from Sandstone Gully.

The "Sandstone Gully" represents a wide valley in the upper reach of Mundic Creek, which was historically used as a repository for tailings. Starting in 1982, the historic tailings were dredged from Sandstone Gully and treated using the carbon-in-pulp (CIP) process before being backfilled into the open cut. 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 (Fig. 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% S 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.

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 Fig. 1 for location). Anecdotal evidence suggests that tailings were initially deposited in the Mundic drainage without proper containment.

EWL Sciences (2001) reviewed the limited geochemical testing data available for the tailings material. Elutitration tests showed that the Mundic Red tailings were unreactive whereas the Mundic Grey tailings are highly reactive and can release significant amounts of sulphate, iron, aluminium and copper. As much as 50% of the released copper was readily leachable during the initial washing step (EWL Sciences 2001).

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

Waste Rock		Tailings	
Unit	Estimated Tonnage (Mt)	Unit	Estimated Tonnage (Mt)
Horse Paddock 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&D Dumps (& others)	8.4	Shepherds Tailings	3.9

a. OCSG = Open Cut & Sandstone Gully.

2.4 Seepage Interception System

Acidic seeps have been observed discharging from the various mine waste units for an extended period of time. Over the years, the mine operators developed a seepage interception system (SIS) to capture acidic seepage and pump it back to the open cut pit. The SIS consists of 8 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” (see Fig. 1 for location). These sumps are located in the Mundic creek valley, originally draining Sandstone Gully. This valley was historically used for tailings discharge and was subsequently overdumped with as much as ~50m 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 backfilled open cut pit/sandstone gully.

3 Field Investigation

A detailed field investigation was carried out between May and July 2003, consisting of drilling, monitoring well installation, hydraulic testing and water quality sampling. Subsequently, a routine monitoring programme was implemented to determine seasonal variations in groundwater levels and groundwater quality.

3.1 Methods

In total, 19 monitoring wells were drilled and completed as a part of the field investigation (see Fig. 3 for location). Drilling was performed using a Pioneer B540 multi-purpose drill rig equipped with an Ingersoll-Rand 700 CFM 350 PSI compressor. Down-hole percussion drilling was carried out for the majority of wells completed in natural formation. At those locations, where loose, unconsolidated alluvium or mine waste material (waste rock and/or tailings) were encountered, a 127 mm TUBEX system was used for drilling and piezometer installation. In all boreholes, air was used as a “drilling fluid” to determine the yield and water quality (pH and electrical conductivity) of groundwater encountered at different depths.

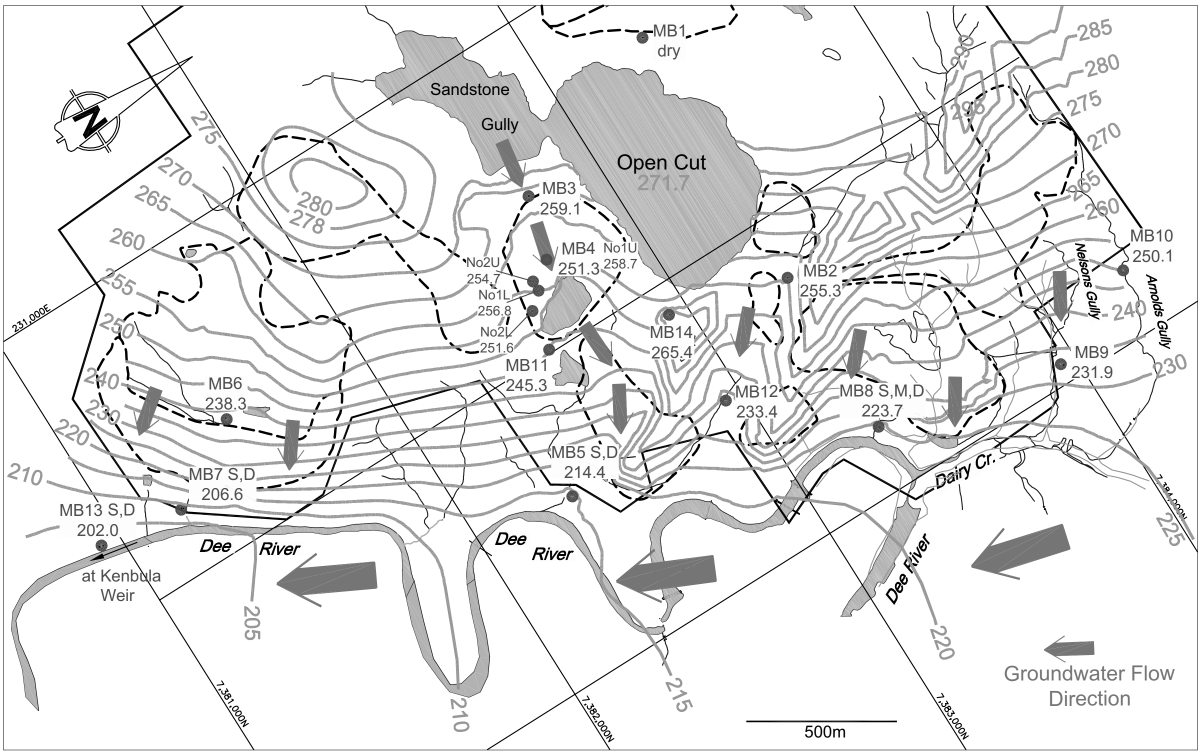


Fig. 3. Observed groundwater levels (July, 2003).

Slug tests and/or pump tests were performed on the majority of monitoring wells to obtain estimates of the in-situ hydraulic conductivity (K) of the materials in the vicinity of the well. The slug tests were interpreted using the Bouwer and Rice (1976) and the Cooper et al (1967) analytical methods. Air-lift 'pump tests' were performed on selected high yielding wells. The pump test data were analysed using the Cooper and Jacob method (1946), which allows an estimation of transmissivity (=K*screen length) from the maximum drawdown observed.

Routine water quality monitoring (quarterly sampling) commenced in June 2003 (only MB3 and MB4 were first sampled in October 2003). All monitoring wells were purged until the field parameters (temperature, pH, EC and Eh) had stabilized. Additional samples were taken in seeps and sumps across the site (representing part of the seepage interception system) and at several private wells on the east side of the Dee River (representing "background" water quality).

All samples were filled into pre-washed sampling bottles and shipped to ALS Environmental Laboratories in Brisbane for analysis. Major chemistry parameters were determined on the raw (unfiltered) sample. Laboratory measurements include bulk parameters (pH, alkalinity and acidity), major cations and anions (sulfate, chloride, calcium, magnesium, sodium, potassium) and dissolved metals (Al, As, Be, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Se, and Zn). Dissolved metals were determined on a subsample, which was filtered (0.45 mm) and acidified in the laboratory (June 2003) and in the field (October 2003). QA/QC procedures included the use of duplicate sampling, replicate lab analyses and charge balance analysis. No significant difference was observed in dissolved metals concentrations determined on sub-samples filtered/acidified in the laboratory (June 2003) and in the field (October 2003).

3.2 Results

3.2.1 Hydrostratigraphy

Drilling confirmed the spatial distribution of the major lithologies (volcanics and intrusives) described by others and shown in Fig. 2. In both lithologies, the profile consisted of ~2-10m of unconsolidated material (in-situ weathered saprolite and/or alluvium/colluvium) over 5-10m of fractured bedrock over competent (tight) bedrock.

The results of hydraulic testing are summarized in Table 2. The various hydrostratigraphic units showed characteristic differences in permeability. The permeability of the saprolite is controlled by the fines content and varies from $7\text{x}10^{-7}$ m/s in clay rich material (MB7S) up to $\sim 1*10^{-6}$ m/s in coarser material (MB11). The higher permeabilities observed in the other two shallow monitoring wells ($4.6*10^{-5}$ m/s in MB5S and $9.0*10^{-6}$ m/s in MB8S) are believed to be a result of the presence of historic (coarse) tailings within the screening interval.

The lowest K values ($\sim 1.4\text{x}10^{-7}$ m/s) were obtained for the deeper, tight volcanic bedrock with very limited fracturing and/or weathering (e.g. MB4D, MB8D and MB5D). Generally, higher K values ($1.4 \text{ x}10^{-6}$ m/s) were obtained for wells screened in fractured, minimally altered tonalite (MB10 and MB13D). This range of K is considered more typical for fractured tonalite than the high value obtained at MB6 (10^{-4} m/s). The permeability of the fractured tonalite may be generally higher than in the fractured volcanics because the volcanics weather to clay, which would tend to seal individual fractures. The alluvial deposits in the Dee River and the underlying fractured bedrock have a relatively high hydraulic conductivity ($4*10^{-6}$ to $1*10^{-5}$ m/s) and are therefore capable of transmitting significant quantities of groundwater relative to Dee River baseflow.

Table 2. Summary of hydraulic testing results.

		Slug Test			Pump Test		Best Engineering Judgement	
Bore ID	Screened lithology	Bouwer and Rice[a]	Cooper et al[b]		Drawdown[c]	Recovery[d]		
		Avg. K[e] (m/s)	K[f] (m^2/s)	S -	K[f] (m/s)	K[f] (m/s)	K (m/s)	S -
MB4D	volcanics	9.8E-08	9.1E-08	2.7E-04	-	-	9.4E-08	2.7E-04
MB5S	tailings & var. weathered volcanics (saprolite)	4.6E-05	-	-	-	-	4.6E-05	-
MB5D	fractured volcanics	3.8E-07	-	-	-	-	3.8E-07	-
MB6	leached, fractured tonalite	5.9E-04	-	-	1.6E-04	3.8E-05	1.E-04	-
MB7S	highly weathered tonalite (saprolite)	7.2E-07	-	-	-	-	7.2E-07	-
MB7D	hard, silicified intrusive (breccia pipe?)	2.3E-07	-	-	-	-	2.3E-07	-
MB8S	tailings & highly weathered volcanics (saprolite)	9.5E-06	-	-	8.7E-06	2.7E-06	9.0E-06	-
MB8M	moderately weathered saprolite and fractured volcanics	3.7E-07	5.8E-07	7.7E-04	-	-	4.6E-07	7.7E-04
MB8D	fresh, moderately fractured volcanics	4.3E-07	N/A	N/A	-	-	4.3E-07	-
MB9	fresh tonalite (fractured?)	5.1E-07	-	-	-	-	5.1E-07	-
MB10	partially weathered, fractured tonalite	-	-	-	1.4E-06	3.2E-07	1.4E-06	-
MB11	moderately weathered volcanics (saprolite)	1.3E-06	-	-	-	-	1.3E-06	-
MB13S	alluvium	9.1E-06	-	-	2.0E-05	5.0E-06	1.5E-05	-
MB13D	fresh, fractured tonalite	5.0E-06	4.9E-06	3.7E-04	2.0E-06	3.4E-07	5.0E-06	3.7E-04

a. Bouwer and Rice (1976)
b. Cooper, Bredehoeft and Papadopulos (1967)
c. Cooper and Jacob (1946) straight line method. Based on maximum drawdown measured after 1800s of pumping, assuming S = 0.0001(except MB13D, where S = 0.00037). K was determined from T assuming K= T/b where b
d. Theis (1946) recovery method.
e. Geometric average of Bouwer and Rice results.
f. K was determined from T assuming K = T/b where b = screen length for Cooper et al , Theis and Cooper and Jacob methods.
N/A. Data not suitable for analysis.

3.2.2 Groundwater Levels

Figure 3 shows a contour map of the inferred groundwater table across the Mt. Morgan mine site. The blue arrows indicate the general direction of groundwater flow. In general, groundwater flow is inferred to follow natural topography, with groundwater flowing from the mine site in an easterly direction towards the Dee River Valley. The primary source of recharge for the local groundwater system is inferred to be seepage from the various mine waste units, in particular seepage from the flooded Sandstone Gully/Open Pit along the historic Mundic valley and seepage from the Shepherds and No. 2 Mill Tailings Dams. Seepage from the various waste rock dumps may also contribute significantly to groundwater recharge.

The hydraulic gradients vary considerably across the site, ranging from ~2% in the Mundic delta (near Frog Hollow) to as high as ~10% in the Shepherds reach. In general, the hydraulic gradients correlate fairly well with pre-mining topography with higher gradients observed along the steeper side slopes and smaller hydraulic gradients observed along the flatter drainage channels (Arnolds Creek, Nelsons Creek) and the Dee River valley.

The nested monitoring wells installed in vicinity of the Dee River indicate only very small (or negligible) upward hydraulic gradients, suggesting that deeper groundwater originating from the Mt Morgan mine site is not discharging directly into the Dee River. Instead, the deeper groundwater (in fractured bedrock) is discharging into a more permeable aquifer along the Dee River valley.

Little information on groundwater flow is available for the upland areas (upgradient of the Sandstone Gully/Open Pit). No water was encountered during drilling of MB1 (located immediately upgradient of the open cut, see Fig. 3) to a depth of 55m, some 2m below the lake level in the open pit. The monitoring well has remained dry since start of monitoring suggesting that the groundwater level is <281.6m AHD. These results would suggest that groundwater flow in the upland areas might be limited to small, perched zones in valley fill and/or occurs at greater depth in bedrock.

3.2.3 Groundwater Quality

The groundwater quality observed at Mt Morgan is summarized in Table 3. The water quality of the open cut, selected sumps and the Dee River is shown for comparison. Most groundwater on the Mt Morgan mine site is heavily impacted by acid rock drainage (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 generally 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. As a first approximation, the groundwater on the Mt Morgan mine site can be grouped into four categories according to the degree of impact by ARD:

1. 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);
2. 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);
3. 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);
4. 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).

Note that Type 4 groundwater was not encountered on the mine lease but is inferred to be present upgradient of all mine-impacted areas (based on water quality observed in “background” wells located off the mine site).

Table 3. Summary of initial water quality survey, June 2003.

LIST OF SAMPLES	LABORATORY DATA													
	Major Chemistry								Dissolved Metals					
	pH	**TDS**	**Acidity**	**SO42-**	**Cl**	**Ca**	**Mg**	**Na**	**Al**	**Cd**	**Cu**	**Fe**	**Mn**	**Zn**
	Units	mg/L	mg/L CaCO3	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Open pit - Mundic System														
Open Cut	2.72	21,300	5,990	12,600	584	526	1,380	813	860	<0.10	43.9	288	101	29.2
MB3[a]	3.44	15,730	5,350	11,600	568	459	1,420	770	618	0.145	47.6	116	89	26.4
MB4[a]	3.56	45,770	n/a	36,100	140	437	3,650	330	2,520	0.663	18.6	2,000	422	138.0
MB14	5.28	9,490	246	5,970	37	447	1,170	172	9	<0.050	91.2	1.7	101	11.5
Mundic West[a]	2.91	21,890	7,660	16,800	326	464	2,010	662	1030	0.187	58.4	352.0	134	41.8
MB11	3.32	25,400	3,170	15,000	199	465	3,050	334	295	0.13	20.4	137	391	29.1
Frog Hollow[a]	2.94	18,390	6,530	14,000	207	445	1,530	276	734	0.278	94.7	948	109	41.6
MB5S	3.11	17,000	6,790	14,010	124	538	1,400	151	954	0.25	124.0	883	92.4	26.4
MB5D	3.66	16,300	4,270	10,510	133	513	1,290	274	503	0.20	72.5	747	132.0	21.0
Linda Creek														
MB2	2.39	15,700	7,120	12,500	72	420	1,480	136	879	0.03	45.0	338	61.1	15.8
MB12	5.75	9,570	5,870	5,870	94	503	1,050	308	5	<0.050	0.6	24	230	4.0
Shepherds area														
MB6	3.76	11,900	3,020	8,290	52	448	1,170	192	556	<0.050	13.8	2.6	74.4	11.2
MB7S	3.21	54,100	24,600	41,700	128	568	4,050	114	4,760	0.09	89.0	21.4	265	43.6
MB7D	3.02	54,600	26,900	38,500	95	527	3,430	62	4,810	0.07	87.8	128	229	39.5
No 2. Tailings Dam														
MB8S	3.63	26,400	8,210	18,400	130	524	2,370	194	946	0.11	30.3	1,920	153	39.3
MB8M	6.34	17,600	544	12,300	145	531	2,770	554	5	<0.050	<0.10	251	71.6	3.2
MB8D	3.87	20,900	3,020	11,600	215	550	1,940	302	205	0.02	3.2	939	118	15.0
Nelson's & Arnolds Gully														
MB9	7.42	10,100	146	5,760	65	713	1,260	368	<1.0	<0.020	<0.10	0.9	0.07	<0.10
MB10	7.04	37,700	293	23,810	151	550	6,340	308	8	<0.050	<0.10	<0.10	301	1.2
Dee River System														
Dee River @ Kenbula	3.22	5,780	1,430	3,740	34	261	487	121	223	0.06	20.5	5.83	34.1	6.94
MB13S	7.59	5,090	47	2,900	112	635	427	271	1.1	<0.005	0.07	1.18	2.36	0.1
MB13D	6.38	27,200	231	18,300	165	460	4,460	469	5	0.05	<0.10	<0.10	345	5.8
Background Groundwater														
Private Bore (Jim Orr)	8.03	644	13	74	116	72	32	104	0.2	<0.005	0.16	0.11	0.32	0.03
Private Bore (Boyd Park)	7.87	300	6	50	8	14	9	58	<0.1	<0.005	0.03	<0.01	0.09	<0.01

a. First sampled in October 2003.

Despite the overall impact of ARD, the groundwater quality shows significant spatial variation across the mine site. Groundwater in the Mundic & Linda Creek drainage system is generally acidic but shows significant local variability in water quality (predominantly Type 1 and Type 2 water). Groundwater entering the Dee River system in this reach (MB5S/D) has a very poor water quality (very high Al, Cu, Fe, Mn, and Zn) and is clearly impacted by seepage from Mundic Creek and Linda Creek.

Groundwater in the Shepherds Drainage Area is highly acidic (Type 1 water) suggesting limited (or exhausted) buffering capacity in the local bedrock. Groundwater entering the Dee River along the Shepherds reach (at MB7S/D) has very high TDS and acidity and highly elevated dissolved metals (in particular Al, Cu and Zn). This groundwater is likely caused primarily by seepage from the Shepherds Outer Dump.

Groundwater downstream from No 2 Tailings Dam is also acidic with Type 1 water in shallow groundwater (tailings) and Type 2 water in deeper groundwater (bedrock). Groundwater entering the Dee River system in this reach (MB8S/D) shows highly elevated Fe and Mn concentrations and is clearly impacted by seepage from the No. 2 Tailings Dam.

Groundwater in Nelson’s Gully (MB9) and Arnold’s Gully (MB10) is well-buffered (Type 3 water) with low concentrations of dissolved metals. Carbonate minerals present in the bedrock (tonalite) are responsible for the buffering of the local groundwater in this area. However, groundwater in Arnold’s Gully shows much higher TDS (~5 times higher SO4 and Mg concentrations) than in Nelson’s Gully suggesting significantly higher ARD loading (presumably seepage from Horsepaddock Dump and recharge from the highly contaminated Arnolds Creek).

Groundwater in the Dee River Valley (in the alluvial aquifer as well as underlying fractured bedrock) at Kenbula weir is also well-buffered (Type 3 water) due to the presence of carbonate minerals in the alluvial sediment and underlying fractured bedrock (tonalite). Note, however, that groundwater in the alluvial sediments is significantly more dilute than groundwater in the underlying fractured bedrock, likely due to mixing with the Dee River water. The buffering in the “Dee River aquifer” represents a major attenuation mechanism, which limits the current release of metals into the Dee River and the downstream environment.

4 Discussion

4.1 Conceptual Model of Groundwater Flow

A generalized conceptual model of groundwater flow at the Mt Morgan mine site was developed based on the results of the 2003 field investigation. The conceptual hydrogeological model for the Mt Morgan mine site is illustrated in Fig. 4 and is summarized below.

The local aquifer system can be subdivided into the following hydrostratigraphic units: (i) mine waste material (waste rock and/or tailings); (ii) highly weathered bedrock (“saprolite”); (iii) partially weathered, fractured bedrock, and (iv) tight bedrock (“basement rock”). In general, the majority of groundwater flow occurs in permeable mine waste (where placed in topographic lows where they may saturate) and in shallow bedrock (saprolite and fractured bedrock). The deeper bedrock (say >20m below original ground surface) is typically significantly less permeable and does not carry significant amounts of groundwater flow.

Historic drainage channels (e.g. Mundic Creek, Linda Creek) typically represent areas of preferred groundwater flow owing to the historic placement of more permeable mine waste, the presence of more permeable colluvial/alluvial deposits, and/or the presence of fracturing and/or leaching in the underlying bedrock.

The backfilled and flooded Open Cut/Sandstone Gully (OCSG) represents an important local source/sink for groundwater and seepage on the mine site. Groundwater originating upgradient of the OCSG (including seepage from Dam 8 and Western Dumps) discharges into the Open Pit. At the same time, the flooded OCSG represents an important source of recharge to the groundwater system downgradient of the OCSG. The majority of seepage occurs along the Mundic Valley (through permeable mine waste). There is no indication, however, of seepage from the Open Cut towards Linda Gully.

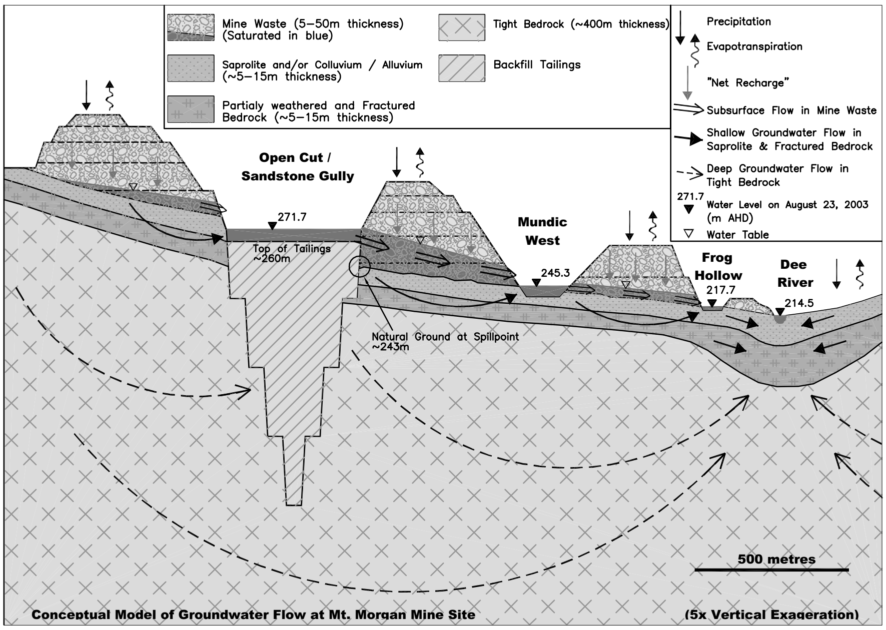


Fig. 4. Conceptual model of groundwater flow at Mt Morgan.

The primary source of recharge to the groundwater system (other than seepage from the OCSG) is via net infiltration (precipitation – evapotranspiration) into the natural ground and mine waste units (waste rock dumps and tailings impoundments). Net infiltration into mine-disturbed areas is believed to be significantly higher than in undisturbed areas due to the unconsolidated nature of the material (increasing surface infiltration) and lack of vegetation (reducing evapotranspiration);

The Dee River aquifer is believed to represent a discharge zone for regional groundwater flow. In other words, significant movement of groundwater beyond the Dee River valley (towards the west) is not believed to occur (note that this hypothesis is primarily based on water quality data rather than water level measurements).

4.2 Estimate of Open Cut Seepage to SIS

The conceptual model suggests that seepage from the Open Cut/Sandstone Gully represents a major source of current seepage to the seepage interception system (and potentially the Dee River) (Fig. 4). A quantification of seepage from the Open Cut was required to evaluate the net benefit of alternative rehabilitation options for the open cut (e.g. dry backfill vz. water cover). Water quality data were used to estimate the relative contribution of seepage from the Open Cut/Sandstone Gully to the seepage intercepted along Mundic Creek and Linda Creek.

Figure 5 shows a scatter plot of chloride versus sodium for various water samples collected from monitoring wells, seeps and sumps in the Mundic Creek/Linda Creek area in June 2003 (where missing, results from October 2003 are shown). It can be seen that the open cut water is significantly enriched in sodium and chloride compared to local groundwater not influenced by open cut seepage (e.g. MB2 and MB14). The majority of groundwater and seepage samples show intermediate concentrations of sodium and chloride along a "mixing line" between those two "endmembers". The elevated concentrations of sodium and chloride in the open cut are likely due to the use of reagents containing sodium (primarily NaCN and NaOH) and chloride during tailings reprocessing.

Sodium and chloride were used as tracers to estimate the relative contribution of seepage from the Open Cut/Sandstone Gully to various seeps and groundwater using the following mixing equation:

$$\text{\% Seepage from Open Cut} = \frac{(C_{\text{obs}} - C_{\text{net recharge}})}{(C_{\text{open cut}} - C_{\text{net recharge}})} \qquad (1)$$

where C = concentrations of sodium or chloride in mg/L.

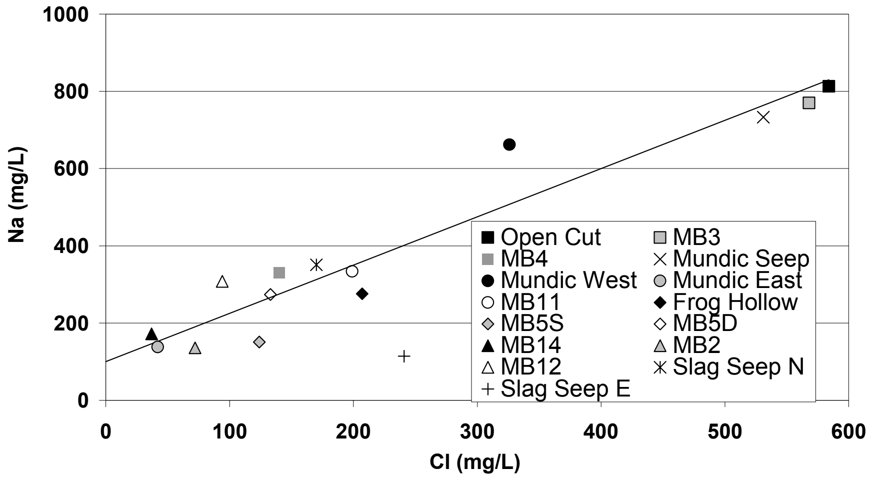


Fig. 5. Sodium versus chloride in open cut and downstream monitoring wells.

Table 4 summarizes the results of these mixing calculations using the June 2003 and October 2003 round of sampling. Note that the sumps were only sampled in October 2003 while the Open Cut was only sampled in June 2003. Average concentrations of both sampling rounds were deemed acceptable because (i) the October round of sampling was carried out before the first major rainfall events (i.e. is still representative of baseflow conditions) and (ii) the water quality in the open cut is not expected to change significantly seasonally due to the large volume of water relative to inflows and outflows.

The mixing calculations suggest that seepage from the Open Cut represents about 79% of all seepage intercepted in Mundic West but only about 25% of the seepage intercepted in Frog Hollow (under baseflow conditions!). Assuming seepage extraction rates of 7.0 L/s and 4.0 L/s for Mundic West and Frog Hollow under current baseflow conditions (Greg Bartley, pers. Comm.), the total amount of seepage from the Open Cut currently intercepted in the SIS would be about 5.5 L/s (Mundic West) plus 1 L/s (Frog Hollow) for a combined total of about 6.5 L/s.

Note that the concentrations of Na and Cl observed in the Linda Creek area (MB2, MB12 and Slag Dump Seepage East) were generally much lower than those in the Open Cut and Mundic Creek area suggesting only minor contributions (if any) from the Open Cut to this drainage. Similarly, low concentrations of Na and Cl were also observed in seepage in the Shepherds area (MB6, MB7S/D) suggesting that seepage from the Open Cut to this part of the mine site is also insignificant (data not shown here).

In summary, our analysis suggests that seepage from the Open Cut/Sandstone Gully is primarily restricted to the Mundic Creek valley. Seepage from the Open Cut to the SIS has been estimated to be about 6.5 L/s (based on water quality), representing only about 60% of all seepage extracted in the Mundic area. The remaining 40% represent subsurface flow (discharging as toe seepage) and groundwater flow (discharging into the sumps below natural ground). While some of this seepage may represent water released from storage in the natural aquifer material, the majority likely represents seepage released from storage in the mine waste units (“net recharge”).

4.3 Estimates of Seepage to Dee River System

One of the primary objectives of this study was an assessment of the amount of seepage by-passing the existing seepage interception system and entering the Dee River. A preliminary assessment of these seepage rates was made using Darcy’s Law. For this purpose, the Dee River was subdivided into three reaches (Table 5). For each reach, representative estimates of hydraulic conductivity, saturated thickness and hydraulic gradients were used to estimate groundwater flow to the Dee River.

Table 5 summarizes the input parameters and resulting estimates of seepage from the mine site to the Dee River along the three reaches. These Darcy calculations are based on a limited number of boreholes and hydraulic testing data and therefore have to be considered preliminary. Nevertheless,

Table 4. Estimated contributions of Open Cut/Sandstone Gully

	Observed Tracer Concentration (Baseflow)						**Seepage from Open Cut (%)**		
	Chloride (mg/L)			Sodium (mg/L)			using Cl as a tracer	using Na as a tracer	
Location	June '03	Oct '03	Avg	June '03	Oct '03	Avg			**Average**
Sources (Endmembers of Mixing Model)									
Open Cut	584	n/a	584	813	n/a	813	100%	100%	**100%**
assumed background	n/a	n/a	0	n/a	n/a	100	0%	0%	**0%**
Upper Mundic Valley									
MB3	n/a	568	568	n/a	770	770	n/a	94%	**94%**
MB4D	n/a	140	140	n/a	330	330	24%	32%	**28%**
Mundic Seep North	581	n/a	581	700	n/a	700	99%	84%	**92%**
Mundic Seep ("Waterfall")	531	262[a]	531	733	722	728	91%	88%	**89%**
Mundic West	n/a	326[a]	n/a	n/a	662	662	n/a	79%	**79%**
Middle Mundic Valley									
MB14	37	8[a]	37	172	131	152	6%	7%	**7%**
MB11	199	52[a]	199	334	312	323	34%	31%	**33%**
Mundic East	n/a	42[a]	n/a	n/a	136	136	n/a	5%	**5%**
Lower Mundic Valley									
Slag Dump Seepage North	n/a	170[a]	n/a	n/a	351	351	n/a	35%	**35%**
Frog Hollow	n/a	207[a]	n/a	n/a	276	276	n/a	25%	**25%**
MB5S	124	41[a]	124	151	139	145	21%	6%	**14%**
MB5D	133	57[a]	133	274	295	285	23%	26%	**24%**
Linda Creek									
MB2	72	47	60	136	124	130	10%	4%	**7%**
MB12	94	75	85	308	354	331	14%	32%	**23%**
Slag Dump Seepage East	241	42[a]	241	114	121	118	41%	2%	**22%**

a. Inconsistent lab results (excluded from analysis).

Table 5. Estimates of seepage to Dee River (including underlying aquifer system).

Dee River Reach	Aquifer Unit	Linear Length of Reach (m)	Hydraulic gradient (m/m)	Aquifer Thickness (m)	Hydraulic Conductivity (m/s)	Estimated Seepage from Mine Site	
						L/s	m^3/day
Dee River Dams (Dams 6, 4 and 5)[a]	Saprolite/Tailings[a]	650	0.013	5	9.00E-06	0.38	32.9
	Partially weathered, fractured bedrock	1650	0.013	20	4.00E-07	0.17	14.8
Mundic Reach (from Meyenburg Crossing to Redhill Crossing)	Saprolite/Tailings[b]	150	0.023	5	4.60E-05	0.79	68.6
	Partially weathered, fractured bedrock	750	0.023	10	4.00E-07	0.07	6.0
Shepherds Reach (from Redhill Crossing to Kenbula Weir)	Saprolite	800	0.1	5	7.00E-07	0.28	24.2
	Partially weathered, fractured bedrock	800	0.1	10	2.00E-07	0.16	13.8
					TOTAL	**1.85**	**160.2**

a. Permeable tailings present only along Dam 6 reach.

b. Permeable tailings believed to be present only in historic Mundic & Linda Creek channels.

they illustrate that the majority of seepage to the Dee River likely occurs as shallow seepage, in particular along old stream channels, which have been in-filled with relatively coarse tailings during the early stages of mining. Additional drilling would be required to better delineate the extent of these tailings deposits and to refine these preliminary seepage estimates.

The total seepage from the Mt Morgan mine site to the Dee River has been estimated to be about 1.8 L/s (160 m^3/day). This seepage rate is orders of magnitudes 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, but some underflow in the very permeable stream sediments below Kenbula weir undoubtedly occurs.

Note that the SIS currently collects approximately 20.0 L/s annually and 13.8 L/s during baseflow conditions (Greg Bartley, pers. comm.). The higher annual rates are due to significantly higher pump-back rates during the wet season (primarily because of higher surface runoff). These calculations would suggest that the SIS currently intercepts at least 90% of all seepage from the site.

5 Conclusions and Future Work

The hydrogeology of the Mt Morgan mine site has been profoundly altered by historic and recent mining activities. Excavation, backfilling and flooding of the Open Cut/Sandstone Gully (OCSG) has resulted in significant subsurface flow though the fill material placed in Mundic Valley (above the natural ground surface). This subsurface flow represents as much 79% of all seepage intercepted in Mundic West and 25% of seepage intercepted in Frog Hollow (for a combined total of about 6.5 L/s) under baseflow conditions.

In addition, placement of waste rock and tailings in other parts of the mine site has significantly altered the recharge pattern to the groundwater system. Seepage from these mine waste units now represents a major component of the overall recharge to the local groundwater system.

The total amount of groundwater seepage entering the Dee River system (Dee River and underlying aquifer) has been estimated to be about 1.8 L/s. This seepage rate is significantly smaller than the amount of seepage currently intercepted even under baseflow conditions (13.8 L/s) suggesting a very high efficiency of the existing SIS. Detailed monitoring of groundwater levels and groundwater quality is currently on-going to evaluate the seasonal variation of groundwater flow and seepage rates to the Dee River system.

The results of the 2003 field investigation were used to develop a numerical groundwater flow model for the Mt Morgan mine site (in progress). The observed groundwater levels and the estimated seepage rates provide calibration targets for this model. Once calibrated, this groundwater flow model will be used to obtain independent estimates of seepage bypassing the SIS and reaching the Dee River system. This groundwater flow model will also be used to evaluate the influence of alternative rehabilitation strategies on seepage rates to the SIS and contaminant loading to the Dee River system.

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