Investigating the Linkage between Water fluxes, Geochemistry and Water Quality in the Post-Closure Landscape of the Mt Leyshon Mine, Queensland

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1 INTRODUCTION

Since the closure of the Mt Leyshon Gold mine in Queensland, Australia, the quality of surface receiving waters in the mine area has significantly improved. However, uncovered stockpiles of mill rejects (scats), partially covered heap leach material and, covered waste rocks and tailings remain as potential sources of low pH waters with high concentration of sulfate ions, high metals (cadmium, copper, zinc, manganese), and arsenic concentrations. The remobilization of secondary acid mine drainage minerals and the neutralizing effects of flow path minerals obscure the relationship between pH and contaminants, but the obvious correlations between conductivity and sulfate (and metals) are useful tools for assessing the quality of receiving waters. Mine water fingerprinting showed that seepage sumps at the base of tailings, waste rock dumps and scats stockpile have distinctive chemical characteristics. A re-assessment of the cover systems found greater infiltration rates compared to the previously predicted figures. Based on the Mt Leyshon experience, it is suggested here that revisiting of rehabilitation measures and monitoring systems in a post-mining landscape are necessary for improving and optimising management strategies.

2 SITE SETTING

The Mt Leyshon Gold Mine, now in a post-closure monitoring phase, is 24 km south of Charters Towers, Queensland, at 20° 17′ 31″S, 146° 16′ 15″E. The mine with a lease boundary of 2400 ha, operated between 1986 and 2002. Mining started with a heap leach operation of oxide ore, then continued with a carbon in pulp processing of primary un-oxidised ore from a large open cut, and towards the end used low grade stockpiles. The ore body at Mt Leyshon was a reserve of 1.5 Mt at 1.5 g/t Au. It was hosted by units of the Mt Leyshon Intrusive and Breccia Complex, which occurs within a northeast trending corridor of Permo-Carboniferous sub-volcanic rocks. The Mt Leyshon Complex consists of highly altered volcanic breccias and felsic dykes, which are confined to a roughly circular shaped area across the boundary of Fenian Granite and the metasediments of Puddler Creek Formation (Newberry, 1998). The complex includes a plug like body of rhyolitic porphyry and numerous porphyry and tuffisite cross-cutting dykes. The dominant sulfides within the ore body were pyrite, chalcopyrite, galena and sphalerite and the main gangue minerals included chlorite, carbonates, mica and quartz.

The climate of Mt Leyshon minesite site is semi-arid with 660 mm of annual precipitation falling in high intensity storms between November and March. The average annual pan evaporation is approximately 2000 mm. Daily temperatures range from 21-35°C in December to 7-26°C in July (Scott et al., 1996). The geomorphology of the Mt Leyshon area has been described as a combination of rugged terrain with moderate to high elevations dominated by hills of volcanic rocks rising up to 120 m, and the gently undulating terrain developed on granite and metasediments where saprolite is preserved on hills and topographically high areas. Before mining operations, Mt Leyshon stood at 520.88 m above sea level (Newberry, 1998). The soils in the area are generally shallow and depth to the bedrock is <10 m in the mine area. Sandy alluvium up to several meters in depth can be seen in the existing creek channels.

The native vegetation of the surrounding area at Mount Leyshon is dominated by *Eucalyptus drepanophylla* (narrow-leafed iron bark), *Eucalyptus melanophloia* (silver-leafed iron bark), *Acacia argyrodendron* (black gidgee), *Acacia bidwillii* (corkwood) and the grass species *Heteropogon contortus* (black spear grass).

Prior to mining operations at Mount Leyshon, the land was classed as open woodland/ grassland savannah and was subjected to low intensity grazing. The proposed post-mining land use of the lease is generally characterised as that of fauna habitat and low intensity grazing. The final land use is further defined as:

- for the predominantly undisturbed areas, a native open vegetation community that will have a pastoral land use; and
- for disturbed areas, there is potentially three end land uses – industrial, tourist/educational and fauna habitat.

The water ways and creek system is explained in Fig. 1. The northern part of the mine drains to Clarke Creek. Southern sections of the mine drain to Puddler Creek and a section of the Eastern Waste Rock Dump drains to Fenian Creek running to the east of the site. All three waterways are ephemeral in nature and flow to the Broughton River, which in turn discharges into the Burdekin River approximately 26 km to the north-east of the mine.

Figure 1 shows a plan of the minesite and major waste disposal areas including (1) The tailings dams (New Northern Tailings Dam, Old Northern Tailings Dam and Southern Tailings Dam); (2) The waste rock dumps (North Western Waste Rock Dump, Eastern Waste Rock Dump and Southern Waste Rock Dump), (3) Scats tockpiles area; (4) Old plant area; (5) Heap leach area; and the (6) Open pit. The minesite also contains a number of dams which, with the exception of the Raw Water Dam were constructed for the purpose of containment of poor quality surface water, and a number of sumps which are required for the interception of shallow unwanted seepages.

Figure 1 Post-mining landscape of the Mt Leyshon mine environment.

3 STUDY APPROACH

The Mt Leyshon water quality monitoring does not involve charge balanced analysis of samples, nor does it cover a range of trace elements which are normally associated with gold mineralization. Besides, in accordance with the requirements of the Environmental Authority the monitoring has always been based on total analysis of samples without field filtering. In November 2005, CMLR participated in a benchmark surface water sampling program at Mt Leyshon minesite, that included field filtering and a charge balance analysis, to assess the necessity of adding previously unmonitored determinants to the monitoring list, and more importantly to investigate potential mine water fingerprinting, so that contaminants could be related to their major sources. In collaboration with the Newmont site staff, water samples were collected from 9 sumps and dams near major facilities. Samples were field filtered (<0.45 μm) and acid preserved for metals and were immediately sent to Australian Laboratory Services (ALS) for chemical analysis. This study is based on a review of existing water quality monitoring data and the results of the recent surface water sampling. The geochemistry of the heap leach material was characterised by total digest elemental analysis, Net Acid Generation (NAG) and Acid Base Accounting (ABA). The results were compared with those of other waste materials on-site.

The development of a water management strategy requires also a good understanding of the parameters of the water balance. Amongst the variability of climatic conditions and their outcome in the capacity of water to be stored in or draining through the covers, the properties of the uptake of water is focus of this assessment. For this reaspn, infiltration tests were performed at eight locations across the covers of the tailings storage facilities. The test locations were chosen based on an attempt to evenly distribute the measurement locations and to include information in respect to the success of plant growth. At each location the hydraulic properties were determined for the topsoil (surface) and at ca. 20-40 cm below the lower boundary of the topsoil, which reflected the properties of the cover (hydraulic barrier). A disc infiltrometer was used for the infiltration tests primarily for greater time efficiency and higher accuracy. Some of the tests were backed up by comparisons with double ring infiltrometer tests. On the sites with very rocky material, double ring infiltrometer tests had an advantage over the disc infiltrometer test.

4 OVERVIEW OF GEOCHEMISTRY

The pre-mining weathering profile of the mineralized zone of Mt Leyshon has been described as a stratified supergene system consisting of an oxide zone above a supergene enrichment zone. Large amounts of weathering solutions rich in $SO4^{2-}$, Fe^{3+}, Al^{3+}, and K^{+} migrated through system. In the oxidized zone, Au was associated with Fe-oxides, jarosite, alunite and kaolinite in cavities and veins and was generally disseminated throughout the host rocks (Newberry, 1998). The supergene zone contained abundant chalcocite, digenite and minor bornite (secondary copper minerals) (Orr and Orr, 2004). Copper and silver where strongly enriched in the supergene zone. Mine drill hole assays showed inter-element correlations between Bi, Au, Cu and As. Approximately 84 vol. % of the total Au was associated with Bi sulfides and sulphosalts, either as inclusions or at grain boundaries (Orr and Orr, 2004).

In the post-mining landscape of Mt Leyshon mine, Old Northern Tailings Dam (ONTD) covers an area of 57 ha, Southern Tailings Dam (STD) 55 ha, and New Northern Tailings Dam (NNTD) covers 100 ha of mined land. Environmental Geochemistry International (EGI, 1999) reported total sulfur levels of 1.8 to 7.8% in the tailings with the coarser tailings, located towards the perimeter of the dams, associated with the higher S concentrations. The bulk of the tailings are likely to be potentially acid forming. To establish stable landforms and control acid mine drainage, tailings have been capped with engineered covers comprising a base platform of Run Of Mine (ROM) waste rocks, overlain by compacted heap leach, and covered with top soil.

Similarly, the Southern Waste Rock Dump (SWRD) has been covered with compacted heap leach and topsoil, whereas the Eastern Waste Rock Dump (EWRD) has been covered with compacted porphyry materials and topsoil, and the North Western Waste Rock Dump (NWWD) was covered with either porphyry or heap leach and topsoil. The low pH and poor water quality of local seepages, the presence of acid mine drainage precipitates in a few places and spectacular displays of heated gas emanating from a few locations in EWRD suggest active acid mine drainage processes and reactions in a few locations within the waste rock dumps.

Scats Stockpile is currently at the angle of repose and has not been capped. It is a stockpile of approximately 14 million tonnes of mill rejects, which could not be economically processed during the mine life. They are crushed unprocessed ore with high percentage of silicates. Although the stockpile appears to be physically stable and less eroded compared to other waste piles on site, the scats contain sulfides that have the potential to produce acid that may in turn leach heavy metals into the associated run-off. The scats contain up to 3.8% sulfide sulfur (Woodward-Clyde, 1993) and high concentrations of Cu (203-442 ppm), Pb (60-127 ppm), Zn (180-1470 ppm), As (10-63 ppm), Cd (1-9 ppm), Mn (1770-3310 ppm), Mo (10-68 ppm), Ni (17-22 ppm), and up to 6% Fe. The run-off from scats may enter surface and ground waters, if not contained.

The spent heap leach materials have been used in the cover systems for the tailings storage areas, and other areas including parts of the waste rock dumps, ROM stockpile, the plant area, and the magazine area. The material has been also used in the structure of dams. Remnants of the heap leach materials are stockpiled in the "heap leach stockpiles". The area has been partly covered with topsoil and seeded**.** In spite of the near-neutral pH values, most heap leach materials analysed contained a range of sulfur concentrations that indicate the potential for acid drainage formation with time. Figures 2 and 3 compare the potential acidity of scats, heap leach and the tailings.

Compared to trace element compositions for average felsic and intermediate rocks (e.g. Levinson, 1974), arsenic (10-49 mg/kg), cadmium (<1 to12 mg/kg), copper (14-334 mg/kg), lead (12 to 130 mg/kg), molybdenum (<2 to 88 mg/kg), zinc (10 to 328 mg/kg), and bismuth (0.6 to 11.9 mg/kg) concentrations are all enriched in the samples analysed. Samples also show wide range of concentrations for Mn (23 to 1100 mg/kg), Co (<2 to 7 mg/kg), Fe (22200 to 47400 mg/kg), Ni (<2 to 88 mg/kg), Zn), Ti (20-420 mg/kg), and cyanide (0.5 to 19 mg/kg). The concentrations, however, are much lower than those values in scats as reported by Woodward-Clyde (1993). Antimony, tin, tungsten, mercury and selenium, which are normally associated with gold, are all below detection limits.

Table 1 Summary of geochemical test results for the heap leach material

Paste pH	Total S (%S)	Sulfide S (%S)	Soluble sulfate (mg/kg)	Fizz Rating	ANC Kg H_2SO_4	NAPP Kg H_2SO_4/t	NAG Kg H_2SO_4/t	Final pH
5.2-8.9	0.02-2.08	<0.01-1.5	210-5550	0	1.9-10.3	-1.5-58.8	<0.1-14.9	2.8-8.4

The open pit is 1.2 km long, 700 m wide and 310 m deep. In the last year of production, approximately 4.5 Mt of tailings material and approximately 2,400 ML of decant water was disposed of into the pit. Yellow-orange acid rock drainage minerals which have formed locally in fractured areas of the pit wall show the presence of sulfides in the rocks surrounding the pit.

5 WATER QUALITY TRENDS AND SIGNATURES

The post-closure landscape of Mt Leyshon minesite can be divided into five major hydrogeochemical domains as shown in Figure 1. The run-off is generally contained by dams, but if the dams overflow, the decant water from the dams and the rest of the overland flow in each domain, combine and flow through natural creeks. Appendix 1 summarizes the sub-catchments comprising each domain.

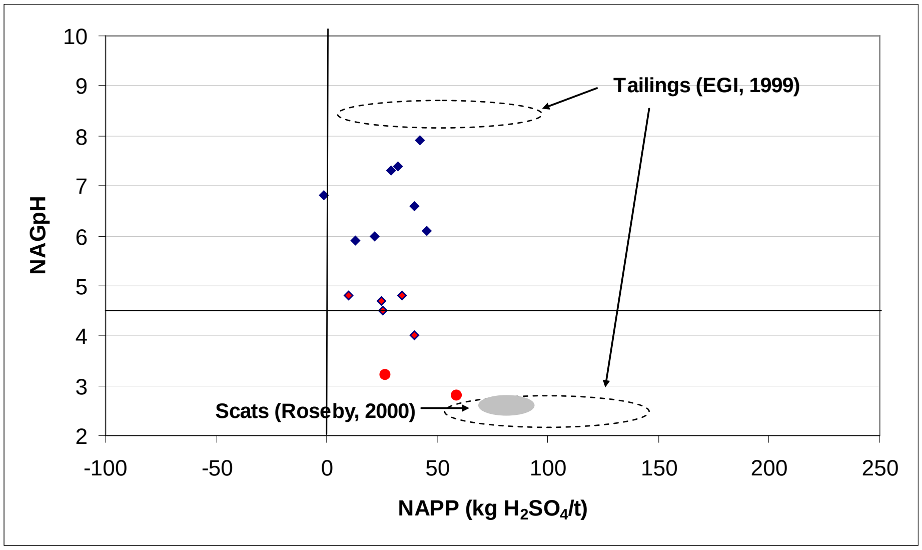

Figure 2 **Plot of NAGpH versus NAPP shows 4 samples are potentially acid forming, three samples are near the 4.5 NAGpH and the rest are uncertain**

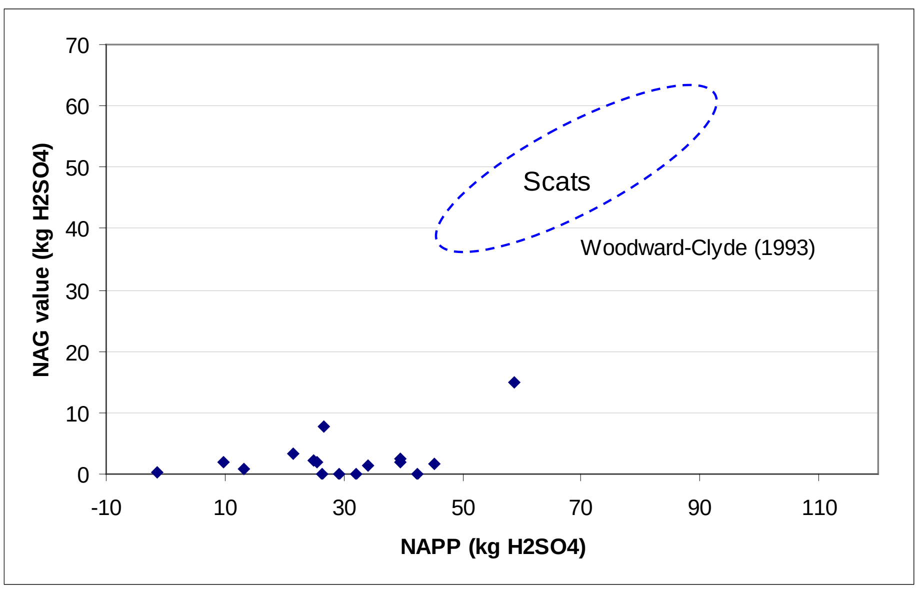

Figure 3 **The NAG and NAPP values for the heap leach are lower than those of the scats**

5.1 Monitoring database

A review of the surface water monitoring data collected from late 1980’ shows an apparent increasing trend in the concentrations of sulfate with values often exceeding ANZECC (2000) water quality guidelines for stock drinking water. The range of pH values measured fall into two broad categories of near neutral and acidic (Figure 4a).

In a series of sampling locations known as “regional receiving waters” but in fact within the lease boundary, a gradual increase in the sulfate concentrations has been recorded from late 1980’s to 2002 with obvious exceedance levels in late 1990’s for last monitoring points on-site, in the Clark and Puddler Creeks. Measured pH values are mostly in the range of environmental standards, between 6.5 and 9. Cadmium, copper and zinc concentrations have often been recorded higher in the Puddler Creek. Arsenic, lead and manganese concentrations have been often elevated in the south-eastern domain (Domain 3) and have been particularly high downstream from the Mt Mawe area in the tributaries of the Fennian Creek. Since the mine closure, the water quality in the receiving waters has significantly improved.

Discharges from the waste containment facilities have been more closely and regularly monitored at 9 sampling locations known as “Near facility” points. The pH values measured at these locations are commonly near neutral, except in domain 4, upstream from the Settlement Pond. High (>1000 mg/L) concentrations of sulfate has been recorded in all domains. Cadmium is typically elevated in domain 1 and 4, mainly at downstream locations from Scats, Heap Leach, Plant and Supergene areas, and the highest copper concentrations have been recorded downstream from the supergene area. Zinc concentrations have been usually high in domain 1 and 4 and downstream from the spine drain in domain 3.

The seepage sumps and run-off containment dams are commonly enriched in metals and sulfate due to evapo-concentration and minimum dilution effects and usually show heavy metals concentrations that exceed the contaminant limits for livestock drinking water and hazardous waste dams.

A number of water quality samples collected from various locations in the open pit which are now drowned were tested between 1995 and 1999 showed occasional acidic seepage and elevated sulfate, Cd, Cu and Zn for the pit floor sump. Recent test of pit water shows pH values of 4.5 and elevated sulfate, Cd, Cu and Zn concentrations exceeding the guidelines for dams containing hazardous waste.

In the past, water levels and concentrations of a range of chemical constituents in the groundwater has been monitored in a number of bores within the mine lease boundary, more consistently since 2001 in 16 monitoring bores. Unlike surface water, the pH values measured are mainly in the near-neutral range (Figure 4b). Compared to surface waters, sulfate, Ca, Cd, Cu, Mn, Zn, As, Pb concentrations are typically lower in the groundwater data (Table 2).

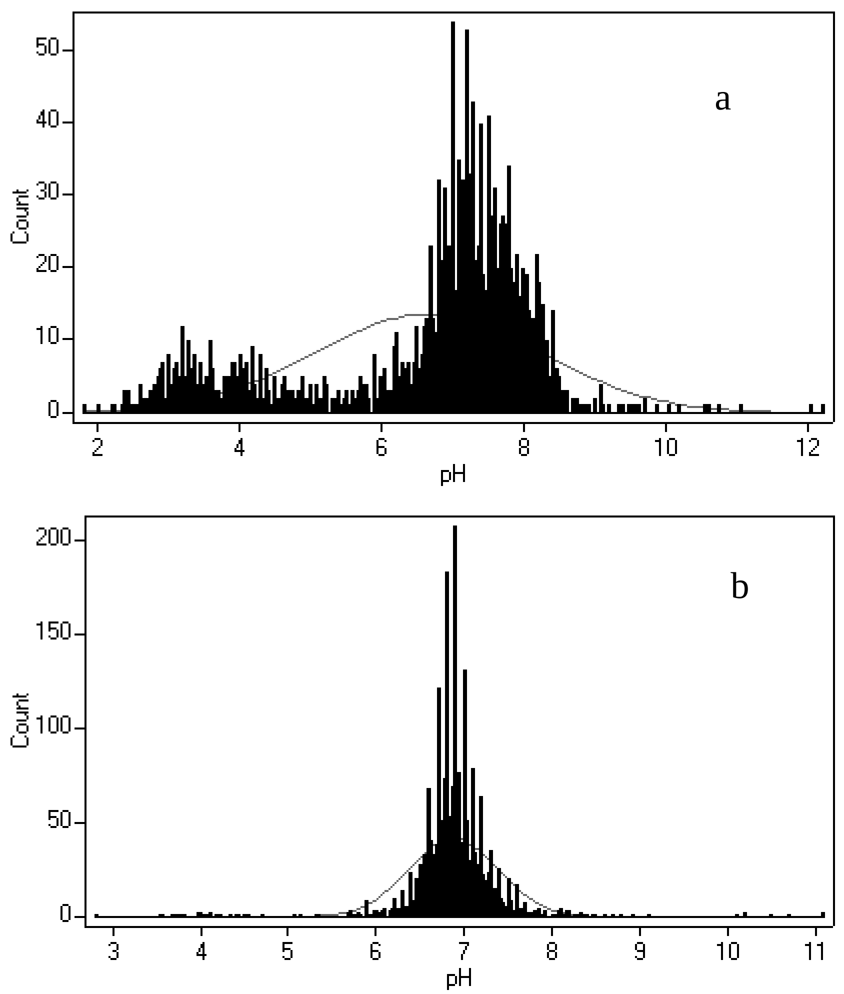

Figure4 **Frequency distribution of pH values measured in (a) surface waters and(b)groundwater**

Table 2 Summary of water quality monitoring data. Elemental concentrations are in mg/L. Electrical conductivity (EC) is in mS/cm.

	DWT	pH	EC	Ca	Mg	SO_4	Cd	Cu	Mn	Zn	As	Pb
							Groundwater					
Mean	2.9	6.9	3.98	353	270	1404	0.3	1.18	4.65	0.86	0.04	0.22
StDev	2.9	0.5	2.2	172	116	984	0.35	6.3	15.87	6.57	0.18	0.17
Min	0	2.8	5.3	11	26	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Max	15.6	11.1	54.4	892	579	15500	3.87	78.3	269	143	1.88	0.9
							Surface water					
Mean		6.65	3.38	383	221	1953	0.67	9.16	46.77	21.67	0.18	0.09
StDev		1.6	3.99	301	399	2639	1.32	32.83	131.88	69.99	2.0	0.29
Min		1.81	BDL	3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Max		12.23	67.7	1581	5180	47600	21.6	949	1790	844	32.8	5

DWT= depth to water table (m); BDL=below detection limit

Review of the groundwater data shows that a few bores with higher sulfate concentrations are aligned along a north-south line through domains 1 and 4. It is also interesting to note that shallower groundwater levels have been recorded along this line. Whether this indicates a connected hydrogeological zone needs to be verified. A definitive knowledge of the subsurface geology and distribution of hydraulic conductivities has not been reported for the bores. North-south trending fracture zones in the immediate vicinity of the new north tailings dam and the presence of two significant alluvial channels have been reported (PosGold, 1994; Coffey, 1994; Klohn-Crippen, 1999).

A first attempt to generate empirical models based on all water quality data at Mt Leyshon, shows that some correlations exist, for example between measured electrical conductivities and sulfate concentrations (Figure 5). However, the models have relatively large residual errors which could be related to the discontinuity of surface and subsurface geochemical processes, for example surface evaporation and the formation of highly soluble secondary minerals. Nevertheless, when the surface and groundwater data are modelled separately, obvious correlations emerge and the residual errors are reduced (Figure 5). There is a significant correlation between conductivity, sulfate, calcium and magnesium for both surface and groundwater data sets. These correlations are, however, weaker at "regional" locations where most concentrations are close or below detection limits. A further positive correlation exists between sulfate and heavy metal concentrations in surface waters (Figure 6).

The lack of correlations between pH values and the concentrations of sulfates and metals, on the other hand, suggests the important role of precipitation and dissolution of secondary minerals and the neutralizing effect of minerals such as carbonates and chlorite on the site water chemistry. The correlation between Mn and Zn in both surface and groundwater data, which is particularly stronger in the case of surface waters, is the result of similar geochemical properties and mode off occurrence particularly in secondary minerals. For example, the banks of the scats dam were covered with white precipitates at the time of water sampling. The X-ray diffraction (XRD) analysis of these precipitates showed the dominant presence of Epsomite [($Mg\ SO_4$ $(H2O)_7$], Groutite [MnO

(OH)] and some Morenosite [Ni SO_4 $(H2O)_7$]. The chemical analysis of the precipitates by ICP-MS revealed extremely high concentrations of Mn (up to 34750 mg/kg) and Zn (up to 15390 mg/kg).

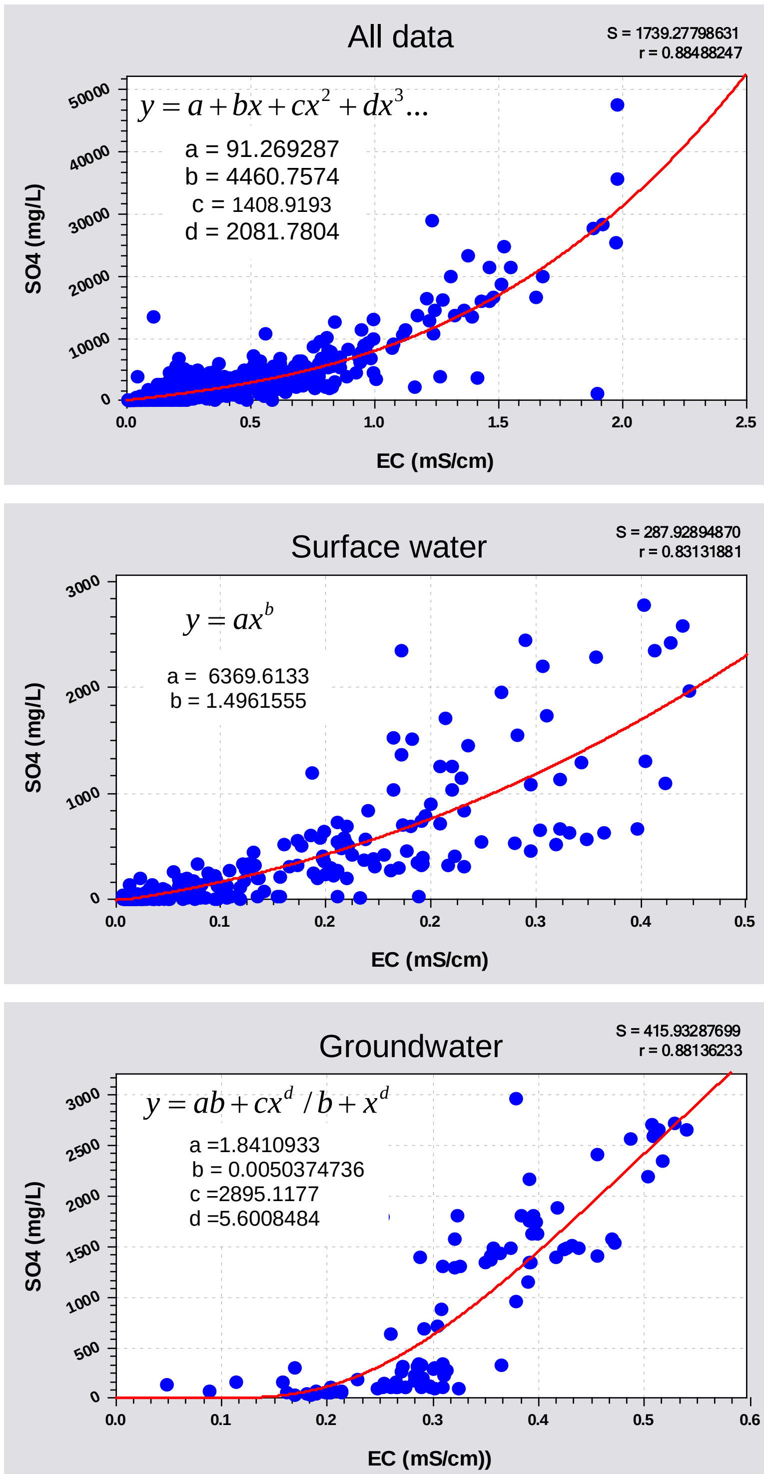

Figure 5 **The correlation between electrical conductivity and sulfate**

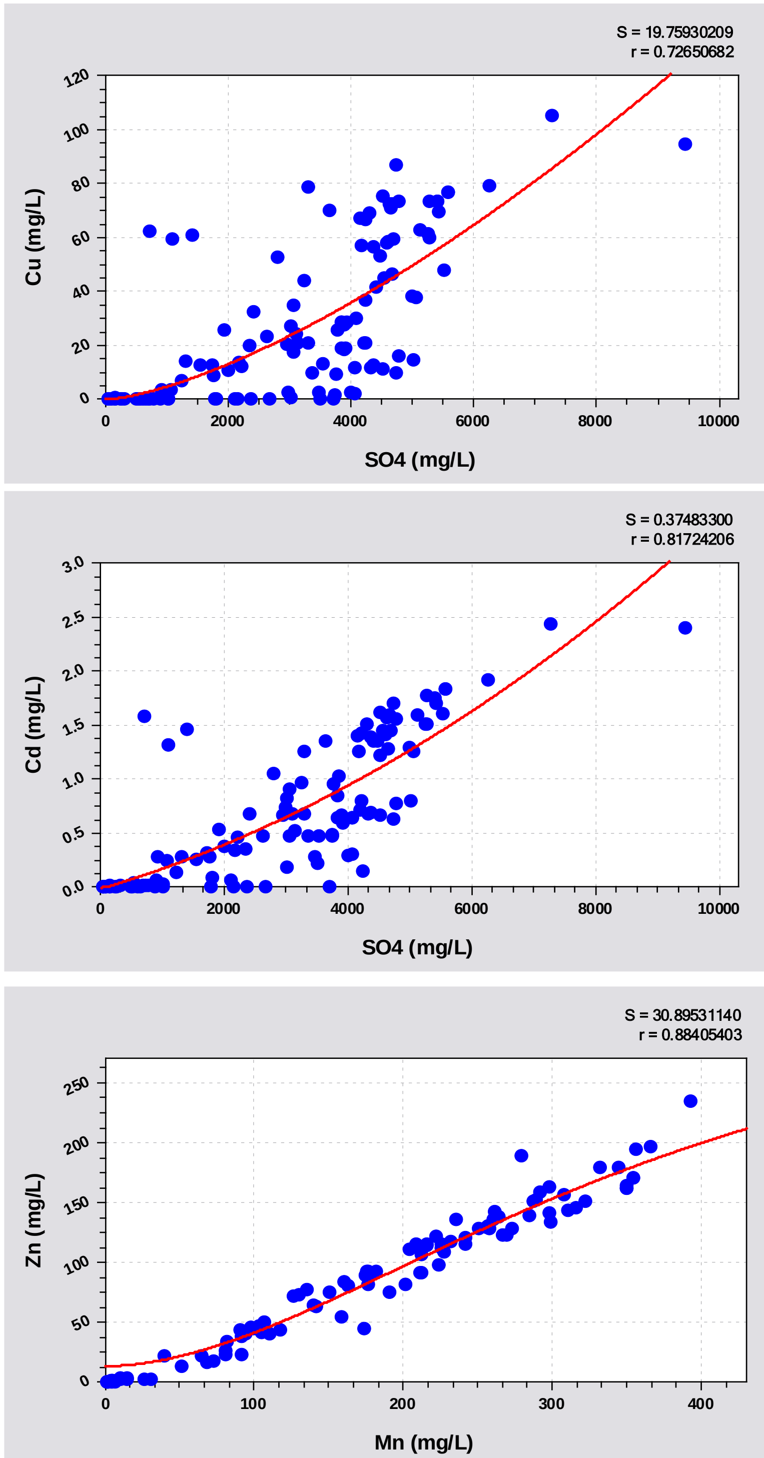

Figure 6 Sulfate-metals and Manganese-zinc correlations in surface waters

5.2 Recent results

A comparative analysis of the 2005 results shows that the dam at the base of the scats, the Mt Mawe Sump, and the Supergene Dam, being close to the sources of oxidizing sulfide bearing rocks and hence acid mine drainage, have the lowest pH values (3.07-3.92), whereas the sumps at the base of tailings have circumneutral pH values (as high as 7.70). The low pH locations are also characterized by high concentrations of dissolved metals (hydrated cations and chelates or anions) that includes SO_4 and heavy metals (Cu, Pb, Zn, Cd, Ni), Mg, Fe, Mn, U, Se, as well as As.

The concentrations of dissolved ferrous iron are much higher in the Scats Dam and the Mt Mawe Sump than any other sampling points. Iron concentrations of up to 50800 mg/kg has been reported for scats (Rosby, 2000).

In acid mine drainage environments, dissolution or oxidation of pyrite initially produces Fe^{2+} that is immediately oxidized to Fe^{3+}, which is either precipitated as an oxyhydroxide or reduced by pyrite, generating more Fe^{2+} and increased acidity. A more plausible source of Fe^{2+} in the Scats Dam is the dissolution of secondary salts such as Melanterite ($Fe^{2+}SO_4.7H2O$).

The Supergene Dam contains extremely high concentrations of Cu (82.7 mg/L). Orr and Orr (2005) reported high concentrations of Cu in the supergene materials (1-2%).

The "tailings sumps" have a lower and narrow range of 3650-4230 mg/L for sulfate concentrations. These sumps are characterised by higher concentrations of Sr and Mo and distinctly higher concentrations of As in the southern tailings sump. The "tailings sumps" also have higher alkalinity and are enriched in Na and Cl in comparison with the scats and supergene dams and the sump near the eastern waste rock dump (Mt Mawe).

Higher concentrations of Sr and Mo in the tailings sumps can be attributed to the natural soils in the Mt Leyshon environment (Orr and Orr, 2005). The higher concentrations of Arsenic can be thermodynamically related to higher pH values (Miller et al., 1996). In circumneutral-alkaline oxic environments Arsenic forms species such as $H_nAsO_4^{-(3-n)}$ (Bowell, 1994). These molecules form "sparingly" soluble solids and as they are not strongly adsorbed on precipitates (mainly hydrous ferric oxide) their dissolved concentrations can increase in the sumps. It is also important to note that in these waters "evapoconcentration" is an important mechanism for the enrichment of As.

The concentrations of a few elements which were selected based on the geochemistry of the ore and host rocks and were measured for the first time in Mt Leyshon mine waters including Bi, Ag, Au, Sn, Hg, and W were all bellow detection limits. Only one sample has Sb concentrations and one sample V concentrations above detection limits. Manganese concentrations, however, are far greater than the average values in natural waters. Cobalt, Ni and Se concentrations exceed the guideline values in a few samples. An elevated uranium concentration (1.36 mg/L) is measured for the Scats Dam.

A comparison of the major ion chemistry of all samples using Piper diagrams (Figure 7) indicates that the anion proportions are similar between different locations. As a proportion of total anions (HCO_3, SO_4, Cl), all samples contain less than 20% HCO_3 and Cl. In comparison, cation (Na, K, Ca and Mg) proportions show greater variations. The tailings sumps generally have higher proportions of Na over Mg+Ca.

Piper diagrams, however, can not be used alone to distinguish between the water types, because the difference in the concentrations of chloride and sulfate is not easily detectable. A more detailed plotting of anions based on

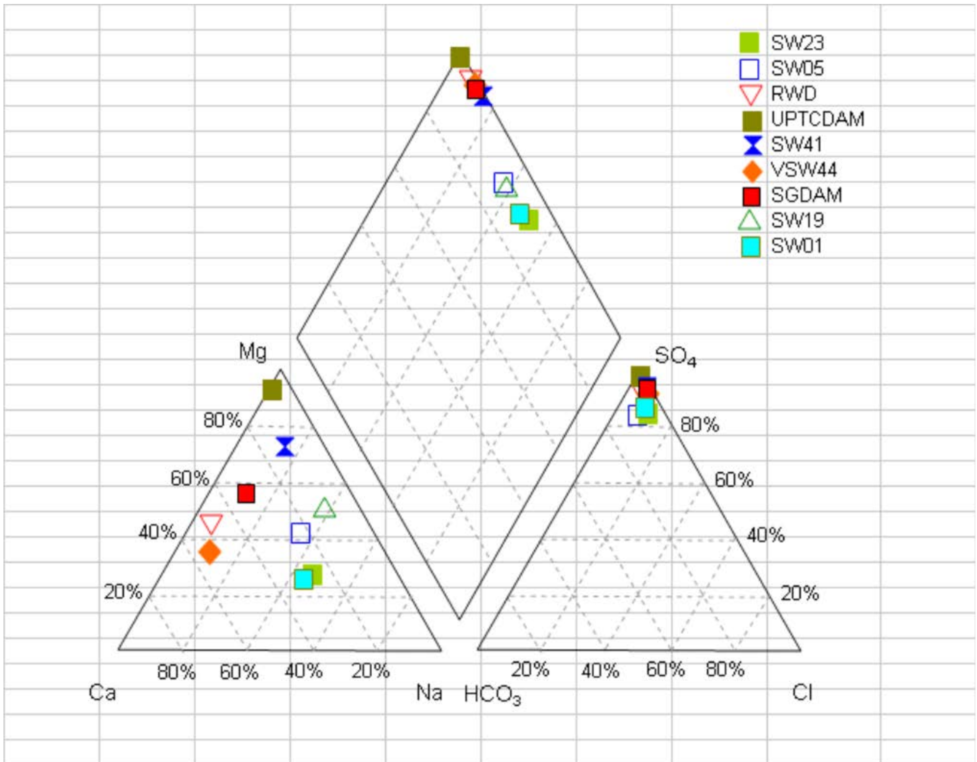

Figure 7 Major ion proportions in Mt Leyshon water samples plotted in a Piper diagram. SW1, SW05, SW19, SW23 are sumps at the base of tailings dams; VSW4 is close and upstream of the settlement pond; SW41 is collected from Mt Mawe sump; SGDAM is from Supergene Dam; RWD is Raw Water Dam; and UPDAM refers to Upper Plumtree Creek dam at the base of Scats Stockpile.

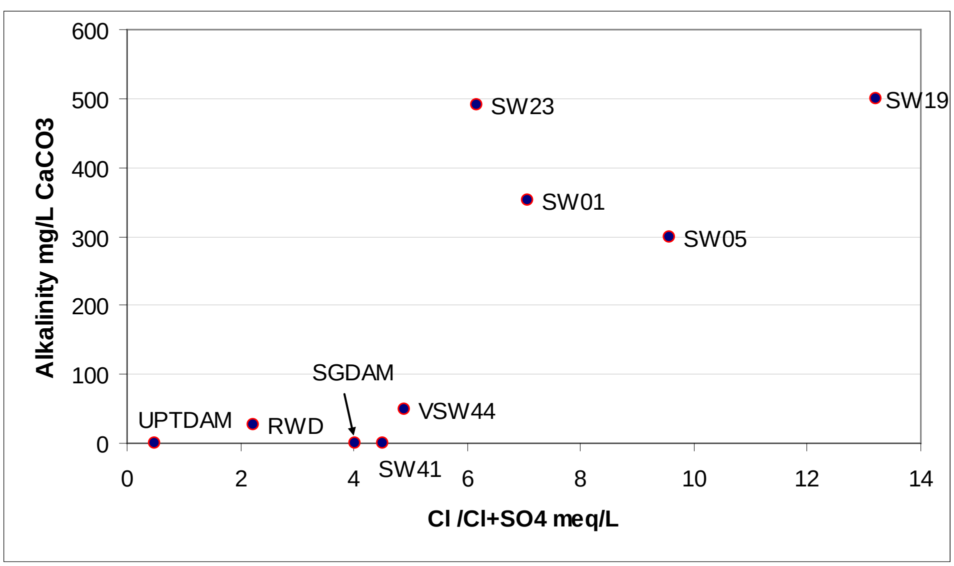

Figure 8 Bivariate plot of total alkalinity versus $Cl/Cl+SO_4$ for Mt Leyshon waters

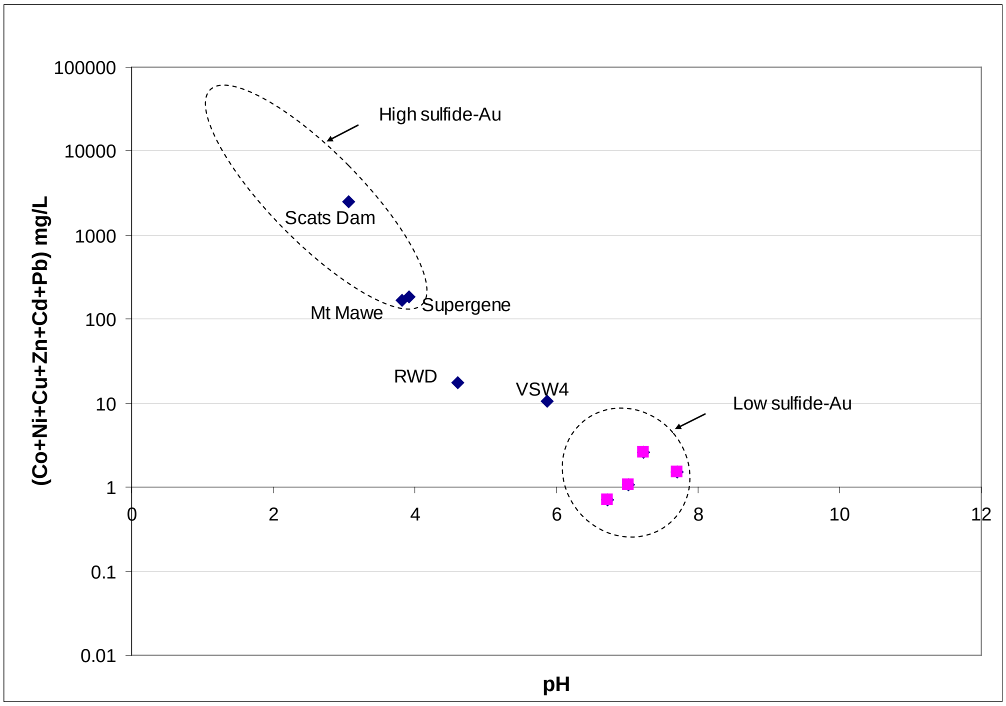

Figure 9 **Plot of metal concentrations versus pH showing two major grouping of waters at Mt Leyshon mine. The squares represent the tailings sumps. The original diagram is from Flicklin et al. (1992).**

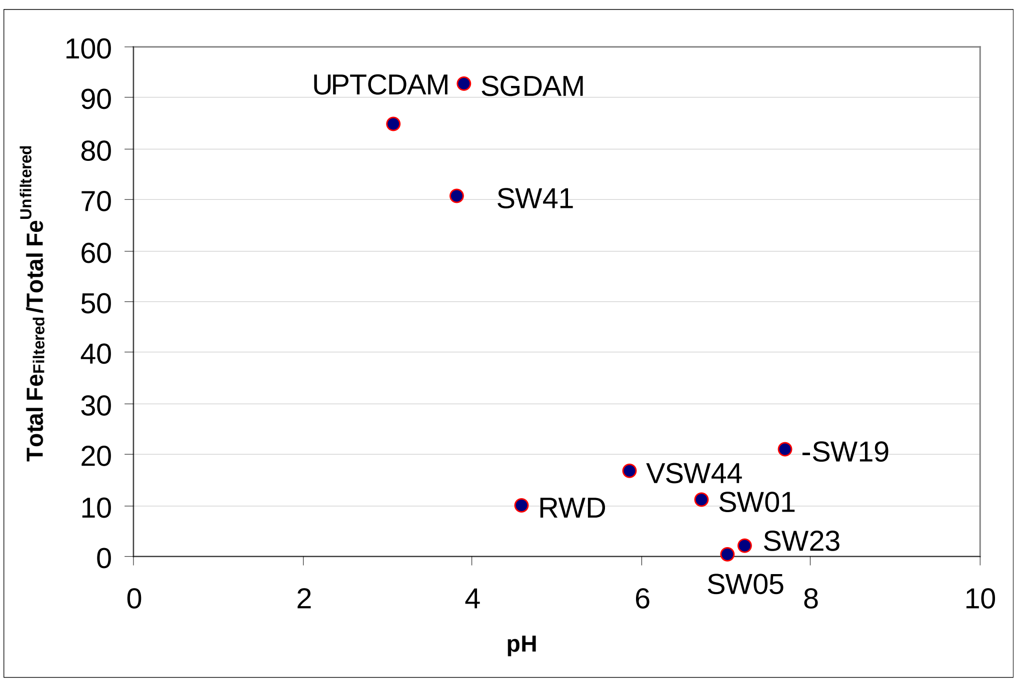

Figure 10 **The ratio of filtered to unfiltered iron concentrations plotted against pH. Most samples have less than 20% dissolved iron concentrations. Samples from the Scats Dam, Supergene Dam and Eastern Waste Rock Sump are exceptionally enriched in iron**

their milliequivalent values of chloride and sulfate shows that tailings sumps are characteristically more alkaline and have higher proportions of chloride (Figure 8).

Using the "Flicklin Diagram", which plots the variation of divalent metal cations with pH and ore deposit types (Flicklin et al., 1992), it is possible to differentiate between the tailings sumps waters with those of scats, supergene dam and waste rocks (Figure 9). Raw water dam and VSW44, which most probably had influence from the tailings, plot in an intermediate position. It is interesting to note that all samples plot within the Au-sulfide deposits with the tailings sumps at the low sulfide end.

Another way of showing an apparent chemical difference between mine waters at Mt Leyshon is by plotting the variations of iron concentrations with pH (Figure 10). The scats, supergene and waste rock waters have much higher concentrations of dissolved iron. This chemical property can obviously change by aeration, dilution and mixing with other waters.

In summary, based on the elemental concentrations, there are distinctive differences between samples collected at different locations. These differences are the result of one or a combination of (1) the geochemistry of the source materials, (2) the physical properties (hydraulic conductivity, permeability, texture) of those materials, (3) the efficiency of covers in impeding infiltration, hence less chance of interaction of tailings with waters, and (4) the influences from sources in natural soils (e.g. Na, Cl, Sr, As, Mo).

6 COVER SYSTEMS AND INFILTRATION

Covering potentially reactive waste material with non-reactive material is a technically and economically viable possibility to achieve the purpose of minimisation of contact of the waste material with water. Hence, the purpose of the cover is to reduce water flow into the waste material to a minimum. This is usually achieved by highly compacting benign material, which serves as a hydraulic barrier. The smaller the amount of water draining into the waste rock, the smaller is the chance of reaction of water with the waste rock and the occurrence of seepage.

Studies prior to the construction determined hydraulic conductivities for the growth layer of 5.3×10^{-6} m/s and for the compacted heap leach layer of 1.7×10^{-6} m/s. A scatter of values was mentioned and related to different intensities of compaction. It was assumed that a hydraulic conductivity of 1.0×10^{-7} m/s should be realised at 100 % standard compaction in the heap leach (EGI, 1999).

The accurate calculation of the water balance and valid evaluation of the functioning of the cover as a whole therefore, requires increased knowledge of the hydraulic properties (hydraulic conductivity/sorptivity) of the materials, mainly the layer with the lowest hydraulic conductivity, i.e. the highly compacted barrier. This basic information is also essential for any further modelling studies of the water balance.

In-situ Infiltration tests provide a very significant method to assess the properties and quality of a hydraulic barrier, which can also be used to derive the saturated hydraulic conductivity. In addition, hydraulic conductivity is a sensitive input parameter necessary for any water balance modelling.

The objectives for the infiltration tests were to determine the spatial distribution of infiltration rate/hydraulic conductivity of the covers of tailings and waste rock; to evaluate the functionality and homogeneity of the constructed covers; and to use this information to also allow an estimation of surface runoff following rainfall events.

As a general material characterisation, the topsoil can be characterised as brown to red-brown earth of sandy-loamy texture with varying contents of clay. The cover material consisted, in some places, of waste rock with larger rocks and visible signs of sulfide-oxidation, other sections of the cover consisted of compacted heap leach material.

The results show, that the hydraulic conductivity of the topsoil ranges between 3.6×10^{-5} and 6×10^{-6} m/s, which is very typical for natural soils. The partly high hydraulic conductivities can be attributed to the sandy texture and partly to the fact that over time the topsoil layer developed a pronounced secondary pore system, i.e. continuous macropores with high potential flow rates.

The measured hydraulic conductivities of the cover can be distinguished between the cover consisting of waste rock (cover-WR) and the cover consisting of heap leach (cover-HL). The hydraulic conductivity of cover-WR is in average higher than cover-HL. Moreover, for one location the permeability is orders of magnitude higher due to very rocky material, which has been used as cover. Heap leach material, which has been compacted on the tailings, can reach quite low values (as low as $5.3 \cdot 10^{-7}$ m/s). However, these values are still substantially higher than the assumed values used for modeling and prediction of water flow through the cover ($1 \cdot 10^{-7}$ m/s). The importance of compaction of the heap leach material is revealed when comparing the results of the highly compacted tailings cover with the cover on a slope. The hydraulic conductivity for the cover-HL is in comparison the highest and plant root density is also high, indicating a relatively loose state of compaction due to topographical reasons.

There is a tendency for a semi-logarithmic relationship between bulk density and hydraulic conductivity for the cover material. The topsoil shows no relationship to packing density due to its heterogeneity caused by soil structure formation processes overriding texturally related properties.

The results clearly show the importance of field tests at in-situ conditions. The topsoil or growth layer has higher hydraulic conductivities in 5 of 8 cases than initially determined at test plots, but is probably in the to be expected range of hydraulic conductivities. The variability may partly be attributed to the soil structure development over time and textural heterogeneities.

The heap leach shows higher conductivities then proposed and predicted ($6.5 \cdot 10^{-6}$, $8.3 \cdot 10^{-7}$, $3.2 \cdot 10^{-6}$, $5.3 \cdot 10^{-7}$, $1.5 \cdot 10^{-5}$ m/s). Although test plots showed hydraulic conductivities around $5.3 \cdot 10^{-6}$, it was concluded that improved practice in constructing the cover, the hydraulic conductivities could be reduced to $1 \cdot 10^{-7}$ m/s. This objective has not been reached satisfactorily. Reasons for it may be found in deficiencies in the quality control during construction. Often emphasis is put on test trials in regard to choice of material and procedure of installation/construction, while during construction of large areas other constraints may overcome initial concepts.

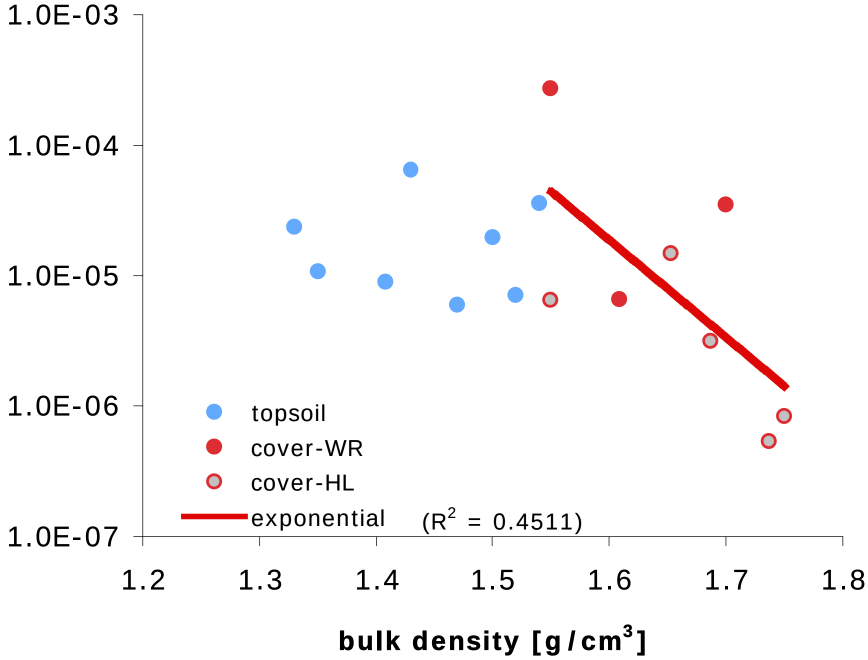

Figure 11 Bulk density and hydraulic conductivity for topsoil, cover-WR and cover-HL

7 SUMMARY AND CONCLUSIONS

This study confirmed the linkages between the geochemistry of mine wastes and water quality at Mt Leyshon mine. Scats and the heap leach stockpiles are active oxidation zones with the highest rates of acid generation and are potential sources of contamination. Charge balanced water analysis showed grouping of samples with similar chemistry from certain locations on the minesite: The waters draining from scats, supergene materials and waste rocks have distinctly lower pH and higher concentrations of dissolved iron, sulfate, heavy metals, Mg, Mn, U, Se and As, whereas the tailings sumps are more alkaline, contain less sulfate and heavy metals, and are enriched in Na and Cl. Surface waters are more acidic, however, the concentrations of sulfate and metals are not always related to the pH of waters. The functional relationships between conductivity, sulfate and metals established here can be used as an indirect measure of the quality of receiving waters.

The long-term mine discharges and their environmental impacts will depend on the overflows and seepages from the containment dams and the open pit. It also depends on the interaction of the mining wastes with run off and infiltrating waters, hence the stability and the performance of the vegetative cover on tailings storage facilities and waste rock dumps. Since there are no records of quantitative measurements of water flow (e.g. v-notch weirs) understanding of the spatial infiltration characteristic helps to identify areas which have to be re-assessed in regard to their purpose to minimise infiltration. In addition they provide data (including their statistical scatter), which support a more accurate modeling of the water balance. The results from this study serve as a basis for future planning strategies regarding construction and monitoring of subsequent waste storage facilities requiring encapsulation to prevent the production and potential seepage of poor quality water.

This study showed that when a mine is closed there is a need for revisiting the rehabilitation strategies and the monitoring systems based on the post-closure landscape which may also involve collection of new data. For example, there were a few elements that have been overlooked in pre-closure monitoring. Newmont Australia is currently reviewing water management options while scoping further groundwater studies. Given the complexity of the geological structures and lithological boundaries, questions remain open on the characteristics of aquifers and connectivity of groundwater flow paths.

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Appendix 1: The hydrogeochemical domains and contributing sub-catchments

Domain 1: *north-western domain*	Run-off from the area between Scats Stockpile and NWWD, western part of the ONTD, and western slopes of the NNTD
Domain 2: *north-eastern domain*	Run-off from the PAF and NAF oxide stockpile footprints, flat top area of NNTD, north-eastern slopes of ONTD and eastern slopes of NNTD
Domain 3: *south-eastern domain*	Run-off from Roche Hill, SWRD, flat top area and western slopes of EWRD, and eastern part of STD
Domain 4: *south-western domain*	Run-off from Heap Leach area, Supergene area, plant area, and the western sections of the STD
Domain 5: *central domain*	Open pit and partial run-off from EWRD and NWWD