

ASSESSMENT OF GROUNDWATER IMPACTS AT THE HISTORIC MOUNT MORGAN MINE SITE, QUEENSLAND, AUSTRALIA¹

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Abstract: The Mount Morgan Mine is a historic mine site located in Central Queensland, Australia. Between 1882 and 1981, a total of 7.6 million ounces of gold and 360,000 tonnes of copper were extracted using underground and later open mining methods. The mine closed in 1990 after the re-treatment of 28 Mt of tailings, which were placed into the open cut. Most of the mine waste is acid-generating and acidic runoff and seepage has heavily impacted portions of the adjacent Dee River.

A groundwater flow model was developed for the Mount Morgan mine site to evaluate current seepage conditions and assess closure options. The calibrated groundwater flow model indicates that the backfilled (and flooded) Open Cut/Sandstone Gully represents the largest single source of ARD seepage (8.0 L/s) on the site with tailings impoundments representing important secondary sources of seepage. An estimated 80% of all seepage is collected in a seepage interception system (SIS). The remaining 20% (or ~3 L/s) of ARD impacted seepage by-passes the SIS and enters the Dee River and underlying aquifer.

The model predicts that seepage from the open cut would increase exponentially with a further increase in the water level in the open cut. The model suggests that a grout curtain or sealing the upstream side of Sandstone Gully Dam using a “blanket” of low permeability tailings would reduce seepage out of the open cut by about 40%. The amount of seepage reduction in response to placing a dry cover system onto mine waste (tailings and mine rock) is predicted to vary significantly across the site. The modeling results suggest that a combination of rehabilitation measures (including the placement of dry cover system and measures to control seepage out of the flooded Open Cut/Sandstone Gully) will be required to effectively control seepage at Mount Morgan. The calibrated groundwater flow model is currently being used to assess the effects of different closure scenarios (e.g. cover placement versus full relocation) on seepage rates and loading to the Dee River.

Additional Key Words: acid rock drainage, mine closure, hydrogeology

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Introduction

The Mount Morgan Mine is a historic mine site, 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 Au, but considerable quantities of Ag and Cu were also discovered. During the 108-year life of the mine approximately 262 t of Au, 37 t of Ag and 387,000 t of Cu were recovered from underground and open cut operations. The mine closed in 1990 after the re-treatment of 28 Mt of tailings.

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 site. 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 January 2000 the Department of Natural Resources and Mines (NR&M) 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 (Robertson GeoConsultants Inc., 2003). The primary objectives of this study were (i) to determine the sources of ARD seepage collected in the existing SIS (ii) to quantify the amount of seepage by-passing the existing SIS and entering the Dee River and (iii) to provide guidance in the overall site rehabilitation strategy. This paper summarizes the results of this hydrogeological study.

Background

Climate & Hydrology

The climate at the site is seasonal, with average maximum daily temperatures ranging from 32°C in January to 23°C in July (O’Kane Consultants Inc., 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 potential evapotranspiration (PET) is estimated to be about 1840 mm.

The Mount Morgan mine site 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 mine site catchment area contributing runoff to the river is estimated to be 3.5 km² (EWL Sciences 2001).

The stream flow 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).

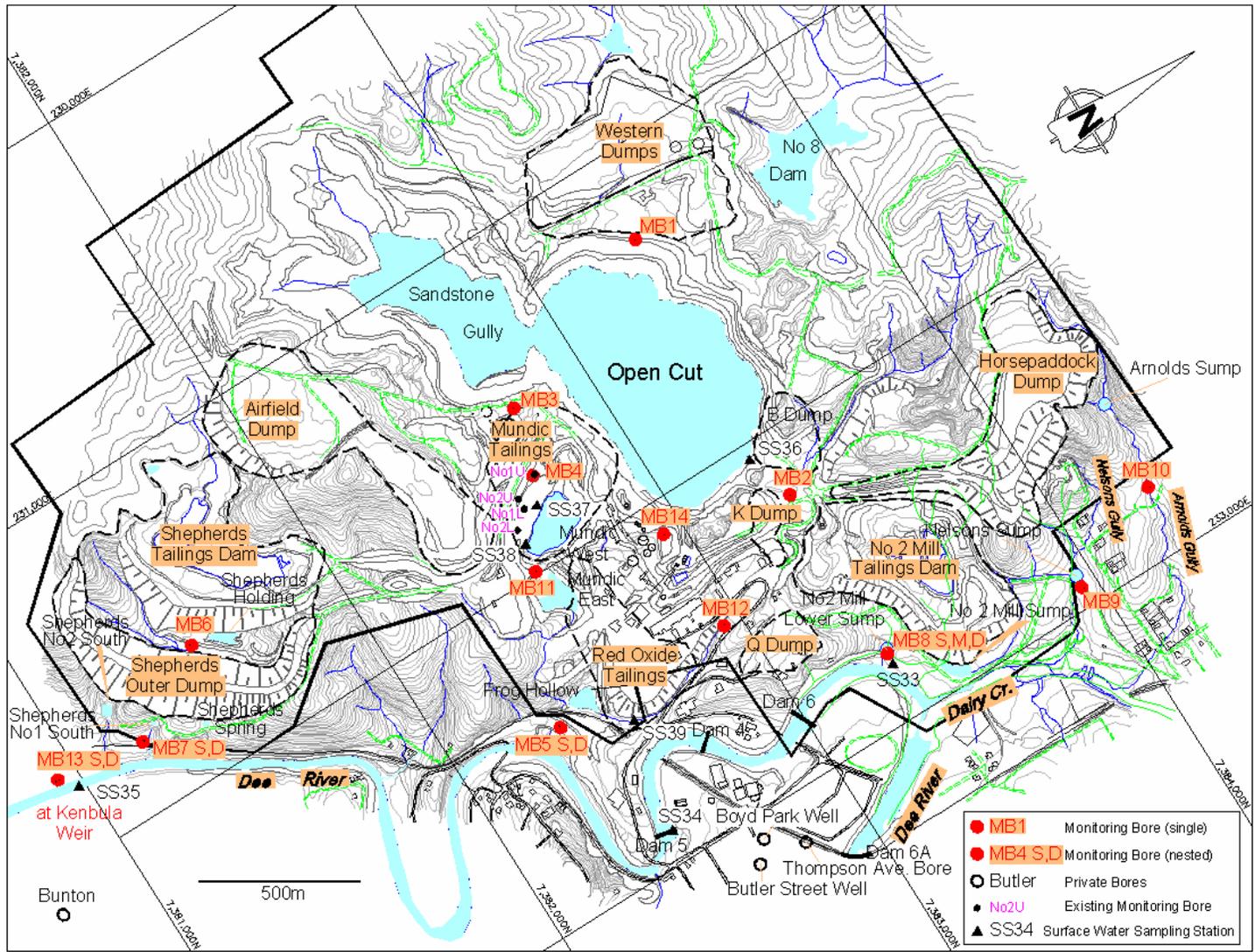


Figure 1. Location map of Mount Morgan mine site.

Geology

The geology of the Mount Morgan Au-Cu deposit has been described in detail by Taube (1990, 2000). Figure 2 shows the major lithological units and mapped structures at the Mount Morgan mine site. The major lithological units encountered on the mine site include the Mount Morgan tonalite, the banded mine sequence (interbedded tuff, sediments, chert and jasper) and the upper and lower mine pyroclastics (quartz feldspar lithic tuff). The latter three units comprise the mine corridor volcanics. The Mount Morgan ore body occurs at and below the level of the banded mine sequence, extending well down into the lower mine pyroclastics.

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). No information, however, was available on the hydrogeological properties of these structures and/or associated fractures. 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 mine site (Forbes 1990 quoted in Water Studies 2001).

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 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.

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

Waste Rock Unit	Estimated Tonnage (Mt)	Tailings Unit	Estimated Tonnage (Mt)
Horse Paddock	15	Reprocessed Tailings	28
Dump		(OCSG) ^a	
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 “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

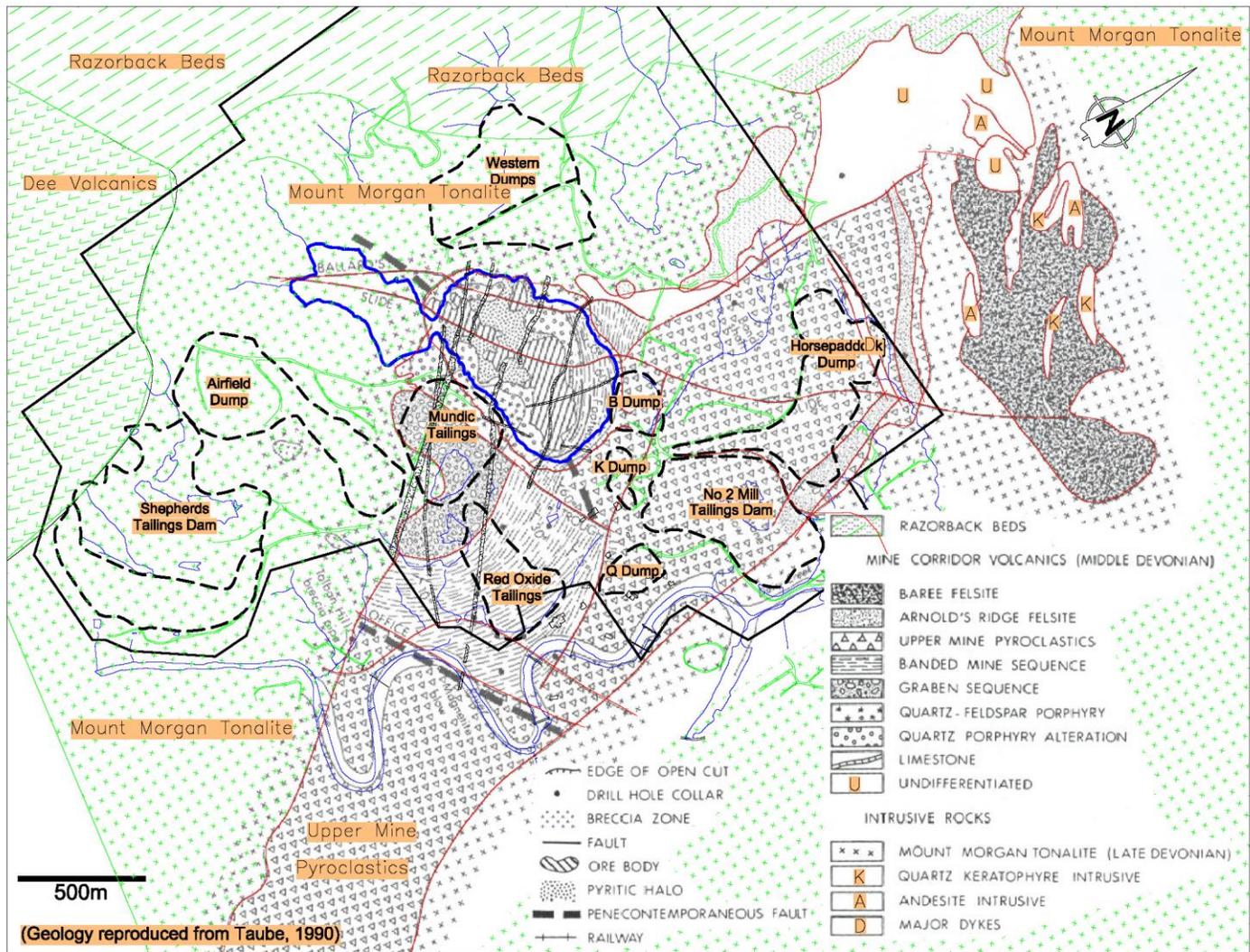


Figure 2. Generalized geology at Mount Morgan (from Taube, 1990).

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 sulfide 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-neutralizing 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 limited geochemical testing data available for the tailings material. Elutitration tests showed that the Mundic Red tailings were un-reactive whereas the Mundic Grey tailings are highly reactive and can release significant amounts of SO_4^{2-} , Fe, Al and Cu. As much as 50% of the released Cu was readily leachable during the initial washing step (EWL Sciences 2001).

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 pit. In 2004, the SIS consisted 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 ~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 backfilled open cut pit/sandstone gully.

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 (Robertson GeoConsultants Inc., 2004). Subsequently, a routine monitoring program was implemented to determine seasonal variations in groundwater levels and groundwater quality (Robertson GeoConsultants Inc., 2005). The following sections provide a brief summary of the main results of the field investigation. A more detailed description of the field methods and results of the field investigation are provided in Robertson GeoConsultants Inc. (2004) and Wels et al. (2004).

Groundwater Occurrence

Drilling confirmed the spatial distribution of the major lithologies (volcanics and intrusives) described by others (see Fig. 2). In both lithologies, the profile consisted of ~2-10m of unconsolidated material (in-situ weathered saprolite and/or alluvium/colluvium) over 5-10 m of fractured bedrock over competent (tight) bedrock. The various hydrostratigraphic units showed characteristic differences in permeability. The permeability of the saprolite is controlled by the

finer content and varies from 7×10^{-7} m/s to 1×10^{-6} m/s. Higher permeabilities were observed in shallow monitoring wells and are believed to reflect the presence of historic (coarse) tailings within the screening interval. The alluvial deposits in the Dee River and the underlying fractured bedrock have a relatively high hydraulic conductivity (5×10^{-6} to 1×10^{-5} m/s) and are therefore capable of transmitting significant quantities of groundwater relative to Dee River baseflow.

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 lowest K values ($\sim 2 \times 10^{-7}$ m/s) were obtained for the deeper, tight volcanic bedrock with very limited fracturing and/or weathering.

Groundwater flow is inferred to follow natural topography, with groundwater flowing from the mine site in an easterly direction towards the Dee River Valley (Fig. 1). The hydraulic gradients vary considerably across the site, ranging from $\sim 2\%$ in the Mundic delta (near Frog Hollow) to as high as $\sim 10\%$ 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 the vicinity of the Dee River indicate only very small (or negligible) upward hydraulic gradients, suggesting that deeper groundwater originating from the Mount 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.

Groundwater Quality

The groundwater quality observed at the Mount Morgan mine site is summarized in Table 2 (grouped by reaches). The water quality of the open cut, various seeps and sumps and the Dee River is also shown for comparison (highlighted in blue). Most groundwater on the Mount 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 SO_4^{2-} , Mg, Ca, and (if acidic) Al. 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 Mount 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 CaCO_3) 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 CaCO_3) 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 CaCO_3) and low concentrations of most dissolved metals (except Mn);
4. Type 4: Un-impacted groundwater with circum-neutral pH (7.0-8.0), moderate to low alkalinity (< 500 mg/L CaCO_3) and low TDS (including dissolved metals).

Table 2. Summary of Groundwater Quality at Mount Morgan (average of quarterly monitoring between June 2003 and August 2004).

Sample ID	LABORATORY DATA																					
	Major Chemistry										Dissolved Metals											
	Lab-pH	TDS	HCO ₃ as CaCO ₃	Acidity as CaCO ₃	SO ₄	Cl	Ca	Mg	Na	K	Al	As	Cd	Co	Cr	Cu	Fe	Mn	Ni	Se	Zn	
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
Arnolds and Nelsons Gullies																						
Horsepaddock Seep	2.90	59,882	0	23,000	47,720	12	466	6,945	105	4.2	3,865	0.046	0.399	8.02	0.087	87.6	174	391.5	3.450	0.148	96.7	
MB10	6.51	35,733	1,172	360	26,042	23	514	6,640	310	1.4	8.8	0.005	0.01	0.47	0.004	0.17	2.04	313.0	0.520	0.038	1.2	
MB9	7.08	9,326	1,132	172	6,004	44	572	1,352	370	1.1	0.30	0.001	<0.001	0.001	0.007	0.03	0.39	0.1	0.003	0.003	0.04	
No. 2 Mill Sump																						
MB8S	3.49	24,910	0	8,032	18,530	17	477	2,118	178	0.8	987	0.009	0.10	2.60	0.042	35.5	2014	140.2	0.864	0.031	40.3	
MB8M	6.07	15,562	274	542	11,382	48	467	2,426	429	4.3	2.3	0.004	0.002	0.622	0.070	0.07	347	77.9	0.093	0.012	3.1	
MB8D	4.00	16,242	0	3,113	11,276	57	475	1,674	264	4.7	257	0.004	0.04	1.43	0.006	5.40	1063	110.6	0.398	0.018	17.6	
BH - Dairy Creek	3.20	39,589	0	16,750	30,470	56	471	3,475	227	23.9	2,395	0.030	0.26	7.06	0.343	103.0	2070	233.0	2.040	0.123	53.1	
NP1	3.73	11,288	0	1,115	8,177	250	430	1,437	551	8.0	17	0.003	0.01	0.96	0.002	1.39	333	79.7	0.085	0.012	3.0	
NP2	3.15	26,540	0	7,355	20,215	115	456	2,640	382	19.2	1,110	0.022	0.11	3.90	0.026	24.8	1370	175.5	0.951	0.104	27.7	
Linda Gully																						
MB2	2.36	15,100	0	6,025	11,932	15	396	1,348	123	1.2	840	0.010	0.07	1.47	0.031	46.9	359	54.5	0.561	0.040	14.2	
MB12	5.08	8,942	20	472	6,318	72	455	1,108	326	5.1	6.7	0.003	0.02	0.53	0.002	1.37	52.9	280.4	1.142	0.020	5.0	
Open Cut - Mundic System																						
Open Cut	2.76	18,492	0	5,658	13,118	243	511	1,408	805	5.1	842	0.014	0.15	2.59	0.033	44.5	284	96.7	0.778	0.039	29.2	
MB3	3.34	16,582	0	4,890	12,395	283	442	1,395	761	10.4	772	0.007	0.16	2.59	0.043	50.2	281	90.4	0.828	0.042	27.1	
MB4	3.59	44,769	0	14,267	34,733	78	451	4,400	287	2.9	2,280	0.023	0.63	9.34	0.113	12.7	1958	407.8	2.718	0.138	127.3	
Mundic Seep SW	3.13	22,302	0	6,690	16,328	217	462	1,956	729	9.4	1,083	0.007	0.19	3.18	0.022	57.4	345	130.8	0.955	0.042	39.7	
Mundic Seep NW	3.14	30,783	0	10,850	21,540	173	476	2,355	662	2.5	1,645	0.009	0.20	3.97	0.031	62.2	789	147.0	1.065	0.039	48.9	
Mundic West Sump	2.88	22,619	0	7,580	17,395	203	465	2,043	696	8.3	1,168	0.011	0.20	3.39	0.035	57.7	366	138.8	0.976	0.055	42.3	
MB11	3.47	20,140	0	2,375	14,582	61	435	2,798	295	7.4	278	0.011	0.18	6.04	0.011	19.0	102	397.0	1.404	0.050	30.0	
Mundic East Sump	2.47	15,448	0	7,568	12,015	38	310	1,103	111	0.7	900	0.052	0.42	2.71	0.088	89.1	764	77.0	0.457	0.050	34.4	
MB14	4.47	8,224	0	589	5,912	10	422	1,102	125	24.2	23	0.005	0.10	2.24	0.001	155.2	1.02	127.4	0.616	0.028	19.2	
Slag Dump Seep E	2.73	24,630	0	12,340	18,722	20	448	1,690	106	0.5	1,598	0.016	0.10	3.11	0.070	132.2	1260	86.4	0.769	0.034	22.2	
Slag Dump Seep N	3.18	19,023	0	5,685	14,268	123	469	1,635	318	2.1	612	0.009	0.31	3.35	0.028	43.5	1358	125.0	0.746	0.041	51.0	
Frog Hollow Sump	3.01	17,859	0	6,673	13,435	104	432	1,470	271	4.1	767	0.009	0.30	3.19	0.034	87.2	1106	110.2	0.710	0.041	41.6	
MB5S	3.10	17,410	0	6,803	13,518	32	488	1,276	139	5.6	997	0.006	0.27	2.69	0.024	132.8	937	94.2	0.824	0.030	29.0	
MB5D	3.54	14,211	0	4,265	10,286	71	454	1,130	271	10.1	574	0.005	0.22	2.26	0.017	83.1	771	107.4	0.610	0.025	21.3	
Shepherds Area																						
Shepherds Holding	2.95	14,280	0	1,815	11,060	65	456	1,805	391	37.9	227	0.006	0.02	0.60	0.010	3.74	155	66.3	0.164	0.024	12.0	
MB6	3.72	10,898	0	3,230	8,236	28	441	1,115	227	4.6	529	0.005	0.03	1.45	0.009	11.1	1.17	66.6	0.391	0.024	9.8	
Shepherds Spring	3.05	18,517	0	5,390	14,640	36	438	1,950	323	4.2	913	0.007	0.08	2.53	0.016	27.4	52.8	109.3	0.495	0.043	18.5	
MB7S	3.17	44,783	0	20,725	35,742	8.3	479	3,520	150	5.4	3,980	0.015	0.14	9.62	0.084	74.1	12.9	263.8	1.355	0.086	40.7	
MB7D	3.18	45,489	0	23,220	35,602	10	510	3,138	53	2.2	4,388	0.019	0.11	7.14	0.143	81.8	100	201.4	1.135	0.102	37.4	
MB13S	5.38	5,410	156	636	3,744	106	478	524	245	2.6	87	0.002	0.02	0.37	0.004	6.83	2.37	19.5	0.131	0.007	3.2	
MB13D	5.88	25,327	283	256	18,862	45	451	4,386	475	2.9	8.5	0.008	0.12	1.79	0.004	0.21	0.08	327.0	0.229	0.026	7.3	
Dee River																						
Dam 6	3.05	10,200	0	2,308	7,712	117	268	1,049	283	8.0	383	0.005	0.052	1.085	0.009	17.3	204	58.9	0.293	0.019	11.9	
Dam 5	3.15	2,620	0	538	1,863	84	106	277	134	7.2	49	0.001	0.004	0.168	0.001	1.47	10.3	15.5	0.045	0.004	1.9	
Red Hill	2.81	5,223	0	1,565	3,960	83	219	493	155	4.9	202	0.002	0.057	0.667	0.008	21.0	39.9	34.6	0.160	0.011	6.7	
Kenbula Weir	2.98	5,485	0	1,768	4,020	81	241	517	146	4.6	221	0.002	0.058	0.750	0.008	19.9	18.9	35.5	0.175	0.008	6.8	
Background Groundwater																						
Boyd Park Well	7.26	247	82	7	45	60	17	9.2	57.3	0.4	0.035	<0.001	<0.001	<0.001	<0.001	0.007	0.022	0.019	<0.001	<0.01	0.002	
Jim Orr Bore	7.43	437	271	13	40	39	54	23	81	0.4	0.057	<0.001	<0.001	<0.001	0.002	0.038	0.144	0.001	0.001	0.001	0.026	
Thompson Ave Bore	7.17	804	429	0	120	129	117	52	123	0.5	0.009	0.001	<0.001	<0.001	0.004	0.027	0.000	0.028	0.001	0.002	0.030	

Notes:

Surface water samples in blue, groundwater samples in black.

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).

Conceptual Model of Groundwater Flow

A generalized conceptual model of groundwater flow at the Mount Morgan mine site was developed based on the results of the 2003 field investigation. The conceptual hydrogeological model for the Mount Morgan mine site is illustrated in Fig. 3 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 they may saturate) and in shallow bedrock (saprolite and fractured bedrock). The deeper bedrock (say >20 m 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.

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.

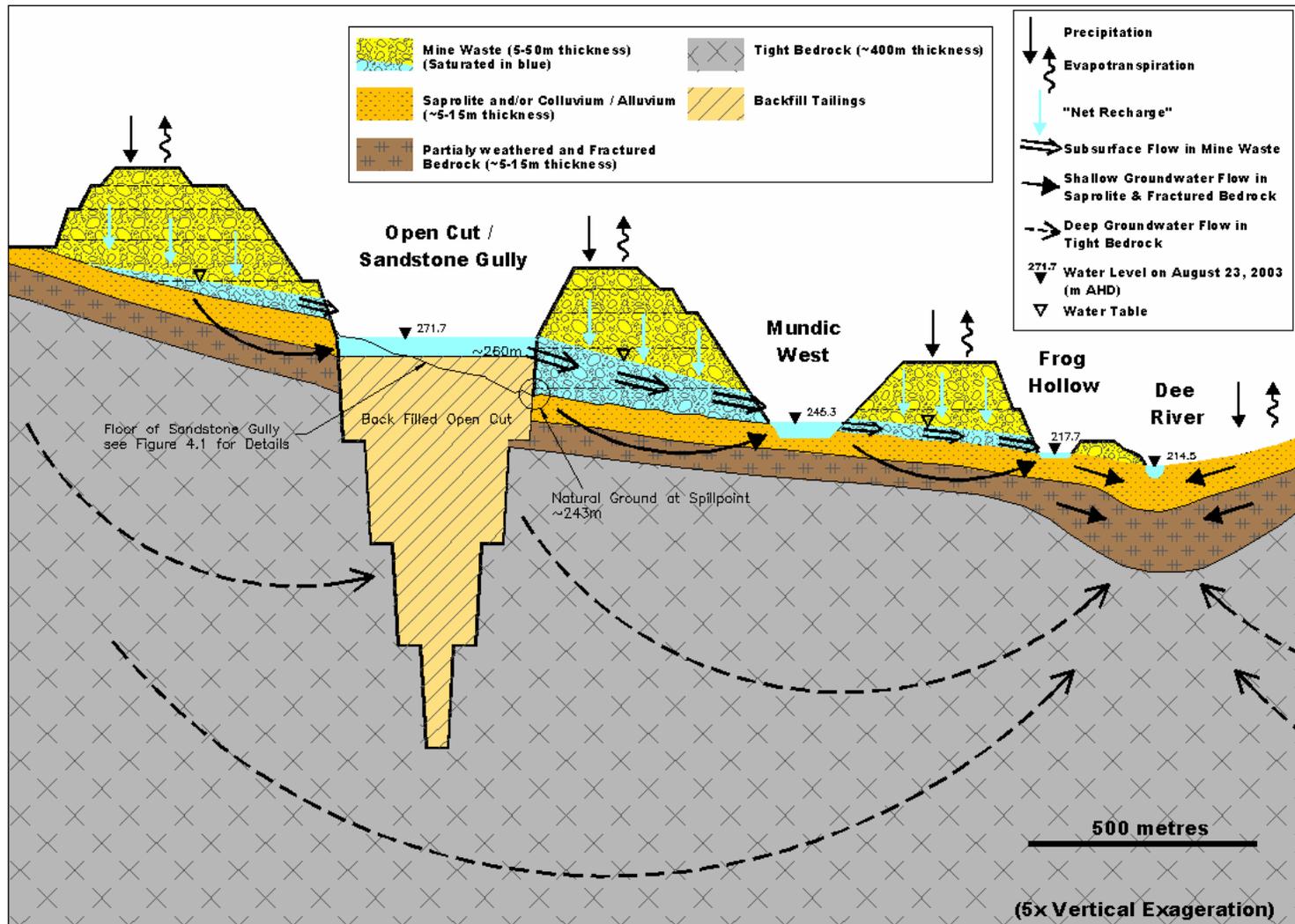


Figure 3. Conceptual model of groundwater flow at Mount Morgan.

Assessment of Current Seepage

Model Development

A three-dimensional groundwater flow model was developed for the Mount Morgan mine site to estimate current and future seepage rates from the various mine waste units to the seepage interception system and the Dee River. The model domain covers a surface area of about 7.7 km² and includes the entire Mount Morgan mine site. The model domain is bounded by topographic highs to the west and south and the Dee River and Arnolds Gully to the east and north, respectively. The groundwater flow model included four hydrostratigraphic units (mine waste, saprolite, fractured bedrock and tight bedrock). The current topography and the pre-mining topography (inferred from historic maps and drill logs) define the spatial extent and thickness of the mine waste units and were included explicitly in the model (using a 3D digital terrain model).

Figures 4 and 5 show the boundary conditions for model layer 1 (“mine waste”) and layer 2 (“saprolite”). Model layer 1 is only active within the foot print area of the major mine waste units. Most mine waste units are bounded on all sides by no-flow boundaries. Groundwater from layer 1 (“subsurface water”) may either infiltrate into model layer 2 (below natural ground) or discharge along seepage faces along the downgradient dump faces (“toe seepage”). These seepage faces are represented as drain nodes in MODFLOW (Harbaugh and McDonald, 1996).

Model layers 2 and 3 have essentially the same external boundary conditions, with no-flow boundaries to the west and south, representing watershed divides, and a no-flow boundary to the north (along Arnolds Gully) representing a groundwater flow line. To the east, layers 2 and 3 are bounded by constant heads representing the Dee River aquifer. Model layers 4 and 5 (tight bedrock) are bounded by no-flow boundaries along all four sides, implying that all groundwater from the Mount Morgan mine site discharges into the Dee River valley aquifer. In other words, the model assumes that there is no trans-basin flow of deep, regional groundwater in the vicinity of Mount Morgan and the Dee River valley aquifer represents a regional discharge zone for groundwater flow.

The various surface water bodies within the model domain, including the Open Cut/Sandstone Gully, Mundic sumps and other components of the seepage interception system, were represented as internal sinks and sources within the numerical model (Fig. 4 and 5).

The model domain was subdivided into different model regions representing different mine waste units and/or hydrogeological areas assumed to have different hydraulic properties. The mine waste units (layer 1) were subdivided into 10 subunits, primarily according to waste type (tailings impoundments, waste rock dumps, mixed waste) and time of deposition. The natural aquifer system was subdivided into two sub-regions, representing the two principal lithological units in the area, i.e. volcanic rocks and intrusive rocks (tonalite). In addition, the pre-mining drainage channels of Mundic Creek, Linda Gully and Shepherds drainage (to Shepherds Spring) were delineated as separate sub-zones in model layers 2 and/or 3. For more details on the model setup, the reader is referred to Robertson GeoConsultants Inc. (2004).

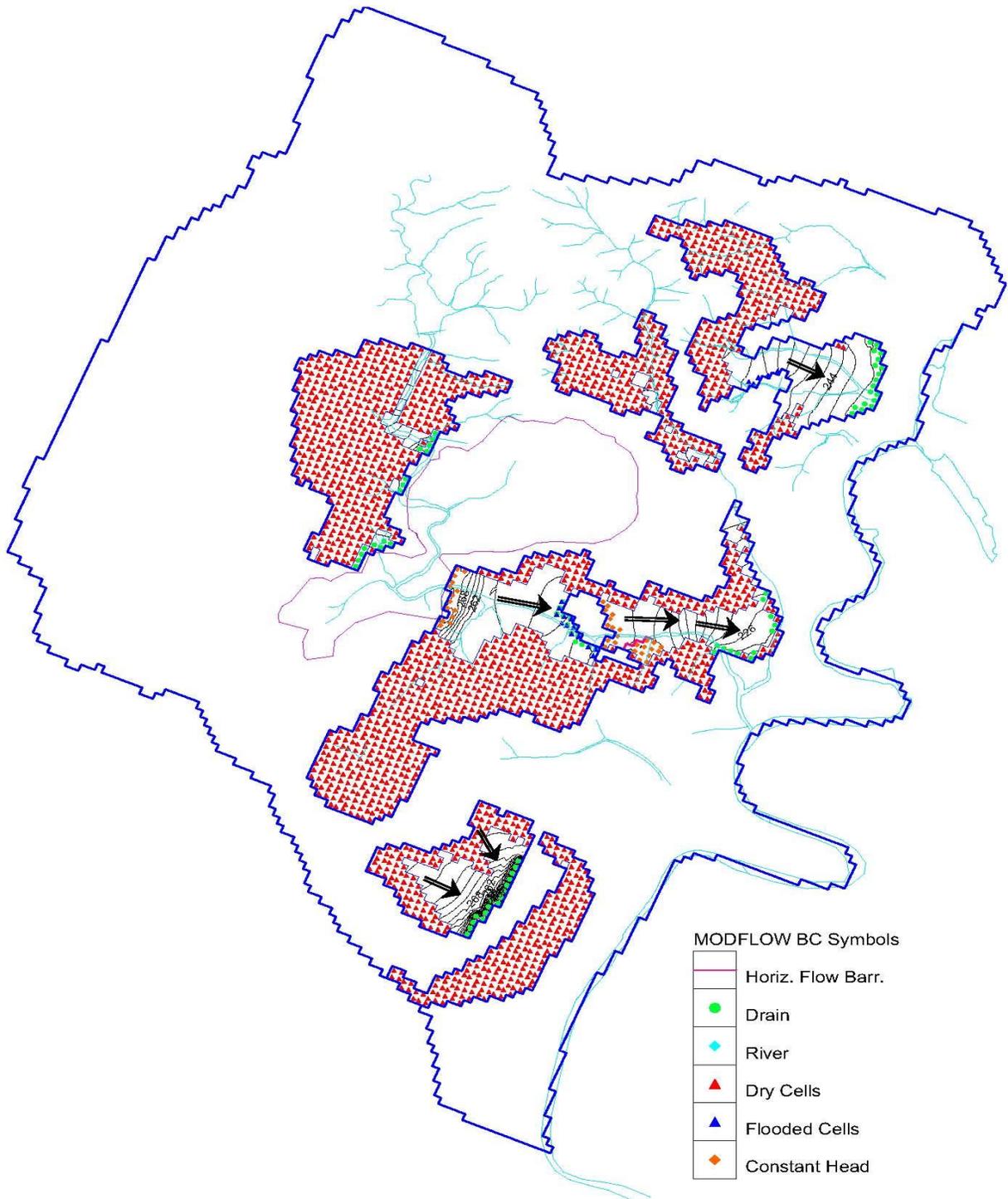


Figure 4. Simulated heads in model layer 1 (mine waste).

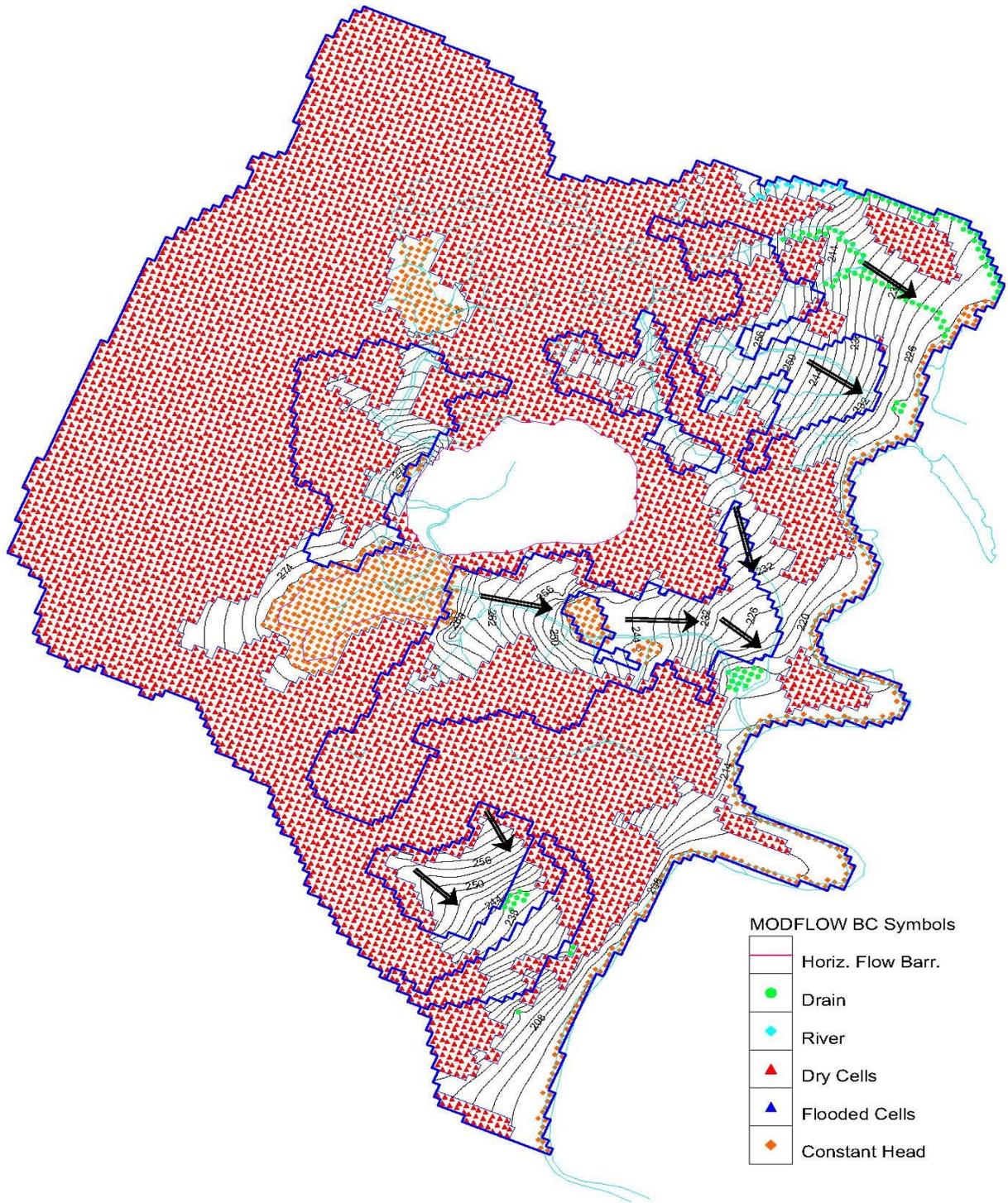


Figure 5. Simulated heads in model layer 2 (saprolite/alluvium).

Calibration of Groundwater Model

The groundwater flow model was calibrated using groundwater levels observed in 23 monitoring bores (August 2003) and estimates of seepage into various reservoirs, sumps and river reaches (Robertson GeoConsultants Inc., 2004). The calibrated model matched the observed groundwater levels quite well ($r^2=0.98$), with the majority of simulated groundwater levels within the target range of $\pm 2.5\text{m}$ deemed acceptable for this study. Table 3 shows the simulated seepage rates to/from the various reservoirs, sumps and river reaches. It should be emphasized that the groundwater flow model was calibrated for dry season (baseflow) conditions. The match of simulated and observed seepage rates was also judged to be good, in particular for those sumps where direct measurements were available (highlighted in blue, Table 3). Note that the simulated seepage out of the Open Cut/Sandstone Gully (8 L/s) was significantly lower than earlier estimates (11.8-13.0 L/s) presented by Water Studies (1992, 2001). In our opinion, the simulated (lower) seepage rate is more realistic than earlier estimates, which did not take into account groundwater flow and recharge from the mine waste units along Mundic and Linda Creek.

Table 3. Comparison of simulated seepage versus "observed" seepage from/to reservoirs, sumps and river reaches

Item	Type of Seepage	Calibration Target ^{1,2}	Simulated Flow ²
		m ³ /day	m ³ /day
Reservoirs & Sumps			
Dam 8	Net seepage out of Dam 8	n/a	38
Open Pit	Seepage into OCSG	150 - 375	170
	Seepage out of OCSG	900-1150	687
Mundic West	Seepage into Mundic W	n/a	782
	Seepage out of Mundic W	n/a	202
	Net Inflow (pumped)	605	580
Mundic East	Net seepage out of Mundic E	55-70	65
Frog Hollow	Net seepage extracted	350	336
Shepherds Holding	Net seepage extracted	105	69
Shepherds Spring	Net seepage extracted	86	92
Shepherds No. 2 South	Net seepage extracted	17-21	8
No. 2 Mill Sump	Net seepage extracted	17-21	13
River Reaches			
Dairy Creek Reach (from Arnolds Crk to d/s of Nelson Creek)	Discharge into Aquifer System (creek and/or underlying aquifer)	5-35	20.3
Dee River Dams Reach (from Dairy Creek confluence to Dam 5)	Discharge into Aquifer System (creek and/or underlying aquifer)	90-260	75
Mundic Reach (from Meyenburg Crossing to Redhill Crossing)	Discharge into Aquifer System (creek and/or underlying aquifer)	50-145	57
Shepherds Reach (from Redhill Crossing to Kenbula Weir)	Discharge into Aquifer System (creek and/or underlying aquifer)	40-125	106

Notes:

¹ only those values highlighted in blue represent actually measured baseflows (Sept 2003), all others are estimated (see text)

² black values indicate flow out of the groundwater system (flow model); red values indicate flow into the groundwater system (flow model)

Figure 4 shows the simulated flow conditions for subsurface flow through mine waste (model layer 1). The arrows illustrate the general direction of flow. The majority of subsurface flow (in mine waste) under baseflow conditions occurs in the Mundic Creek valley and in the two tailings dams (Shepherds and No. 2 Mill). Most of this subsurface flow discharges directly into existing sumps (e.g. Mundic West) or is collected as toe seepage. All other mine waste units (various waste rock dumps (WRD)) are predicted to maintain unsaturated conditions during baseflow and water percolating through these units infiltrates into the underlying groundwater system.

Figure 5 shows the simulated flow conditions for groundwater flow in model layer 2 (in saprolite and/or streambed material). Shallow groundwater flow is primarily concentrated in the original creek valleys draining the mine site (Mundic Creek, Linda Creek, Shepherds drainage, Nelsons Gully and Arnolds Gully) and the Dee River valley. Shallow groundwater flow is either intercepted in excavated sumps (e.g. Mundic West, Frog Hollow) or flows directly into the Dee River aquifer.

Deeper groundwater flow (in fractured bedrock) generally follows pre-mining topography with the majority of groundwater flow moving towards the Dee River valley (not shown). Much of the groundwater flow in fractured bedrock from the upland areas is intercepted in the Open Cut pit. Seepage from the Open Cut/Sandstone Gully and other mine waste units entering fractured bedrock is not intercepted and discharges directly into the Dee River aquifer.

Seepage By-Passing Existing SIS

One of the primary objectives of this study was an assessment of the seepage by-passing the existing seepage interception system and entering the Dee River. The calibrated groundwater flow model suggests that the total seepage from the Mount Morgan mine site to the Dee River under baseflow conditions is about 258 m³/day (3.0 L/s). This seepage rate is orders of magnitudes less than the stream flow 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 undoubtedly occurs.

Note that the SIS currently collects about 13.8 L/s during baseflow conditions (Greg Bartley, pers. Comm.). These calculations would suggest that the SIS currently intercepts about 82% of all seepage from the site (all 2003-04 figures). 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).

Assessment of Future Seepage

The calibrated groundwater flow model was used to predict future seepage rates in response to (i) changes to the water levels in the Open Cut/Sandstone Gully and (ii) implementation of selected rehabilitation measures at the Mount Morgan mine site.

Seepage from Open Cut/Sandstone Gully

Figure 6 shows the predicted seepage rate out of the Open Cut/Sandstone Gully as a function of the assumed water level in the OCSG. The seepage rate can be expected to increase at an increasingly higher rate with further increase in the open cut water level. This non-linear increase in seepage is a result of the increase in saturated surface area in the mine waste (layer 1) in contact with “free water” in the Sandstone Gully Dam area.

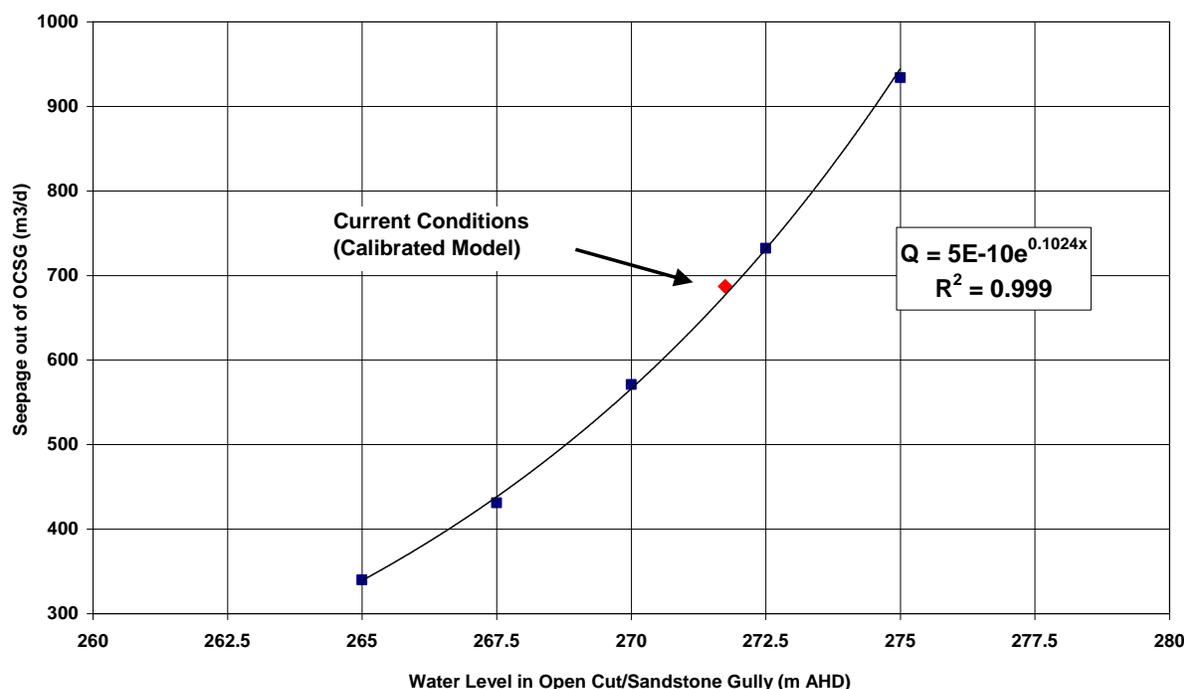


Figure 6. Predicted seepage rates as a function of the water level in the OCSG.

According to the groundwater flow model, a further increase of the water level in the Open Cut/Sandstone Gully to 275.0m AHD (i.e. the elevation of the emergency spillway) will result in a steady-state seepage rate out of the OCSG of about 934 m³/day (10.8 L/s), i.e. an increase of ~36% beyond the estimated current seepage out of the OCSG. This increased seepage out of the OCSG is predicted to result in an equivalent increase in seepage discharging into Mundic West.

The seepage rates to Frog Hollow and the Dee River are not predicted to be influenced by the water level in the OCSG (provided the water level in Mundic West is maintained by pumping), illustrating that the Mundic West sump is very effective in intercepting most of the seepage from the Open Cut/Sandstone Gully.

Assessment of Seepage Control Measures for Sandstone Gully Dam

The field investigation and groundwater modeling has demonstrated that the majority of seepage from the Open Cut/Sandstone Gully occurs through relatively permeable mine waste used for construction of the Sandstone Gully Dam (Fig. 7). The groundwater flow model was used to evaluate the effectiveness of reducing this seepage out of Sandstone Gully by (i) sealing the Sandstone Gully Dam using a grout curtain or (ii) sealing the upstream side of Sandstone Gully Dam using a “blanket” of low permeability tailings. The different options evaluated are illustrated in Fig. 7. The modeling results suggest that sealing off the mine waste in Sandstone Gully Dam using a grout curtain or a “tailings blanket” would result in very similar reductions in seepage out of the OCSG (39-41%) and seepage to Mundic West sump (~32-36%). However, the remaining seepage leaving the OCSG would still be substantial (~400-420 m³/day or 4.7-4.9 L/s) resulting in significant total seepage into Mundic West (502-529 m³/day or 5.8-6.1 L/s).

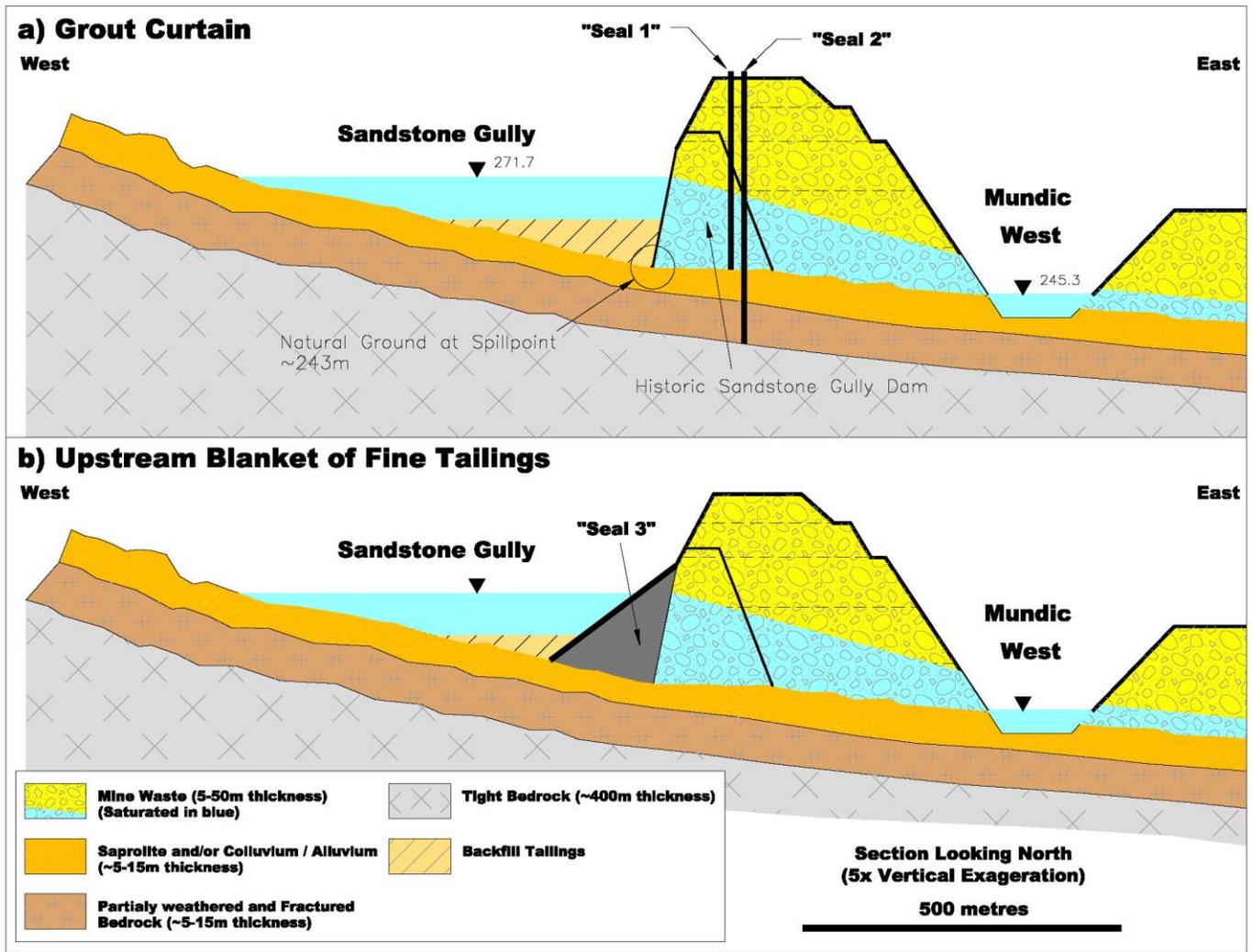


Figure 7. Seepage Control Options for Sandstone Gully Dam.

According to the model, extending the grout curtain into the permeable saprolite/stream sediments and underlying fractured bedrock would significantly improve the reduction in seepage out of the OCSG. Using this approach, the model predicts a reduction of ~75% of all seepage out of the OCSG. Nevertheless, the steady-state seepage out of the OCSG is still predicted to be about 173 m³/day (2.0 L/s), which would result in significant seepage discharging into Mundic West for this “best-case” scenario (274 m³/day or 3.2 L/s). These modeling results illustrate that “complete” sealing of the Sandstone Gully will likely be impossible and that some form of seepage interception in Mundic West will likely be required long-term.

It should be noted that the incremental reduction in seepage from the OCSG complex would represent only a relatively small percentage of the overall water balance of the open cut. The total inflows to the OCSG complex have been estimated to be about 50 L/s, including about 20 L/s of highly contaminated water pumped back from the seepage interception system (Water Studies, 2001). Hence, the estimated 40-75% reduction in seepage from the OCSG complex (3.2 – 6.0 L/s) would only represent about 6-12% of the current water balance for the OCSG complex. As a result, implementation of any of the simulated seepage reduction measures is not expected to result in a significant increase in pit water quality over time.

While the groundwater flow model has highlighted the potential for a reduction in seepage down Mundic Gully from the OCSG using a grout curtain or fine tailings blanket, an evaluation of the geotechnical and practical feasibility of such sealing measures, including the potential limitations in controlling the effective permeability of these heterogeneous fill materials, was beyond the scope of this study and would have to be further evaluated.

Reduction in Seepage due to Cover Placement

The calibrated groundwater flow model was also used to evaluate the reduction in seepage to the SIS and the Dee River as a result of placing dry cover systems onto the various mine waste units. The modeling results suggest that cover placement will have a profound effect on the seepage rates in most parts of the Mount Morgan mine site. As expected, the seepage intercepted in the various sumps and the Dee River will decrease substantially, with maximum reduction for the cover system with the lowest assumed net percolation (31mm for a water-shedding cover with grey clay) and the least reduction for the cover system with the highest assumed net recharge (90 mm for a store-and-release cover using waste rock). Net recharge values for the two cover scenarios were determined in a separate modeling study (O’Kane Consultants Inc., 2002).

However, the amount of seepage reduction in response to cover placement is predicted to vary significantly across the site. In general, the amount of seepage reduction in the Mundic Creek area is relatively small (only 6-11% in Mundic West and 8-18% in Frog Hollow) owing to the (assumed) continued seepage from the OCSG. The steady-state seepage bypassing the SIS and discharging into the Dee River along the Mundic reach under those conditions would still be significant (~50 m³/day or 0.58 L/s). Clearly, a combination of rehabilitation measures (including the placement of dry covers and measures to control seepage out of the OCSG) will be required to effectively control seepage along the Mundic Creek area.

The largest reductions in seepage are predicted for the Shepherds reach, primarily because of the large reduction in seepage from the Shepherds tailings area. The model predicts that Shepherds Holding would essentially “dry up” and seepage to Shepherds Spring would decrease

dramatically (by 73-100%). The steady-state seepage bypassing the SIS and discharging into the Dee River along the Shepherds reach after in-situ rehabilitation is predicted to range from 71-86 m³/day (0.82-1.0 L/s), depending on cover system design.

The predicted decline in seepage to the Dee River reach along the No 2 Mill tailings area are similar to those predicted for the Dairy and Shepherds reaches (~8-32% decline), with long-term seepage rates to the Dee River system predicted to range from 51-69 m³/day (0.59-0.80 L/s) depending on the selected cover system.

It should be kept in mind that all model predictions of future seepage rates after cover placement assume long-term (steady-state) conditions. In reality, it will take many years, if not decades, before these new seepage conditions will have been established, in particular in those areas with thick deposits of low-permeability mine waste (e.g. Shepherds tailings dam). A simulation of these transient changes in seepage conditions and the time required for complete “draindown” of the partially saturated mine waste units was beyond the scope of this study.

Implications for Rehabilitation Planning

This study has demonstrated that the vast majority of seepage out of the OCSG complex occurs along the historic Mundic Creek drainage, now overdumped with permeable mine waste. The installation of a grout curtain across “Sandstone Gully Dam” or placement of an upstream “blanket” of low-permeability tailings are anticipated to reduce this seepage significantly but will not eliminate it. In other words, any of these options would require interception (and treatment) of seepage along Mundic Creek post-closure.

Complete backfilling of the OCSG complex (or at least the Sandstone Gully) with low-permeability tailings represents a third option of reducing seepage from Sandstone Gully. This option may be more effective in reducing seepage than placing a tailings “blanket” on the up-gradient side of Sandstone Gully Dam because it would (i) seal the entire foot print area of the Sandstone Gully and (ii) reduce the high hydraulic head (=water level of the pit lake) currently forcing seepage through the mine waste and natural ground towards Mundic West. A simulation of this option required a change to the numerical model (i.e. an explicit representation of the tailings in model layer 1) and is currently in progress.

If tailings backfill was to be used for sealing Sandstone Gully Dam, additional laboratory testing and field trials would likely be required to demonstrate that the target permeability can be met with the proposed tailings material and discharge pattern. Clearly, the benefits of reduced seepage (and hence reduced cost of pump & treat) would have to be weighted against the cost of relocation (and/or reprocessing).

The three principal rehabilitation options for the other mine waste units located outside of the OCSG complex (i.e. waste rock dumps and other tailings impoundments) include (i) partial (or full) relocation of the waste material to the Open Cut/Sandstone Gully, (ii) in-situ rehabilitation of the mine waste unit (resloping and cover placement) and/or (iii) seepage interception. In light of the significant cost of relocation and the limited space available in the OCSG complex, relocation will likely have to be limited to those mine waste units which have the greatest potential for ARD loading and impact to the Dee River.

The results of this study suggest that all mine waste units located in vicinity of the Dee River (including Mundic waste rock and tailings, Shepherds tailings and Shepherds Outer Dump, No. 2

Mill tailings) produce contaminated seepage, some of which is reaching the Dee River. The calibrated groundwater flow model suggests that the Shepherds tailings currently produce the highest net recharge (475 mm compared to 100-150 mm for the other waste units). However, these results should be considered preliminary and will have to be confirmed. Furthermore, the modeling results only reflect baseflow conditions and higher seepage rates can be expected for the wet season, in particular from the coarser waste rock dumps.

Finally, it should be emphasized that a “walk-away” solution is, in our opinion, likely not achievable for the Mount Morgan mine site considering the large historic impact on the surface water and groundwater system, the large volumes of potentially acid-forming mine waste and the proximity to the aquatic receiving environment (Dee River). In other words some form of seepage interception and treatment will probably be required long-term. Therefore, the feasibility of seepage interception should be taken into consideration when selecting a preferred rehabilitation option for a given mine waste unit. For example, mine waste located in an area where an effective seepage interception is feasible (such as in Mundic Creek) may not require relocation or even a “high quality” cover.

Conclusions

A comprehensive hydrogeological study was carried out at the Mount Morgan mine site to determine the extent of ARD seepage and to assist in closure planning. The study included a detailed field investigation and groundwater flow modeling. The study indicated that seepage from the now flooded Open Cut/Sandstone Gully, primarily through permeable mine waste placed in the Mundic Creek drainage, represents the largest single source of ARD seepage at the Mount Morgan mine site (8 L/s). Two historic tailings impoundments (No. 2 Mill and Shepherds) represent important secondary sources of seepage. An estimated 80% of all seepage is collected in a seepage interception system (SIS). The remaining 20% (or ~3 L/s) of ARD impacted seepage by-passes the SIS and enters the Dee River and underlying aquifer.

The groundwater flow model predicts that seepage from the open cut would increase exponentially with a further increase in the water level in the open cut. The model suggests that a grout curtain or sealing the upstream side of Sandstone Gully Dam using a “blanket” of low permeability tailings would reduce seepage out of the open cut by about 40%. The amount of seepage reduction in response to placing a dry cover system onto mine waste (tailings and mine rock) is predicted to vary significantly across the site. The modeling results suggest that a combination of rehabilitation measures (including the placement of dry cover systems and measures to control seepage out of the flooded Open Cut/Sandstone Gully) will be required to effectively control seepage at the Mount Morgan site.

The calibrated groundwater flow model is currently being used to assess the effects of different closure scenarios (e.g. cover placement versus full relocation) on seepage rates and loading to the Dee River.

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