LISHEEN MINE

PRELIMINARY HYDROGEOLOGICAL STUDY OF THE TAILINGS MANAGEMENT FACILITY UNDER CLOSURE CONDITIONS

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# REPORT REVIEW SHEET

**PRELIMINARY HYDROGEOLOGICAL STUDY OF THE TAILINGS MANAGEMENT FACILITY UNDER CLOSURE CONDITIONS**

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1 BACKGROUND

1.1 Site layout

The Lisheen mine is located some 12 km to the north east of the town of Thurles, and some 4 km to the south west of Templetohy, in Co. Tipperary. The mine exploits a "Mississippi valley" type ore deposit hosted in Carboniferous Waulsortian limestone. Development of the mine started in 1997 with the construction of the main decline and main site facilities. The mine has been in production since 1999, producing an average of about 165,000 tonnes per year of zinc and 20,000 tonnes of lead.

The ore is mined from four principal areas:

- Main Zone; which forms the largest mining area, and was the first to be opened up. It lies at the base of the main decline.
- Derryville Zone; which has also been mined from the outset via a cross cut from the main decline.
- Main Zone North, which has been mined since 2003, and which forms the only area where the footprint area is currently being expanded.
- Bog Zone; which has been mined since 2007, and consists of three ore pods (Bog Zone West, Central and East).

Ore extracted from the underground is sent to an underground crusher facility. From there, crushed ore is sent by overhead conveyor up the main decline to the processing plant. Processed mineral is transported by road from site in the form of a concentrate. Tailings from the ore extraction process is sent to the Tailings Management Facility (TMF) located in the southeast part of the site. In January 2008 a new tailings discharge system using conventional spigots was implemented and in May 2008 construction of a 'Demonstration Cell' capping system commenced as the first phase of the TMF reclamation programme.

The site layout is shown in Figure 1.1. Other main site facilities include an ore stockpile area, a paste tailings plant, two water treatment plants, several dewatering storage ponds, other infrastructure for mine water management, maintenance areas and the administration/office building.

A wind farm is currently being constructed at the site. The unit will be capable of generating about 36 megawatts of power by means of 18 turbines. The power will be supplied to the national grid. The presence of the wind farm may open up other development opportunities to enhance the local area in the long term, and to provide for sustainable mine reclamation and closure.
1.2 Purpose of this report

Water Management Consultants (WMC) and O’Neill Groundwater Engineering (OGE) have been working jointly on the hydrogeology studies at the Lisheen mine since 1992. During the course of its operations, the mine has been diligent in collecting high quality monitoring data, under the guidance of WMC and OGE. A period of operational monitoring record spanning more than 12 years is now available.

The monitoring record provides an excellent source of empirical groundwater flow and water chemistry data with which to guide the closure and reclamation plan. Predictions that have been made for mine operations using the monitoring data set have generally proven to be accurate, both in terms of predicting future rates of groundwater inflow to the mine and water chemistry. Over the years, a very good understanding of the district-scale groundwater system has been developed.

This hydrogeological study is divided into 2 sections, the first is focused on closure of the TMF as presented in this document and the second addresses closure of the underground mine workings, presented in a separate report.

This current document uses the available hydrogeological data set to provide a preliminary assessment of:

- The seepage rate and seepage chemistry of the reclaimed TMF. Results to date for the TMF demonstration cell are very encouraging. The current modeling predictions assume that the cap design used for the demonstration cell will ultimately be extended over the entire TMF footprint area.

- An assessment of short term and long term hydrogeological conditions in the down-gradient groundwater system, including any down-gradient receptors.

- An assessment of the potential risks for closure, and development of appropriate mitigation plans to reduce long term risks.

1.3 Dewatering history

1.3.1 Initial goals

As was predicted from the outset, the mine has required continuous dewatering to help maintain safe working conditions underground. The original dewatering concept was to install surface dewatering wells to lower groundwater heads in the Waulsortian limestones, prior to the advancing decline reaching the level of the orebodies. It was planned that, once a reasonable amount of underground void space had been opened up, management of water from the underground workings would become progressively more important, and would gradually supersede the surface wells. This proved to be the case.

The early goal for dewatering was to drive the decline in the low permeability argillaceous bioclastic limestone (ABL) unit in the footwall (to the south) of the Killoran fault, and for the decline to enter the Main Zone and Derryville Zone orebodies (both hosted in fractured permeable Waulsortian rocks) in the hangingwall, at the mining horizon. It was planned that, by the time the decline was driven to the level of the ore horizon, groundwater heads in the Waulsortian would be lowered as a result of pumping from the surface wells.
The pre-mining groundwater table at Lisheen was generally between 1 and 3 m below ground surface, depending on the localized topography in the area. Therefore, the earliest underground workings were under about 200 m of groundwater head. Because of this, it would not have been feasible to undertake underground mining without first lowering the groundwater head by dewatering from the surface using wells.

1.3.2  F2/F3

Water was unexpectedly encountered in the advancing decline in 1997, when major north northwest-east southeast trending regional structural geological features (F1, then F2 and F3) were penetrated at a depth of about 120-140 m (vertically) below the surface. The regional structures have caused the Lisduff oolite formation, which underlies the ABL, to become offset upwards. Fracturing associated with the structures created a connection between the oolite rocks and the decline.

Thus, the short term management strategy had to be modified, and a pumping station had to be installed in the decline, at about 140 m depth from surface, immediately below the F2/F3 feature. The pumping station was used to intercept the water at a shallow elevation, prior to it flowing downwards to the workings, and to pump it directly to the surface as clean, non-contact water.

In the first six months after it was encountered, the inflows from F2/F3 were about 33 megalitres per day (MLD). Since then, the F2/F3 inflow rate has progressively reduced with time and is now about 22-24 MLD. It has a seasonal variation in flow of about 2-4 MLD, depending on the amount of rainfall and recharge to the regional groundwater system.

The F2/F3 groundwater inflows are derived from the Lisduff oolite, whereas all other inflows to the mine are from the Waulsortian rocks. As a result, the F2/F3 system behaves differently to the rest of the mine water management system, and it can be treated separately from both a mine operations and mine closure perspective.

1.3.3  Overall inflow rate

For the conceptual model, groundwater inflows to the mine can be considered to be derived from: 1) storage removal in the limestone units, and 2) recharge as a result of rainfall and infiltration over the area of drawdown created by the dewatering system. The groundwater predictions developed in 1998 indicated that inflows would rise to 100-140 MLD in the early years, and would gradually reduce to between 54 and 72 MLD once the full mine footprint area had become opened up.

As dewatering has progressed, it has become clear that the main structural geology influence on the overall hydrogeological system is the north northwest-east southeast trending regional faults. Following the early identification of F1, F2 and F3, about seven other major structures are now identified in the Lisheen area. The “zone” of drawdown surrounding the mine is often elongated in a north northwest-east southeast direction. Site-wide, structures of this orientation form the main influence of the groundwater system.

In the early years, storage removal was the main component of the groundwater inflows. However, the actual required amount of storage removal could not be achieved quickly enough, and the early workings were sometimes under residual groundwater heads of 50 m or more. Because of this, the peak dewatering rate was lower than initially modeled. The total inflows to the mine (including F2/F3) reached a peak of 93 MLD in the spring of 2001.
The total mine dewatering rate versus time is shown in Figure 1.2. Since the initial Main Zone and Derryville Zone workings were opened up in 1998, the amount of required groundwater storage removal has progressively decreased, and regional groundwater recharge to the area of drawdown has gradually become the main source of the sustained inflows. Overall, groundwater inflows have progressively decreased with time, and reached a minimum of 57 MLD in October, 2004. It should be noted that this “low-end” value was achieved after two consecutive “dry” winters when recharge rates were low.

As can be seen in Figure 1.2, the dewatering inflows were stable between about 2002 and 2006. There was a gradual “tailing-off” of inflows, with a seasonal variation superimposed on the overall declining flow rates. By 2006, it was considered that the hydrogeological system was almost in steady state. Virtually all of the groundwater storage removal had taken place, and the dewatering rate was sustained by regional groundwater recharge over the area of drawdown. Water levels in the footprint area of the mine were drawn down close to the top of the workings. The residual groundwater head above most of the mine footprint area was less than 20 m.

1.3.4 District drawdown

Lisheen has prepared an extensive district-wide groundwater well inventory. Groundwater levels in regional wells are monitored by Lisheen staff every 6 months. The drawdown rate is very small (less than 1 m) in most of the outlying regional wells, and is within the magnitude of the normal seasonal variation for most of the regional wells that are monitored. Except in the area immediately surrounding the workings, there has been relatively little impact to the groundwater system. Figure 1.3 shows a plot of the current district-wide groundwater levels.

Monitoring results have shown that a downward hydraulic gradient has developed throughout the district. While the district-wide impacts to groundwater levels at the surface are small to none, the downward hydraulic gradient has created a “zone of capture” for recharge to the mine workings of about 85-90 km². In the original modeling work, the predicted recharge rate to the zone of capture was about 25% of mean annual rainfall, or about 0.7 MLD per square kilometre. The natural recharge rate to the Waulsortian limestone outside the influence of dewatering is about a third of this value.

1.3.5 Bog Zone dewatering

Development of the Bog Zone commenced in 2006 by driving an access ramp eastwards from the main area of mining. At that time, the available groundwater monitoring data for Bog Zone indicated that little drawdown had occurred in the area, primarily because Bog Zone is located perpendicular to the main strike direction of the west northwest-east southeast structures. Although they enhance groundwater flow along the direction of their strike, these structures tend to form hydrogeological barriers to groundwater flow perpendicular to their strike direction.

Therefore, it was clear that Bog Zone would require additional groundwater storage removal and would cause higher sustained inflows. Modeling was carried out and predicted that short term overall inflows during mining of Bog Zone would increase to 82-89 MLD. Once groundwater storage removal had taken place around Bog Zone, the overall groundwater inflows to the mine would reduce to a steady state value between 68 and 75 MLD.
Because the Bog Zone ore is closer to the surface (particularly the Bog Zone East pod), it has more potential to be influenced by short term rainfall cycles. Figure 1.2 shows that the original Bog Zone modeling predictions were reasonably correct. However, because mining and storage removal of Bog Zone occurred co-incidentally with the period of the wet 2007-2008 winters, the actual peak inflow rate reached a peak of 92 MLD, which was slightly higher than predicted.

Now that Bog Zone is substantially mined out, the overall mine groundwater inflow rate has reduced again. The current combined inflow rate to all sectors of the mine is about 76-78 MLD.

1.4 Current mining situation

Much of the ore has now been removed from the full footprint area of all four mining zones. Based on the current mine plan, the footprint area will not be further extended, except for a small area on the east side of Main Zone North.

Between now and the end of the mine life, ore will be extracted from intermediate zones. The plan is to generally carry out intermediate ore extraction first from the peripheral areas, then progressively work inwards to the centre of the mining area. This potentially provides the opportunity to exclude certain inflow zones that occur in peripheral areas by using bulkheads, and to reduce the overall groundwater inflow rate to the mine. An investigation is currently underway to examine this possibility.

It should be appreciated that, as for any active mining operations, the exact mine plan is determined by commodity prices and by on-going interactive monitoring of actual conditions that occur in the mine. Because of the general nature of mining operations, the mine plan between now and closure needs to be flexible. Current planning is for underground ore extraction to cease by 2013 or 2014. However, this may change as commodity prices, or underground conditions and operating costs, change.

In January 2008 the floating head tailings discharge system at the TMF was replaced with a more conventional spigot tailings discharge system to improve deposition of tailings within the facility and generate a more uniform surface for subsequent construction of the reclamation capping system. The first phase of the TMF reclamation programme was initiated in May 2008 with the construction of a ‘Demonstration Cell’ of the capping system.

A tailings paste plant has been operated at Lisheen since 2005. Paste-tailings is placed underground to fill void space. The paste is a cement-based material and acts to seal the walls and floors of the void space where it is placed. However, slight shrinkage of the paste occurs following its placement, and there are typically some small shrinkage voids that develop around the placed paste, principally at the roof of backfilled areas. Ultimately, based on current planning, it is expected that about 40% of the mine void space will be backfilled with paste-tailings.

Going forward, the total mine groundwater inflow rate is expected to remain between 68 and 75 MLD between now and the end of the mine life. However, this will depend on two factors. Firstly, whether any anomalously wet years or dry years occur and influence the recharge rate (which now accounts for nearly all of groundwater inflow). Secondly, whether the current studies allow any measures to be implemented whereby discrete inflow zones at the periphery of the workings can be eliminated or minimized, thereby reducing the overall mine inflow rate.
1.5 Design and operation of TMF

The tailings management facility (TMF) comprises a fully composite-lined impoundment, located on peat and covering a surface area of approximately 78 ha. In January 2008, a new system of tailings deposition was implemented via installation of embankment spigots, and construction of a ‘Demonstration Cell’ capping system commenced as part of the first phase of the programme of TMF rehabilitation. The cover will be progressively installed by expansion of the Demonstration cell.

The TMF is enclosed within a perimeter earth embankment founded on glacial till. The upstream face of the embankment is lined with linear low density polyethelyene (LLDPE) overlying a geosynthetic clay liner (GCL), while the basin area is lined with LLDPE. The underlying peat forms a secondary barrier, so the base of the TMF is also considered to have a composite liner.

The TMF is operated such that:

- Tailings are distributed evenly on the LLDPE in order to avoid differential settlement of the peat and slumping of the tails.
- The shear strength of the LLDPE is not exceeded.
- Water expelled from the underlying peat during consolidation is collected and managed.
- Gas derived from the peat is removed from underneath the liner.
- The tailings are stored in a sub-aqueous manner in order to minimise acid generation due to their oxidation.

Prior to the implementation of the spigot tailings deposition method, the TMF was developed in two stage lifts with respective storage volumes of 1.5 and 3.6 Mm$^3$. Under the perimeter embankment wall of the TMF, the peat layer has been removed and a layer of graded limestone rock fill and mine waste has been emplaced on the exposed glacial till. Finger drains were installed in the perimeter embankments in order to collect seepage water from consolidation of peat and to allow pore pressures within the peat to dissipate. The size of the TMF has been designed so that the annual rise in the tailings depth is limited to 1 m and provides control on the rate of consolidation of the underlying peat. The TMF is typically operated with a minimum depth of 1 m of standing water above the tailings to maintain complete submergence of the tailings during deposition, minimise oxidation and reduce potential for generation of acidic pore water. A freeboard of 1 m is maintained to allow for design flood events.
Figure 1.1 - Lisheen Mine site layout map

KEY:
- Underground mine workings
- Monitoring wells
- Town
- Bog zone
- Derryville Zone
- Main Zone
- Tailings Management Facility
- Underground workings

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Figure 1.2 - Dewatering inflows for Lisheen Mine

- Total clean water
- Total dirty water
- Total inflows

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Figure 1.3 - Map showing current district groundwater levels
2 HYDROGEOLOGY

2.1 Geology

2.1.1 General geological setting

The Lisheen district is underlain entirely by Lower Carboniferous limestones. The most dominant unit locally is the Waulsortian formation (the Waulsortian mud bank complex). Argillaceous Bioclastic Limestone (ABL) dominates the areas to the northwest and northeast of Lisheen. Sequences of Cross Patrick formation and Lisduff oolite are common to the south.

Virtually all groundwater movement within the limestone units in the Lisheen area occurs by fracture flow. The structural geology discussed in Section 2.1.5 below exerts a prominent control on the district and local-scale hydrogeology. Because of the high degree of structural control, the drawdown surrounding the mine is anisotropic and is not the same in each direction. Drawdown is locally elongated along the prominent north northwest-south southeast structures.

2.1.2 Superficial deposits

The alluvial cover is typically thin throughout the area of Lisheen. There are minor, non-connected areas of saturated alluvium along parts of both the Drish and the Rossestown rivers, but these have not played a significant part of the dewatering operation. To the east and southeast of Lisheen, extensive saturated peat deposits occur beneath the area of the Derryville Bog.

The greatest known depth of peat locally is about 14 m, to the north of the TMF area. The TMF footprint largely occurs on peat. The peat deposits are naturally saturated to within about a meter of ground surface (depending on local-scale topography). The eastern part of the Derryville Zone and all of the three Bog Zone pods occur beneath the peat deposits.

2.1.3 Waulsortian Formation

The Waulsortian formation hosts the ore in the Main Zone, Derryville Zone, Main Zone North and Bog Zone. Figure 2.1 shows that the formation is dominant at Lisheen, and outcrops throughout the local mine area. Regionally, this unit shows general fracturing and is somewhat cavernous in its upper 30-50 m. Most fracturing and groundwater flow occurs in the upper 30-50 m depth. Intensity of fracturing below 50 m and towards the top of the orebody at 150 to 160 m depth, is observed to decrease significantly. Locally, above the ore body, there is also a zone of increased fracturing and some cavity development immediately above the mining horizon, as illustrated in the schematic N-S cross section in Figure 2.2.
Except for the main decline, and the extreme southern area of Main Zone (to the south of the Killoran fault), all underground mine workings are located within the Waulsortian. All of the original surface dewatering wells at Lisheen derived their groundwater from the Waulsortian formation.

2.1.4 Argillaceous Bioclastic Limestone (ABL).

The ABL is a massive limestone and is generally unfractured. It does not typically yield any groundwater. It forms a flow barrier between the overlying Waulsortian and the underlying Lisduff oolite.

The main decline is driven through ABL rocks. In the area of the F2/F3 feature, described below in section 2.1.5, the contact between the ABL and the top of the underlying Lisduff oolite occurs within 5-12 m below the floor of the decline.

To the south of Lisheen, the top of the ABL dips to the south and occurs at a depth of over 300 m in the Colleeny area. The main outcrop area of the ABL is to the northwest of Lisheen, and also between Lisheen and Galmoy to the northeast.

The ABL forms an important hydrogeological unit in the context of closure since it occurs in the footwall of the Derryville and Killoran faults and is thought to form a low permeability barrier, reducing potential for groundwater flow at depth from the mine area to the south or southwest.

2.1.5 Lisduff Oolite.

The Lisduff oolite occurs stratigraphically below the ABL, as shown in Figure 2.2. Beneath the area of both the Main Zone and Derryville, it occurs at a depth of below 250 m. However, along the footwall (south) side of the Derryville and Killoran Faults, it occurs within about 70-100 m of the surface. Along much of the strike length of the faults, it is in direct hydraulic contact with the Waulsortian on the hangingwall (north) side. To the south of Lisheen, the Lisduff oolite dips to the south beneath the ABL.

Locally, little is known about the hydrogeology of the oolite. It is evident from the available data that it provides the main conduit for the inflows to F2/3 in the decline. It is known to be fractured and to yield groundwater in the vicinity of the main geological structures. However, away from the main structures, the degree of fracturing and its potential to transmit groundwater in the area south of Lisheen is uncertain. In the extreme south of Main Zone, mining across the Killoran fault and in the oolite to the south of the fault has encountered no major inflow zones.

2.1.6 Geological structures

In general, the regional geology strikes in a northeast-southwest direction along the axis of the Rathdowney Trend. Figure 2.1 shows the main geological structures in the Lisheen area. There are three prominent structural orientations, as follows:

- A north northwest-south southeast structural set forms the dominant regional and local structural trend, and can be clearly seen in a series of faults south of the mine and to the northwest of the Templettouhy area. It is also clearly evident from regional aeromagnetics data. The F2/F3 feature, together with most of the main faulting in the vicinity of the orebodies, is aligned along this trend. A total of at least 10 prominent structures of this orientation have been recognized in the Lisheen area.
• An east northeast-west southwest structural set also occurs within the district. Prominent faults in this direction are evident in the immediate mine area (the Derryville and Killoran faults) and also in the area to the west of Lisheen. Several of the structures of this orientation appear to be stair-stepped.

• A subsidiary east-west structural set also occurs in the Lisheen area, and regionally. Locally, this is somewhat less defined, but structures of this orientation are apparent to the west and south west of the Lisheen area.

2.2 Pre-mining groundwater conditions

2.2.1 Groundwater levels

Figure 2.3 shows a pre-mining water table map of the Lisheen area. Groundwater level elevations in the mine area were generally within the range 119-122 mAOD. The groundwater table occurred within about 1-3 m of the ground surface, depending on local topographical variations. In many areas, the groundwater table occurred within the thin veneer of glacial soils that overlies the limestone units.

2.2.2 Groundwater recharge

All natural groundwater recharge to the limestone units in the Lisheen area occurs due to infiltration of incident rainfall. Recharge typically occurs during the late winter and early spring when the ground is saturated and when evapotranspiration rates are low. Baseline studies undertaken for the mine suggested that the mean annual recharge rate was between 55 and 70 mm per year, which is about 8-9% of the mean annual precipitation.

However, because the groundwater surface occurs within the glacial soils close to the surface, much of the groundwater recharge that does occur during the late winter months is lost to evapotranspiration in the summer. Thus, much of the groundwater flux is very localised and, under natural conditions, most groundwater does not flow laterally for any significant distance.

The pre-mining water table map indicates that a groundwater divide occurred beneath the Derryville bog immediately to the east and northeast of Lisheen. In addition, a groundwater divide to the north occurred some 2.7 km to the north of the Main Zone North orebody. The natural pre-mining upstream groundwater recharge area to Lisheen was of the order of about 5-7 km².

2.2.3 Seasonal water table fluctuation

The natural seasonal water table fluctuation is reflected in the seasonal hydrographs of local shallow wells. Most regional wells typically show a difference in summer and winter water levels of between 0.5 and 2 m. In the winter, the water table rises close to the surface and stays within the capillary zone, where it is removed by evapotranspiration the following summer.

2.2.4 Lateral flow and groundwater discharge

Lateral groundwater gradients and flow rates are very low. Figure 2.3 shows that the overall district-scale groundwater gradient in the Lisheen area was to the south and southwest, towards the River Drish and regionally towards the River Suir. The pre-mining groundwater head difference between the mine area and the River Drish to the south is only about 3 m, which is only marginally more than the seasonal water level fluctuation.
Thus, the natural rate of groundwater flux and transport away from the mine area to the south and southwest was very low. The groundwater model developed prior to mining at Lisheen indicated the overall flux from the mine footprint area to the south and southwest was about 1.7 MLD. Typical natural groundwater velocities were between 90 and 125 m per year.

A minor amount of groundwater discharge also occurred locally to the Rossestown river and also to some of the local drainage ditches. The pre-mining discharge to the Rossestown was indicated to be about 0.35 MLD, all occurring in the winter months when groundwater levels were higher. In the area immediately to the north and northwest of Lisheen, the Rossestown received effectively no groundwater discharge from the limestone units, and summer flows in the river were sustained by discharge from the peat in the upper part of its drainage area.

2.3 Groundwater in the TMF area

Groundwater levels around the TMF are recorded in piezometers within the embankment and in monitoring wells adjacent to the embankment. Figure 2.4 shows monitoring well locations and groundwater levels around the TMF. Water level hydrographs are shown in Figures 2.5 to 2.11, grouped by their positions around the TMF.

Groundwater data has been collected from the end of September 1999, at approximately monthly intervals for the monitoring wells and weekly for the embankment piezometers. The monitoring wells are completed at different depths in the peat and underlying Waulsortian bedrock. Table shows the known depths of many of the monitoring wells around the TMF. Several deeper monitoring wells have been constructed to measure heads in the bedrock. MW04 (31 m deep), MW37 (30 m deep) and MW39 (23 m deep) are measuring bedrock groundwater levels. There are also several medium depth monitoring wells (MW29, MW38) that are completed in bedrock.

2.3.1 North sector (MW01-04 & P1, Figure 2.5)

Groundwater levels have fallen by up to 4 m in the northern area from between approximately 124-126 mAOD (end-Sep 1999) to 120–122 mAOD (Nov-Dec 2008). The long term and seasonal trends are closely matched in all the monitoring wells and the piezometer cluster (P1) indicating hydraulic continuity between the TMF embankment and adjacent groundwater. The groundwater levels in shallow monitoring wells (MW01-03) of 6 m depth show good correlation with the deeper well MW04 (31 m depth). This indicates that there is hydraulic continuity between shallower and deeper groundwater horizons and significant vertical head gradients are absent above about 30 m depth. All of the monitoring wells in this sector have similar historical and current water levels. To date, the groundwater levels show no significant influence of the increase in pumping from Bog Zone.

2.3.2 Northeast sector (MW05-08 & P2, Figure 2.6)

In the northeast of the TMF, groundwater levels fell between 2 to 3m between end-September 1999 and December 2008. The seasonal range of groundwater levels is approximately 1 m, slightly less than in monitoring wells further north. Groundwater levels in MW05 and MW08 show a similar decline as those in North sector, ranging from 123 to 125 mAOD in 1999 to 120 to 122 mAOD by end of 2008. Groundwater levels in the embankment piezometer (P2) are in hydraulic continuity with the surrounding groundwater, showing similar levels and seasonal variations. The monitoring wells and piezometer (P2) in this sector show very similar historical and current groundwater levels.
Table 2.1  TMF monitoring well elevations and depths

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<td>10</td>
</tr>
<tr>
<td>MW33</td>
<td>128.293</td>
<td>6</td>
</tr>
</tbody>
</table>

2.3.3  East sector (MW09-13 & P3, Figure 2.7)

MW09-13 and P3 are positioned along the south-east embankment of the TMF. Seasonal groundwater levels here show a decline of up to 5m over the period monitored (122-126 mAOD in 1999 to 118-121 mAOD in 2008), much of which occurred between September 1999 and September 2003. The hydrograph for MW09 shows a groundwater level decline of just 2.75 m, less than the surrounding wells. Much of the decline in groundwater levels occurs before September 2003, with a reduction in the rate of groundwater level decline since then. The piezometers of cluster P3 become dry from October 2003.

The response in the east sector is different to that in the north and northeast sectors, where monitoring wells show a relatively steady groundwater decline throughout the monitoring period. Seasonal fluctuations in the monitoring wells and piezometer (P3A) are more pronounced in the east sector than in those to the north, showing a range of around 3 m.
2.3.4 South sector A (MW14-21 & P4, Figure 2.8)

Groundwater levels in the southern corner of the TMF show a similar pattern to those of the eastern sector, with the decline in groundwater levels stabilising from September 2003 onwards. Groundwater levels declined by 5.5 m prior to September 2003. The influence of more recent dewatering from the Bog Zone is not evident in the water level data, however a further decline in groundwater levels may be picked up in monitoring towards the end of the year. Seasonal fluctuations of approximately 5 m are evident, which are greater than the seasonal variation registered in the east and northeast sectors. Again, piezometers in the embankment become dry from September 2003.

2.3.5 South sector B (M22-28 & P5, Figure 2.9)

Monitoring wells MW22-28 show a similar seasonal fluctuation of groundwater levels, ranging from approximately 116 mAOD at the end of the summer months to 124 mAOD at the end of the winter months. However, they present a slightly different trend to levels in other monitoring wells, showing only a marginal longer term decline over the monitoring period. Water levels fell by around 1m in this area over the entire monitoring period from March 2000 to December 2008. Groundwater levels in this sector are comparable to those of south sector A in recent monitoring, however water levels here at the beginning of the monitoring period were 2-3 m lower.

2.3.6 Southwest sector (MW29-34, P6 & P7, Figure 2.10)

Groundwater levels in the southwest sector range between 117 and 131 mAOD between 2000 and 2001 and have decreased by between 2 and 8 m over the full monitoring period, ranging from 105 to 124 mAOD by 2008. Generally, monitoring wells located toward the west corner of the TMF are higher, and show less groundwater level decline over the monitoring period than those further south. The seasonal variations are also much more subdued in monitoring holes further west. For MW30, seasonal water levels fluctuate in the summer of 2001 by around 6.6 m, while a seasonal fluctuation of 3.8 m is observed in MW34. All monitoring wells in this sector demonstrate a significant seasonal fluctuation between the winter of 2006 and summer of 2007.

Groundwater levels are significantly higher in monitoring wells towards the west of the TMF, with water levels 15 m higher at MW34 than at MW30 in early 2008. The relative difference in water levels appears to have increased over the monitoring period as dewatering of the workings continues to affect groundwater in the southwest of the TMF to a greater degree. Water levels measured in piezometers P6C and P7A and P7B are 6-9 m higher than those observed in adjacent monitoring wells MW29, MW31 and MW32 indicating presence of a perched water table in this part of the TMF.

2.3.7 West sector (MW35-42, P8 & P9, Figure 2.11)

For December 2008, groundwater levels in the west sector range from 123.3 mAOD at MW35 in the western corner of the TMF to 125.3 mAOD at MW42 in the north. Water levels in the shallow monitoring wells (MW35 and MW36) have decreased by 2 to 4 m and by up to 12 m for deeper monitoring wells (MW37), between September 1999 and December 2008.

Embankment piezometer P9 shows water levels following the trends of the adjacent MW41, again indicating good hydraulic connection between the embankment and adjacent groundwater. Seasonal water level variations are on the scale of 6 m. Water levels in MW36 (depth of 8 m) and MW37 (depth of 30 m) are closely matched in monitoring from 1999 through to early 2007. However the significant decline in water levels in MW37 between January and November 2007 (123.4 to 111.6mAOD) is not
reflected in shallower groundwater levels in MW35 and MW42, indicating localised perching of shallower groundwater and potential vertical head gradients between the shallower and deeper groundwater horizons.

2.3.8 Overall discussion

Monitoring wells and piezometers in the TMF and surrounding area show an induced hydraulic gradient towards the southeast in the direction of the main dewatering activities.

Groundwater levels in the TMF monitoring wells generally show around 2-6 m of drawdown in response to pumping from the workings. Groundwater levels are lowest in the southwest of the TMF, with the lowest elevation recorded as 102.4 mAOD in MW30. Groundwater levels generally show greater seasonal stability and slightly higher levels towards the northern corner of the TMF. Whilst generally conforming to a trend of declining groundwater levels towards the southwest, monitoring shows that the TMF has localised variations, such as the area of high water levels in the west sector of the TMF (MW35-36).

The Waulsortian limestone underlying the TMF is fracture controlled, with groundwater showing a degree of compartmentalisation. The variation in water levels locally around the TMF is the result of the local-scale structural influences. The groundwater flow direction remains towards the southwest in-line with the regional hydraulic gradient.

Comparison of groundwater levels in shallow and deep monitoring wells generally shows little evidence of strong vertical gradients in the vicinity of the TMF, only in the case of shallow (MW35 and MW42) and deeper (MW37) is there evidence of localised perching of shallow groundwater and development of vertical gradient as a consequence of dewatering. Good hydraulic continuity between the shallower and deeper bedrock groundwater in the north sector is reflected in similar water levels for MW01-03 (at 6 m depth) and MW04 (at 30 m depth).

Groundwater levels fluctuate seasonally due to the increase in groundwater recharge during the late winter months. The magnitude of seasonal variations in groundwater levels increases towards the southwest where fluctuations of up to 9 m were recorded in MW30 between winter of 2006 and summer of 2007. In the northern sector, seasonal variability is approximately 1m.

The increase in pumping rate from Bog Zone East is not yet evident in groundwater monitoring of the TMF. The NW trending fault system and compartmentalisation has largely disconnected the TMF area from the main dewatering zones to the southwest.

Shallow groundwater flowing from the TMF will move towards the southwest in the direction of the lowest groundwater levels. Any potential seepage from the southwest of the TMF will be transported by groundwater in this direction. Any potential seepage from the north and northeast of the TMF will move under the TMF footprint area and will not flow away from the TMF.

Groundwater level elevations in the TMF perimeter observation wells range from approximately 115 mAOD in the central section of the southwest facing embankment, to approximately 126 mAOD on the western tip of the TMF, (see Figure 2.4). Where boreholes of different depths were located in close proximity to each other, water levels have been examined to ascertain whether there were any strong vertical head gradients in the area. The current data do not indicate any significant vertical head gradient, at least in the shallow horizons.
Groundwater elevations are generally lowest around the southwest area of the TMF and along the southwest facing embankment, where levels range from around 115 to 118.5 mAOD. Water levels are also low (around 118 mAOD) at MW39 on the mid-point of the northwest facing embankment. The highest surveyed groundwater elevations are observed in the west and northwest sector of the TMF. Groundwater elevations along the west and northwest facing embankment range 120-126 mAOD.

The response to dewatering around the perimeter of the TMF can be summarized as follows:

- In the northeast sector (MW1-8), groundwater levels have dropped by 2-3 m as a result of mine dewatering; and these wells typically show a seasonal fluctuation of 1-3 m.
- In the southeast sector (MW9-19), groundwater levels have dropped by 3-5 m as a result of mine dewatering; and these wells typically show a seasonal fluctuation of 3-5 m.
- In the southwest sector (MW20-34), groundwater levels have dropped by 2-8 m as a result of mine dewatering; and these wells typically show a seasonal fluctuation of 5-8 m.
- In the northwest sector (MW35-42), groundwater levels have dropped 2-12 m as a result of mine dewatering; and these wells typically show a seasonal fluctuation of 2-6 m.

A “stair-step” in groundwater levels is observed between MW13 and MW14 on the southeast side of the TMF, and MW39 and MW41 on the northwest side of the TMF. As discussed above, this may indicate the presence of a northwest trending structure beneath the footprint area of the TMF.

Overall, the hydraulic gradient beneath the TMF is currently from the north to the south southwest. Actual groundwater flow under this gradient is strongly controlled by the local geological structure. All groundwater water occurring beneath the footprint area of the TMF ultimately flows towards the mine dewatering system. However, because of the presence of perched water, there appears to have been little influence of the recent Bog Zone dewatering on the shallow groundwater observation wells around the TMF.

Groundwater levels in the peat deposits have largely been unaffected by the mine dewatering operation, with no notable drawdown influence occurring. However, it is thought that leakage occurs from the bottom of the peat deposits into the underlying Waulsortian, and that this has potentially accelerated during the period of mine dewatering operations. However, the near-surface groundwater level in the peat has been sustained by on-going recharge, and it is likely that a pronounced downward hydraulic gradient occurs through the thicker areas of peat.

2.4 TMF water chemistry

Water samples are taken for analysis on a monthly basis from the TMF, perimeter drain, piezometers and monitoring wells. Sulphate in the TMF is an important indicator of potential seepage from the TMF into the surrounding groundwater system. Sulphate concentration data are available from September 1999 to present and are discussed below.
2.4.1 Sulphate concentrations in the TMF pool

Water samples are collected from the TMF pool in a composite weekly sample. Recent sulphate concentrations of the TMF water are very stable with concentration range of 2,200 - 2,400 mg/l. Some seasonal variation occurs in sulphate concentrations due to dilution from precipitation and evapo-concentration in the TMF pool.

2.4.2 Sulphate concentrations in the perimeter drain

The perimeter drain was excavated to drain water originating from the compaction of peat beneath the TMF. Outflow from finger drains constructed in the embankment is also directed into the perimeter drain. Ponding of water has previously been noted in the drain, the locations of which are highlighted in Figure 2.4. Sampling of the water has been undertaken at 7 locations around the TMF. The sampling locations are shown in Figure 2.4. Locations PD1, 3, 5 & 7 have incomplete sulphate records. Sulphate concentrations in the perimeter drain are highly variable with concentrations of sulphate ranging from less than 10 mg/l to more than 2,500 mg/l in the period monitored (Figure 2.12). The data show a seasonal variability with the lowest sulphate concentrations (i.e. <100 mg/l) reported during the wetter winter months.

Similarities exist between sulphate concentrations in the perimeter drain and sulphate in the embankment piezometers, although the trends are often not directly comparable. Sulphate concentrations in the perimeter drain sampling locations were very low up to November 2000, with concentrations mostly below 50 mg/l. Sulphate at PD2 rises steadily and reached a maximum of 1,290 mg/l in July 2001, a second peak is recorded at 1,201 mg/l in October 2003, after which sulphate in the northern part of the TMF drain declines steadily to below 150 mg/l by December 2006. In the southern TMF area, monitoring at PD4 shows a similar increase in sulphate concentration to 673 mg/l for June 2001. Sulphate concentration at PD4 then remained low (<200 mg/l) before increasing to 1,770 mg/l in October 2003. Sulphate is reported for PD4 at a concentration of 7,145 mg/l for March 2004. This value has been omitted from the plot as it is improbable, given the much lower range of sulphate concentrations in the TMF and surrounding groundwater.

In more recent data, PD1, 2, 4, 5 & 8 show an increase in sulphate concentration between January and June 2007, with a peak sulphate concentration for the April 2007 sample of between approx 3,500-4,500 mg/l. Concentrations of this magnitude are not evident in the monitoring wells but do correlate with a concentration increase in piezometer P2 in the northeast sector and P9 in the west sector. Sulphate concentrations return to lower levels by July 2007 and for PD4 are below 250 mg/l for the 19/7/2007 sample.

2.4.3 Sulphate concentrations in monitoring wells and piezometers

Plots of sulphate concentrations are summarised in Table 2. for 2007 and 2008. A sulphate map of the TMF is shown as Figure 2.13. Current sulphate concentrations are below 250 mg/l for most of the TMF perimeter, but with a few elevated concentrations in the northern area.
### Table 2.2 Summary sulphate concentration values for TMF Piezometers and Monitoring wells

<table>
<thead>
<tr>
<th>Sector</th>
<th>8(^{th}) January 2007</th>
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<th>8(^{th}) January 2008</th>
<th>9(^{th}/13)th July 2008</th>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>South B</td>
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<td>-</td>
</tr>
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<td>968.2</td>
<td>855.3</td>
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<td>182.1</td>
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<td>520.0</td>
<td>47.0</td>
<td>520.0</td>
<td>47.0</td>
</tr>
</tbody>
</table>

**North sector monitoring wells (MW01-MW08, MW35-MW42, Figure 2.14)**

Generally, sulphate is present at less than 1,000 mg/l over the monitoring period. Concentrations prior to November 2000 are relatively low (<200 mg/l) but rose steadily to 1,000-2,000 mg/l by early 2003. Sulphate peaks are evident in September 2003 (2,053 mg/l in MW07, 2,209 mg/l in MW03) and the largest single spike in March 2004 (4,887 mg/l in MW07 and 4,948 mg/l in MW04), which corresponds with a high sulphate event recorded in the embankment piezometers. Sulphate reported for July 2002 in MW39 at a concentration of 3,940 mg/l has been discounted in the plot as an erroneous value.

Following the March 2004 sulphate spike, the elevated concentrations in MW01-MW04 decline to below 500 mg/l for December 2006. The MW05-MW08 wells are below 500 mg/l by September 2004. Sulphate concentrations in the northern sector continue to show seasonal variation with some monitoring wells showing concentrations of less than 100 mg/l in winter sampling. In recent sampling, monitoring wells show sulphate increases in the northeast sector with concentrations of 1,282 mg/l (MW06) and 1,297 mg/l (MW07) for the 9\(^{th}\) July sample. Monitoring wells MW35 and MW37, however, in the west sector, show sulphate at concentrations of 122 mg/l and 62.1 mg/l, respectively, for the July 2007 sample. Monitoring wells MW35-MW38 in the west sector have stable and low concentrations, well below 250 mg/l for the entire monitoring period. For the recent July 2008 sample, the concentration of sulphate at MW35 and MW37 was 120.1 mg/l and 80.6 mg/l, respectively.
North sector embankment piezometers (PD1, PD2, PD6, Figure 2.15)

The embankment piezometer clusters P1, 2, 8 and 9 show very similar trends in sulphate concentration, characterised largely by high concentration spikes between January and April 2004, followed by a trend of sulphate stabilisation and concentration decline.

The sulphate concentrations in P1, P2, and P9 for January to April 2004 exceed the concentrations reported for water in the TMF (<3,000 mg/l), indicating that these peak measurements are erroneous and represent either an analytical or reporting error.

Following the reported period of high sulphate levels, concentrations quickly return to previous, lower levels, which fluctuate below around 1,500 mg/l. Sulphate concentrations by December 2006 for P1 and P2 were below 300 mg/l, and below 500 mg/l for P9. Since March 2004, sulphate concentrations for P2 have declined steadily. More recent data for December-June 2007 show a slight increase in these previously low levels to concentrations approaching 1,800 mg/l for P2. Concentrations in nearby P1 show no similar rise in sulphate.

South sector monitoring wells (MW09-MW18, MW20-MW34, Figure 2.16)

Monitoring wells MW09-MW34 show sulphate concentrations that have largely been below 250 mg/l and have not exceeded 1,000 mg/l in the monitored period. With the exception of a few sporadic observations in MW11, MW12, MW26, MW28, and MW31 between 2001 and 2003, most observed sulphate concentrations in the south sector monitoring wells remain below 250 mg/l over the full monitoring period. Other minor spikes are evident in MW16 (676 mg/l for November 2000) and MW17 (654 mg/l for July 2003). All monitoring wells in the southern TMF have since stabilised, and through to December 2008 show sulphate concentrations below 250 mg/l.

South sector piezometers (PD3-PD5, Figure 2.17)

Piezometers in the southern half of the TMF do not show the sulphate spikes evident in the northern part of the TMF. Concentrations generally remain below 1,000 mg/l. Peaks in sulphate concentration are evident in piezometer cluster P6 and P7 at 2,932 mg/l (August 2002) and 1,686 mg/l (October 2003) respectively, the latter of which coincides with the main sulphate peak in the northern piezometers. For many sampling rounds, data are absent in these piezometers as they have become dry. The highest sulphate concentrations observed in the more recent sampling (August 2007) was 540 mg/l for P6C. All other piezometers in the southern TMF are registered as dry in recent monitoring.

2.4.4 Discussion of sulphate levels

Sulphate concentrations observed in TMF monitoring wells and in embankment piezometers show no recent peaks in concentration and the overall trend is one of decline and stabilisation. Concentrations of sulphate are typically below 250 mg/l. Some elevated concentrations remain in the north and northeast sectors with the most elevated concentrations (>1,000 mg/l) in embankment piezometer P2. Historically, the embankment piezometers show the higher magnitude spikes with a more subdued response in adjacent monitoring wells. The piezometers also show higher magnitude seasonal fluctuations indicating their susceptibility to mixing from rainfall/runoff during wet periods. The lower sulphate concentrations in the groundwater monitoring wells indicate that any potential seepage tends to be localised.
The deposition of tailings against the TMF margins has reduced the future likelihood of seepage occurring, as reflected by the increased stability of recent concentrations in monitoring wells and piezometers.

The overall impact of the elevated sulphate concentrations in the northern area is likely to be minimal. Groundwater flow is towards the southwest, transporting groundwater from the north and northeast sectors under the TMF footprint area. The low sulphate concentrations measured in monitoring wells on the south and south-west margins of the TMF indicate that dispersion and natural mixing is sufficient to reduce these concentrations to below 250 mg/l. As an increased thickness of tailings is deposited in the TMF, generating further consolidation of tailings, underlying peat and glacial till, the potential for future seepage is likely to reduce with time.

2.4.5 Trace elements

Groundwater samples taken from TMF monitoring wells, piezometers and the perimeter drain have also been analysed for trace elements. The results are displayed as summary statistics in Table 2.2 for data from the piezometers and perimeter drain and Table 2.4 for the monitoring well and piezometer data.

**TMF pool**

Samples from the TMF surface water are taken in a weekly composite sample. Data since Jan-2006 have been inspected to gain an understanding of the recent trace element composition in the TMF water. Arsenic concentrations largely fall below 0.15 mg/l with the highest recorded concentration since January 2006 at 0.033 mg/l (December 2006). Lead is stable at concentrations of less than 0.2 mg/l. In recent sampling since November 2006, lead concentrations in the TMF have been mostly below 0.08 mg/l. Iron is present at concentrations not exceeding 0.35 mg/l with one sample showing 0.74 mg/l for February 2007. Concentrations of zinc are between 0.42 mg/l and 9.31 mg/l, with most samples showing concentrations below 5 mg/l.

**Perimeter drain**

Analysis of trace elements in the perimeter drain has been undertaken since January 2006. The concentrations of trace metals are lower than those of the TMF surface water. Concentrations of arsenic are stable with all values below 0.03 mg/l. Some of the higher concentrations are in PD3, which shows arsenic at a concentration of 0.028 mg/l for the July 2007 sample. Cadmium has been reported at concentrations of between 0.00018 mg/l and 0.00168 mg/l and fluctuates over this range. The higher 0.00168 mg/l value was reported for July 2007 at PD2. Manganese concentrations are below 0.2 mg/l in the monitoring data, with most of the results below 0.1 mg/l. Lead concentrations are stable, with most samples showing concentrations below 0.03 mg/l. A steady decline in the concentration of mercury is evident in the monitoring data, with the most recent sample of April 2007 showing mercury below the 0.0004 mg/l detection limit. Iron also shows low concentrations in recent sampling, with the highest concentration at 0.0625 mg/l (PD3) for the July 2007 sample. The highest concentration of iron is 0.398 mg/l for the October 2006 sample for PD5.
Table 2.2 Recent trace elements concentrations in the TMF piezometers and perimeter drain

<table>
<thead>
<tr>
<th>TMF Sector</th>
<th>Piezometers - July 2007</th>
<th>Perimeter Drain - July 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>Arsenic</td>
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<td>0.001</td>
</tr>
<tr>
<td>Cadmium</td>
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</tr>
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<td>Copper</td>
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</tr>
<tr>
<td>Iron</td>
<td>5.35</td>
<td>0.167</td>
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<td>Lead</td>
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<tr>
<td>Nickel</td>
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<td>0.01</td>
</tr>
<tr>
<td>Zinc</td>
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<td>0.001</td>
</tr>
</tbody>
</table>

**TMF monitoring wells**

Analysis for trace elements is done on a quarterly basis. Samples are not filtered prior to analysis so represent both the colloidal and dissolved phases. Consequently, the reported concentrations of iron and many other metals will greatly exceed the actual dissolved values.

Arsenic concentrations in TMF monitoring wells are summarised as follows:

- MW33 shows anomalously high arsenic concentrations reaching a peak of 1.47 mg/l (July 2008), Figure 2.18. Concentrations of arsenic in MW33 do not fall in line with the data from nearby monitoring wells and are higher than the concentrations in the TMF pool water and perimeter drain, suggesting the monitoring well is not producing representative samples.

- Concentrations are generally below 0.05 mg/l in the remaining monitoring wells. However, concentrations are above 0.05 mg/l for MW14, MW29, MW30, MW32, MW33 in the south and MW40 in the west sector.

- A spike in arsenic concentration was recorded in a number of monitoring wells for the April 2006 sample, at which time MW29 had an arsenic concentration of 0.11 mg/l. Since this time a general decline in arsenic concentration is evident.

- MW33 shows consistently higher concentrations. The most recent concentration for MW33 is 1.47 mg/l (July 2008)

- In the more recently reported samples (July 2008), a slight increase in arsenic concentration is evident in some monitoring wells showing previously stable concentrations (MW35, MW37, MW42). The concentrations remain low, below 0.05 mg/l at these locations.

Cadmium concentrations in TMF monitoring wells are summarised as follows:

- Cadmium concentrations are anomalously high in MW33 reaching 0.0092 mg/l for the July 2006 sample, Figure 2.19. Concentrations at this location fluctuate and peak again at 0.004 mg/l in Oct 2007 and 0.006 mg/l in July 2008.
• With the exception of sporadic peaks in concentrations registered in Oct 2007 for MW 31, 32, 33, and 42 and in July-Aug 2008 for MW2, 3, 9, 12, 32, 33, and 35 most of the remaining data show concentrations below 0.003 mg/l.

• Cadmium concentrations have generally declined. Most of the monitoring wells sampled show concentrations below 0.002 mg/l for the Oct and Nov 2008 samples.

Although iron is reported in the TMF pool perimeter drain, much of the reportable values are likely, the result of colloidal material in the sample. The concentration of iron in TMF monitoring wells are summarised as follows:

• Concentrations of total iron exceed 0.3 mg/l in almost all of the TMF monitoring wells at some point since January 2006, Figure 2.20.

• The highest iron concentrations are consistently reported for MW04 (max 11.6 mg/l), MW14 (max 21.8 mg/l), MW30 (max 9.4 mg/l), MW32 (max 16.4 mg/l), and MW33 (max 14.8 mg/l). These locations show peak concentrations for samples taken in July 2006, July 2007 or July 2008.

• Concentrations fall in the Jan 2007 sample event, with the peak concentration at this time of 3.77 mg/l (MW04).

• Concentrations are lower in the embankment piezometers, Figure 2.21. The highest concentrations of iron are for piezometers PD 1 and PD 2 which show peak concentrations of 7.7 mg/l (April 2006) and 5.37 mg/l (Jan 2006) respectively. Piezometers PD 4 and PD 9 show Iron concentrations below 0.3 mg/l.

The concentration of lead in the TMF samples is summarised as follows:

• Anomalously high concentrations of lead are present in MW31 (0.6 mg/l), MW32 (0.9 mg/l), MW33 (1.2 mg/l), all sampled in July 2008, Figure 2.22.

• Several monitoring wells show lower peaks in lead concentration for samples collected in July 2006, Jan 2007, and Jan 2008. The highest concentrations are for MW28 (0.16 mg/l) in July 2006, MW29 (0.33 mg/l) and MW30 (0.22 mg/l). Concentrations have generally declined since this time.

• With the exception of MW32 all lead concentrations measured in most recent samples collected in Oct and Nov 2008 are below 0.03 mg/l.

• Lead concentrations in the embankment piezometers are similar and often higher than those in the monitoring wells, Figure 2.23. Piezometer 6C shows concentrations which range between 0.14 mg/l and 0.465 mg/l, and piezometer 2B a peak concentration of 0.21 mg/l. The highest concentrations in piezometers are for the recent sample taken in July 2007.

Manganese concentrations in the TMF monitoring wells can be summarised as follows:

• Manganese concentrations are stable and for many monitoring wells show an overall declining trend, Figure 2.24.

• Concentrations range from below 0.001 mg/l to 4.17 mg/l. The highest concentrations include 4.17 mg/l for MW12 (July 2007), 2.99 mg/l for
MW18 (April 2007), 2.42 mg/l for MW08 and 1.726 mg/l for MW15 (Jan 2006) and 1.62 mg/l for MW42 in July 2008.

- All manganese concentrations fall to a maximum of 0.34 mg/l for Jan 2007, but increase in the following sample (April 2007) to concentrations at 2.99 mg/l (MW18) and 1.2 mg/l (MW19). Most concentrations subsequently drop to a maximum of 0.6 mg/l in MW30 by Jan 2008 and increase to a maximum of 1.6 mg/l in MW42 by July 2008, reflecting the seasonal pulsing effect of winter dilution from rainfall runoff /recharge and summer concentration.

- Monitoring wells that show concentrations consistently below 0.4 mg/l include MW01, MW03, MW28, MW29, MW30, MW37 and MW38.

- Embankment piezometers also show relatively high manganese concentrations, with PD1 and PD2 showing peak concentrations of 1.34 mg/l and 1.99 mg/l, respectively, Figure 2.25.

Mercury concentrations are generally below 0.0015 mg/l, Figure 2.26. The exceptions are MW33 at 0.0042 mg/l for Jan 2006, 0.003 mg/l for April 2007, and MW40 at 0.004 mg/l for April 2006.
Table 2.4 Trace element values in TMF monitoring wells grouped by sector for the July 2007 sample

<table>
<thead>
<tr>
<th>TMF Sector</th>
<th>North (MW04)</th>
<th>Northeast</th>
<th>East</th>
<th>South A (MW14)</th>
<th>South B (MW28)</th>
<th>Southwest</th>
<th>West</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.022</td>
<td>0.026</td>
<td>0.022</td>
<td>&lt;0.001</td>
<td>0.0432</td>
<td>0.016</td>
<td>0.062</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.00043</td>
<td>0.0004</td>
<td>0.0003</td>
<td>&lt;0.001</td>
<td>0.0007</td>
<td>0.0002</td>
<td>0.0005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.001</td>
<td>0.001</td>
<td>0.00076</td>
<td>0.0055</td>
<td>0.00284</td>
<td>&lt;0.001</td>
<td>0.0036</td>
</tr>
<tr>
<td>Iron</td>
<td>10.29</td>
<td>0.209</td>
<td>0.0005</td>
<td>1.28</td>
<td>0.789</td>
<td>17.7</td>
<td>0.015</td>
</tr>
<tr>
<td>Lead</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.024</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.056</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.847</td>
<td>0.776</td>
<td>0.405</td>
<td>4.176</td>
<td>0.418</td>
<td>0.658</td>
<td>0.0036</td>
</tr>
<tr>
<td>Mercury</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>-</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.0126</td>
<td>0.0123</td>
<td>0.0162</td>
<td>0.0686</td>
<td>0.0458</td>
<td>&lt;0.001</td>
<td>0.00154</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.001</td>
<td>0.0097</td>
<td>0.0036</td>
<td>0.0228</td>
<td>0.0221</td>
<td>0.001</td>
<td>0.0299</td>
</tr>
</tbody>
</table>
Figure 2.1 - District geology of Lisheen

Key:
- Model Area Boundary
- Ballysteen Formation
- Aghmacart Formation
- Crosspatrick Formation
- Waulsortian Limestones
- Regional Fault
- Lisduff Oolite
- Orebody Outline
- Tailings Management Facility
- Town
Figure 2.2 - N-S Geological Section

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Figure 2.3 - Pre-mining groundwater levels at Lisheen

Elevation contours in m AOD
+ Wells with observed data

Galmoy
Templetonhy
Urlingford
Thurles
Figure 2.4 - Groundwater level map of TMF area (mAOD)
Figure 2.5 - Groundwater levels for the TMF north sector

Water level (m a.s.l.)

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Figure 2.6 - Groundwater levels for the TMF northeast sector

Water Level (m AOD)

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Figure 2.7 - Groundwater levels for the TMF east sector
Figure 2.8 - Groundwater levels for the TMF south sector A
Figure 2.9 - Groundwater levels for the TMF south sector B

105
110
115
120
125
130
135

Water Level (mAOD)

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Figure 2.10 - Groundwater levels for the TMF southwest sector

Water Level (mAOD)

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Figure 2.11- Groundwater levels for the TMF west sector
Figure 2.12 - Sulphate concentrations for the TMF perimeter drain

Sulphate concentration (mg/l)

PD1
PD2
PD3
PD4
PD5
PD6
PD7
PD8

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Figure 2.13 - Sulphate concentrations for the TMF monitoring wells
March 2007
Figure 2.14 - Sulphate concentrations for the TMF north sector monitoring wells

Sulphate concentrations (mg/l)

Figure 2.15 - Sulphate concentrations for the TMF north sector embankment piezometers

Sulphate concentrations (mg/l)

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Figure 2.16 - Sulphate concentrations for the TMF south sector monitoring wells
Figure 2.17 - Sulphate concentrations for the TMF south sector embankment piezometers

Sulphate concentrations (mg/l)


P3A
P5A
P5B
P6C
P7A
P7B
P8A
P8C
P9A
Figure 2.18 - Arsenic concentrations in TMF monitoring wells 2006 - 2008
Figure 2.19 - Cadmium concentrations in TMF monitoring wells 2006 - 2008

Cadmium concentration (mg/l)

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Figure 2.20 - Iron concentrations in TMF monitoring wells 2006 - 2008

Iron concentration (mg/l) vs. Dates (01/01/2006 to 01/11/2009) for various monitoring wells (MW 01 to MW 25).
Figure 2.21 - Iron concentrations in TMF piezometers 2006 - 2008

Iron concentration (mg/l)

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Figure 2.22- Lead concentrations in TMF monitoring wells 2006 - 2008

Lead concentration (mg/l)
Figure 2.23 - Lead concentrations in TMF piezometers 2006 - 2008

Lead concentration (mg/l)

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Figure 2.24 - Manganese concentrations in TMF monitoring wells 2006-2008

Manganese concentration (mg/l)

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Figure 2.25 - Manganese concentrations in TMF piezometers 2006 - 2008

Manganese concentration (mg/l)
Figure 2.26- Mercury concentrations in TMF monitoring wells 2006 - 2008

Mercury concentration (mg/l)

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3 CLOSURE MODELLING OF TMF

3.1 General

Based on the monitoring results described in Section 2, and the modelling results described in this section of the report, the operating plan for the TMF has been modified going forward in order that optimal conditions can be achieved at the time of closure. All available data indicate the only practical alternative is to reclaim the facility in an undrained condition, which is highly beneficial for preventing oxidation of the materials in the long term post-closure period. The modelling has shown that the permeability of the deposited tailings materials themselves is sufficiently low to prevent them from draining and to prevent any significant post-closure oxidation from occurring.

Placement of an engineered cover on the surface of the facility will prevent any significant contact between the tailings material and the surface vegetation that becomes established on the cover. Modelling has shown that the post-closure phreatic surface within the TMF will remain within the cover layer. A slight downward hydraulic gradient will be present between the cover and the underlying tailings which will help minimise any potential diffusion or upward movement of chemical constituents. In addition, the recent change in mine water management practices at Lisheen has allowed greater potential for reducing the current water inventory within the TMF between now and the time of closure. This, in turn, has allowed the tailings discharge system to be modified (as described below) to allow a final beach area to be established in the west corner of the facility, thus allowing the construction of a cover "Demonstration Cell" on the surface of the facility.

In selecting the closure plan for the Lisheen TMF, the mine-site closure team and associated consultants have evaluated the monitoring results of many other actual tailings facility closures worldwide. Given the prevailing climatic, geochemical and site-wide conditions, the closure plan which has now been formulated is considered to be the best alternative for the site. All of the contributing components to the closure plan are consistent with best management and closure practices that are currently being applied to mine sites worldwide. The "Demonstration Cell" will provide actual data that can be used to optimise the cover design, as required.

3.2 Design and operation of the TMF

The tailings management facility (TMF) comprises a fully composite-lined impoundment, located on peat and covering a surface area of approximately 78 ha. For monitoring of groundwater levels and groundwater chemistry, monitoring wells (MW01 to MW42) have been installed around the perimeter of the TMF, and piezometers (PD1 to PD9) constructed in the TMF embankment, Figure 3.1. In January 2008, a modified method of tailings deposition was initiated, and in May 2008 construction of a ‘Demonstration Cell’ capping system commenced as part of the first phase of the programme of TMF rehabilitation, (see, Figure 3.2). The cover will be progressively installed by expansion of the Demonstration cell.
The TMF is enclosed within a perimeter earth embankment founded on glacial till. The upstream face of the embankment is lined with linear low density polyethelyene (LLDPE) overlying a geosynthetic clay liner (GCL), while the basin area is lined with LLDPE. The underlying peat forms a secondary barrier, so the base of the TMF is also considered to have a composite liner.

The average ground conditions underlying the TMF comprise:

- Peat up to 5.5 m in thickness.
- Glacial till varying from 0.5 to 3.1 m in thickness.
- Bedrock of Waulsortian Limestone.

In situ permeability tests (falling head) conducted in the peat gave values of between $1.6 \times 10^{-8}$ to $8.3 \times 10^{-8}$ m/s, while laboratory permeability tests yielded permeabilities of $1.0 \times 10^{-8}$ to $5.0 \times 10^{-8}$ m/s. The same testing of the glacial tills yielded in situ permeabilities of $2.8 \times 10^{-7}$ to $8.9 \times 10^{-9}$ m/s and laboratory values of $2.1 \times 10^{-8}$ and $4.2 \times 10^{-11}$ m/s.

The TMF is operated such that:

- Tailings are distributed evenly on the LLDPE in order to avoid differential settlement of the peat and slumping of the tails.
- The shear strength of the LLDPE is not exceeded.
- Water expelled from the underlying peat during consolidation is collected and managed.
- Gas derived from the peat is removed from underneath the liner.
- The tailings are stored in a sub-aqueous manner in order to minimise acid generation due to their oxidation.

Prior to the implementation of the spigot tailings deposition method, the TMF was developed in two stage lifts with respective storage volumes of 1.5 and 3.6 Mm$^3$. Under the perimeter embankment wall of the TMF, the peat layer has been removed and a layer of graded limestone rock fill and mine waste has been emplaced on the exposed glacial till. Finger drains were installed in the perimeter embankments in order to collect seepage water from consolidation of peat and to allow pore pressures within the peat to dissipate. The size of the TMF has been designed so that the annual rise in the tailings depth is limited to 1 m and provides control on the rate of consolidation of the underlying peat. The TMF is typically operated with a minimum depth of 1 m of standing water above the tailings to maintain complete submergence of the tailings during deposition, minimise oxidation and reduce potential for generation of acidic pore water. A freeboard of 1 m is maintained to allow for design flood events.
3.3 Demonstration Cell Cover

Modifications to the tailings deposition method were implemented in January 2008 with the construction of a more conventional tailings discharge system via spigots, located along the inner edge of the TMF embankment wall. The first seven spigots were installed and tailings discharge initiated in the west corner of the TMF, Figure 3.2. This new method allows the formation of large beach areas with slight gradients, continuous and even surfaces and facilitates the infilling of troughs created within previously deposited tailings. The previous method used a floating line, winch, and carriage system, where the winch and two carriages were located on the NE and SW embankment walls and used to transfer the floating pipeline from which tailings was discharged at or beneath the water level in the TMF.

The following summarises the design criteria for the TMF capping system and the construction of ‘Demonstration Cell’ for the capping system:

- Minimise oxygen at the surface of the tailings.
- Generate an acid buffering capacity by incorporating a limestone rock/rubble layer at the surface of the tailings.
- Prevent upward migration of tailings through the cap.
- Formation of a stable platform on the TMF, of sufficient strength to carry various construction vehicles.
- Provision of growth medium to support establishment of vegetation on rehabilitated Demonstration Cell.

Construction of the ‘Demonstration Cell’ commenced in January 2008 with the build up of a tailings beach to a maximum level of approximately 133.5 mAOD in the west corner of the TMF. Following drying of the tailings beach, over 4 to 8 weeks, a Terram 1000 (or equivalent) geotextile woven fabric was placed on the top of the tailings beach, above which was placed an overlying layer of limestone rockfill material from the clean waste rock stockpile, which forms the cell cap. A growth medium (50% peat and 50% glacial till) planted with a mixture of grass seeds, was installed on top of the cell cap in October 2008. The overall cap thickness will vary from 1 to 1.5 m and the construction of the ‘Demonstration Cell’ will continue from the west corner extending out into the TMF some 100 m and extending some 560 m along the south west embankment to cover an estimated area of 5.6 ha.

To date, geochemical monitoring (lysimeter cell test programme and ceramic cup pore water sampling) and geotechnical monitoring and testing (tensiometer and settlement plate instrumentation), indicate that the ‘Demonstration Cell’ capping system is successful in:

- Preventing the upward migration of tailings through the cap.
- Generating less settlement of tailings surface under rock fill cap than previously anticipated.
- Formation of a stable platform on TMF, suitable for movement of various types of construction vehicles.

Ongoing field testwork data is being collected, collated and interpreted for further evaluation of geochemical and geotechnical performance and to determine effectiveness of the growth media of the ‘Demonstration Cell’ capping system.
The seepage modeling for the TMF described below in section 3.4 has been used to help guide the overall closure plan for the facility. The model indicates that the deposited tailings will remain saturated under any reasonable set of climatic variables. The model shows the phreatic surface will generally fluctuate between 0.3 m depth (or shallower) in the winter months, to a maximum of 0.7 m depth in the summer, following the period of maximum evapotranspiration. Based on the model results, the cap thickness of 1 to 1.5 m, currently considered in the 'Demonstration Cell' is a reasonable thickness of cover material for reclamation of the TMF.

3.4 TMF seepage model

3.4.1 Model parameters

A numerical model of the TMF was constructed to assess the current potential seepage rates, and to investigate drainage rates following final deposition of tailings within the facility. A numerical model provides advantages over simple water balance calculations as it allows variations in the TMF liner permeability and the effects of liner weaknesses and potential perforations to be modelled. The current model focused on climatic inputs at the surface of the facility. Release of water in the short term as a result of consolidation was not considered.

The model parameters were based on a conceptual model that reflected the following key points.

- The embankments are permeable and any water in the embankments can enter the underlying groundwater system.
- During construction, peat was removed from the embankment foundations. The embankments were constructed overlying limestone bedrock or glacial till. As would be expected, groundwater was encountered in the excavations.
- Monitoring of sulphate concentrations in groundwater indicates that in several locations of the north and northeast sectors of the footprint area, the liner is not functioning efficiently.
- Progressive tailings deposition has reduced the overall permeability of the liner system, leading to the observed reduction in sulphate and metals values in the piezometers and monitoring wells.
- The underlying fracture-flow groundwater system in the Waulsortian is strongly compartmentalised by the NNW trending fault system that is dominant in the area.

The aim of the groundwater model was to predict post-closure water levels in the TMF with the specific aim of establishing whether the TMF will drain following closure. Uncertainty in parameter estimation is relatively low with many of the model inputs already well constrained. For the construction of the model, data were required in the following key areas:

1) Meteorological – Evaporation and precipitation over the model period.
2) Hydrological – Knowledge of water levels in the surrounding aquifer.
3) Physical – Permeability data for the tailings and underlying geology.

Evaporation and precipitation data are available from nearby meteorological installations and groundwater levels surrounding the TMF are well known. Less well understood are...
the material properties of the TMF. Water seepages draining from the TMF must pass through the tailings material itself, the TMF liner with any perforations, the underlying peat and a thickness of glacial till before moving into the underlying Waulsortian limestone bedrock. The groundwater model is likely to be less sensitive to the permeability of peat, glacial till and bedrock limestone as the initial hydraulic barriers to drainage are the liner and the low permeability tailings.

Grain size analysis of the tailings material is shown in Table 3.1 for a sample (T17) collected as the tailings are piped from the plant. The results of the grain size analysis are presented as % by weight of material passing each sieve of sizes (106, 75 and 45 microns). Table 3.2 shows grain size data for shallow in-situ samples taken at various locations from within the TMF deposits. The data measured as % by weight retained indicate that tailings material is deposited with 60-70% of the material of grain size finer than 45 microns. The mean grain size of in-situ samples indicates 63% of material is finer than 38 microns.

Table 3.1 Results of grain size analysis of tailings (Sample T17) (% by weight passing)

<table>
<thead>
<tr>
<th>Sieve size (microns)</th>
<th>15-21 Jan</th>
<th>22-28 Jan</th>
<th>29 Jan-4 Feb</th>
<th>5-11 Feb</th>
<th>14-18 Feb</th>
<th>19-25 Feb</th>
<th>26 Feb-4 Mar</th>
</tr>
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<tbody>
<tr>
<td>106</td>
<td>91.29</td>
<td>89.10</td>
<td>89.37</td>
<td>91.48</td>
<td>83.54</td>
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<td>84.70</td>
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<tr>
<td>75</td>
<td>82.68</td>
<td>80.58</td>
<td>81.07</td>
<td>83.19</td>
<td>74.21</td>
<td>76.81</td>
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<tr>
<td>45</td>
<td>67.53</td>
<td>65.69</td>
<td>66.54</td>
<td>68.83</td>
<td>58.32</td>
<td>62.48</td>
<td>61.70</td>
</tr>
</tbody>
</table>

The grain size of tailings deposits generally falls into the class of silt (4 - 62.5 microns), however there may be a significant component of clay grade particles of grain size less than 4 microns. The fine grain size of the tailings has led to previous estimates of their permeability as being in the range of $10^{-6}$ to $10^{-7}$ m/s for unconsolidated and consolidated tailings respectively. More recent best estimates put the tailings permeability in the $1 \times 10^{-8}$ to $5 \times 10^{-9}$ m/s range. Tailings deposition typically settles in an uneven fashion producing heterogeneity in distribution of permeability. The tailings permeability estimates assigned to the model are considered to represent the bulk permeability for the entire TMF area.

The layer of peat immediately outside the TMF liner is also of low permeability. Extensive investigations were undertaken on the peat during the design phase prior to TMF construction, firstly to assess the consolidation properties of the peat, and secondly to identify its potential as a secondary liner. The permeability of the peat was established by in-situ falling head tests in investigation piezometers and a range of $1.6 \times 10^{-8}$ to $8.3 \times 10^{-8}$ m/s was derived. The compaction of the peat, however, would be substantial under the loading expected from the deposition of tailings with 90% primary consolidation predicted after 10 years. Laboratory testing showed the peat permeability reduced to between $1.0 \times 10^{-9}$ and $5.0 \times 10^{-11}$ m/s under effective stresses of 40 kPa, and to between $1.0 \times 10^{-9}$ and $3.0 \times 10^{-11}$ m/s at stresses of 160 kPa.
Table 3.2 Results of tailings grain size analysis (<39 microns) for samples of February 2007 (ATC, May 2007)

<table>
<thead>
<tr>
<th>Location</th>
<th>Solids Content (%)</th>
<th>% finer than 39µ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74.9</td>
<td>95</td>
</tr>
<tr>
<td>1</td>
<td>77.3</td>
<td>51.1</td>
</tr>
<tr>
<td>1</td>
<td>80.7</td>
<td>76.2</td>
</tr>
<tr>
<td>2</td>
<td>73.7</td>
<td>96.3</td>
</tr>
<tr>
<td>2</td>
<td>NA</td>
<td>93.2</td>
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<tr>
<td>2</td>
<td>80.5</td>
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</tr>
<tr>
<td>3</td>
<td>78</td>
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</tr>
<tr>
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<td>72.4</td>
<td>69.3</td>
</tr>
<tr>
<td>3</td>
<td>76.6</td>
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<td>95.1</td>
</tr>
<tr>
<td>5</td>
<td>83.8</td>
<td>23.7</td>
</tr>
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</tr>
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<td>69.4</td>
<td>97.3</td>
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<td>23.5</td>
</tr>
<tr>
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<td>75.3</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>77</td>
<td>32.3</td>
</tr>
<tr>
<td>10</td>
<td>79.3</td>
<td>82.1</td>
</tr>
<tr>
<td>10</td>
<td>75.9</td>
<td>80.1</td>
</tr>
<tr>
<td>10</td>
<td>75.7</td>
<td>72.1</td>
</tr>
<tr>
<td>10</td>
<td>74.3</td>
<td>87.7</td>
</tr>
<tr>
<td>Mean</td>
<td>62.77</td>
<td></td>
</tr>
</tbody>
</table>

NA – Not available

The permeability ranges used in the model for the various model layers/zones are shown in Table 3.3.

Table 3.3 Range of permeability values assigned to the model

<table>
<thead>
<tr>
<th>Medium</th>
<th>Kmin (m/s)</th>
<th>Kmax (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embankment/Till</td>
<td>3.00E-07</td>
<td>1.00E-05</td>
</tr>
<tr>
<td>Liner</td>
<td>1.00E-10</td>
<td>1.00E-05</td>
</tr>
<tr>
<td>Deposited tailings material</td>
<td>5.00E-09</td>
<td>1.00E-07</td>
</tr>
<tr>
<td>Peat</td>
<td>1.00E-09</td>
<td>1.00E-08</td>
</tr>
<tr>
<td>Bedrock (Waulsortian)</td>
<td>1.00E-03</td>
<td>1.00E-03</td>
</tr>
</tbody>
</table>
As the model is steady state, storage coefficients are not required. Precipitation and evaporation data are used in the calculation of a recharge rate assigned to the model. A representative precipitation value and evaporation value were selected following analysis of meteorological data. Table 3.4 shows the values selected for the current model.

### Table 3.4 Estimates of model TMF flux

<table>
<thead>
<tr>
<th>Flux</th>
<th>Estimate (1)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>16.9 l/s (900 mm/yr)</td>
<td>Met Éireann-Thurles Sugar Factory Long term Average</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>8.4 l/s (454 mm/yr)</td>
<td>Met Éireann</td>
</tr>
<tr>
<td>Effective precipitation</td>
<td>8.5 l/s (456 mm/yr)</td>
<td>(P-Et)</td>
</tr>
</tbody>
</table>

(1) Flow calculations assume a TMF area of 770mx770m

#### 3.4.2 Model design

The groundwater model of the TMF was constructed with the USGS MODFLOW code and the user interface Groundwater Vistas. A steady-state model was prepared with the following basic characteristics:

- 43 rows and 43 columns.
- 9,245 cells.
- Grid refined around the liner, where cells are 2 m wide.
- Unrefined cells of 70 m².
- Fixed heads around perimeter used to quantify outflow (based on current groundwater levels).
- Drain boundary conditions placed above TSF, with elevation set at 135 m to quantify run-off.

The model was run as steady state as the required output is the long-term equilibrium water levels. As such, no seasonal water level fluctuations are simulated in the model (although these have been estimated separately).

The model design is shown in Figure 3.3. Groundwater levels outside the TMF are reproduced in the model by a constant head boundary surrounding the model TMF embankment, set to levels concurrent with recent data from the TMF monitoring wells. The Waulsortian has the highest permeability of any unit in the model. The till, which is included in the model as a thin layer below the peat, has been assigned the same properties as the embankment since the embankment is largely composed of till derived from local borrow pits. The model has been used to simulate potential breaches in the liner by setting model cells in the liner to the permeability of the adjacent embankment or till. To simulate seepage/runoff, drain boundary conditions were assigned above the upper layer to remove water as runoff where infiltration is impeded by low permeability tailings.
The model provides a good reproduction of the layering present at the base of the TMF and the relationships between the liner, embankments and bedrock. The geometry, assigned properties and boundary conditions are well constrained and true to the conceptual model. The MODFLOW grid shows refinement around the TMF boundary where the liner restricts flow. This has been necessary to help the numerical solution in areas where the simulated hydraulic gradient may be steep.

3.4.3 Model output

A total of 25 steady state model runs were completed for different parameter configurations to assess ranges of potential seepage rates for varying hydraulic conductivities for the peat, embankment and deposited tailings. A range of permeability values was also used for the liner to simulate potential seepage areas and perforations by assigning the embankment permeability to cells within the liner layer.

Considering the range of K displayed in Table 3.3, the estimates of modeled seepage indicate a high sensitivity to the permeability of the tailings and underlying peat, reducing the model seepage for the unlined TMF to 3.8 l/s. For simulations of the TMF with the as-constructed liner (LLDPE), the seepage rates are much lower despite potential liner perforations and a higher K embankment material, a seepage rate of 1.6 l/s was estimated.

The model results indicate that the low permeability of the tailings, peat and liner are sufficient to inhibit draining of the TMF in any configuration within the likely ranges of hydraulic conductivity modelled. The main findings of the model are:

1) The TMF will most likely not drain with the liner currently in place. Even with the highest permeability values used for the liner, the estimated tailings hydraulic conductivity of $10^{-8}$ to $10^{-9}$ m/s would impede drainage sufficiently to maintain saturation in the TMF.

2) Higher values of hydraulic conductivity of the deposited tailings may result in partial drainage of the TMF. The low hydraulic conductivity of the underlying peat ($10^{-9}$ m/s) is also favourable for minimising seepage below the liner.

3) The most likely seepage rates based on the various scenarios modelled are in the 0.9 to 1.6 l/s range, with a likely maximum of 3.8 l/s for a liner with some perforation and high peat and tailings permeabilities.

4) Of the annual mean 16.9 l/s influx from precipitation, evapotranspiration accounts for 8.4 l/s with the bulk of effective precipitation forming runoff at a rate of 6.9 l/s and 1.6 l/s potential seepage.

An assessment of the seasonal variations in TMF water level has been undertaken to compliment the above results. Table 3.5 shows data for monthly long term average (30 year) rainfall at Shannon and Kilkenny and monthly actual evaporation data for the long term record from Oak Park. The net precipitation based on the data show that in the period May-July, evaporation exceeds precipitation and water levels in the TMF are likely to fall. Based on a drainable porosity for tailings of 0.2, the total decline in water level over these three months will range from 0.3 to 0.7 mBGL.
Table 3.5 Annual long term rainfall and evaporation

<table>
<thead>
<tr>
<th>Rainfall (mm) – 30 year average</th>
<th>Shannon/Kilkenny average rainfall (mm)</th>
<th>Actual evaporation (mm) derived from Oak Park pan</th>
<th>Net Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shannon</td>
<td>Kilkenny</td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>97.2</td>
<td>86.3</td>
<td>91.8</td>
</tr>
<tr>
<td>February</td>
<td>72.1</td>
<td>66.1</td>
<td>69.1</td>
</tr>
<tr>
<td>March</td>
<td>71.8</td>
<td>63.9</td>
<td>67.9</td>
</tr>
<tr>
<td>April</td>
<td>55.5</td>
<td>51.4</td>
<td>53.5</td>
</tr>
<tr>
<td>May</td>
<td>60.1</td>
<td>61.9</td>
<td>61.0</td>
</tr>
<tr>
<td>June</td>
<td>62.4</td>
<td>50.5</td>
<td>56.5</td>
</tr>
<tr>
<td>July</td>
<td>57.1</td>
<td>52.5</td>
<td>54.8</td>
</tr>
<tr>
<td>August</td>
<td>82.3</td>
<td>69.4</td>
<td>75.9</td>
</tr>
<tr>
<td>September</td>
<td>81.8</td>
<td>73.5</td>
<td>77.7</td>
</tr>
<tr>
<td>October</td>
<td>92.4</td>
<td>84.9</td>
<td>88.7</td>
</tr>
<tr>
<td>November</td>
<td>94.7</td>
<td>73.8</td>
<td>84.3</td>
</tr>
<tr>
<td>December</td>
<td>99.6</td>
<td>88.6</td>
<td>94.1</td>
</tr>
</tbody>
</table>

3.5 Potential impact on downstream groundwater quality

Overall, trace element and metal concentrations are generally low and stable in the TMF and adjacent groundwater. The elevated concentrations of some trace elements in the monitoring wells are likely due to the inclusion of solid phase material in the analysis of unfiltered samples. It is expected that dissolved concentrations would be more in line with the low concentrations observed in the perimeter drain.

The impact on downstream water chemistry due to any potential seepage from the TMF has been assessed using the numerical seepage model. The analysis has focussed on sulphate, with concentrations being assessed through downgradient mixing and dispersion calculations based on the potential seepage rates of water containing sulphate at a typical concentration of 2,500 mg/l. Table 3.6 shows the range of potential sulphate concentrations in groundwater directly downstream of the TMF.

The figures indicate that, for sulphate values of 2,500 mg/l in potential seepage water, the concentration of sulphate in groundwater is likely to range between 109 mg/l and 209 mg/l. These model results are generally supported by the current observed data set from the TMF monitoring wells. Going forward, as additional tailings material is placed in the TMF and the potential for seepage reduces further, it is likely that stable or declining values will continue to be observed in down-gradient monitoring wells.
Table 3.6 Potential downstream groundwater sulphate concentrations

<table>
<thead>
<tr>
<th>Seepage (% EP)</th>
<th>Modelled TMF Seepage value (l/s)</th>
<th>Resulting downgradient sulfate concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>3.35</td>
<td>507</td>
</tr>
<tr>
<td>16%</td>
<td>1.34</td>
<td>209</td>
</tr>
<tr>
<td>14%</td>
<td>1.17</td>
<td>184</td>
</tr>
<tr>
<td>12%</td>
<td>1.01</td>
<td>159</td>
</tr>
<tr>
<td>11%</td>
<td>0.92</td>
<td>147</td>
</tr>
<tr>
<td>10%</td>
<td>0.84</td>
<td>134</td>
</tr>
<tr>
<td>9%</td>
<td>0.75</td>
<td>122</td>
</tr>
<tr>
<td>8%</td>
<td>0.67</td>
<td>109</td>
</tr>
</tbody>
</table>
Figure 3.1 - Groundwater monitoring locations around the TMF
Figure 3.2 - Demonstration cell and layout of spigots

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Figure 3.3 – Design of TMF groundwater model showing an example x-section (3.10a) and plan view (3.10b) of the model design.
4 POTENTIAL HYDROGEOLOGICAL IMPACTS AND CLOSURE MONITORING

4.1 Introduction
Potential hydrogeological impacts under closure conditions and associated mitigation measures are presented in this section. More specifically, impacts and mitigation measures are presented in context to the TMF these represent one of the more significant potential sources of hydrogeological impact under closure conditions at the Lisheen mine site.

4.2 Potential hydrogeological impacts
Any natural groundwater flow in the Lisheen area would be expected to occur in the upper zone of weathering and fracturing, typically 30-50 m depth. This was indicated by the baseline hydrogeology studies for the project, and has been confirmed by the operational monitoring data. Once the Waulsortian above the workings is completely flooded, the regional groundwater gradient to the south and southwest will become re-established, but the actual groundwater flux rate is expected to be very limited.

In addition, because the flooded workings are deep on the north side of the Killoran fault zone, and because the thickness of the Waulsortian decreases sharply across the fault zone (as shown in Figure 4.1), the ambient geological setting would also cause any groundwater movement to occur only a shallow depth. The fault zone itself, and the thickening ABL sequence to the south of the fault zone, would act to prevent any significant through-flow at the mine horizon or discharge at depth to the south. It is expected that the water at the mining horizon will become trapped against the north side of the fault.

The monitoring record for the TMF indicates that sulphate levels are consistently above 250 mg/l only around the northern margin of the facility. Because this is the upgradient side of the TMF, any transport is likely to move to the southwest, beneath the footprint area of the facility, rather than away from it. Going forward, potential seepage rates from the TMF are shown to reduce with time because of the increasing thickness of deposited low permeability tailings material. As a result, the overall situation with regard to groundwater impacts is not likely to deteriorate.

The current model results indicate that seepage from the reclaimed post-closure TMF will be near to 1.6 l/s. The down-gradient mixing model indicates sulphate concentrations along the flow path to the southwest (down-gradient) of the facility are likely to remain below 250 mg/l for the remaining operational life of the facility and for closure. Because of the active dewatering of the mine workings, they are currently down-gradient from the TMF and form a capture area for any groundwater moving beneath the TMF. This, in turn, provides further protection for down-gradient receptors.
Therefore, the current analysis indicates that the TMF poses little risk to the groundwater system in the Lisheen area. An ultimate fallback mitigation option would be to carry out low-rate pumping from the decline (of the order of 1-4 MLD or less) in order to maintain the capture zone for a given time period after the mine has been shut down. However, based on the current evidence and preliminary modelling results, this is not considered to be necessary at present.

Once the groundwater system has achieved full recovery, the groundwater table over much of the mine area will be within the zone of capture by evapo-transpiration. Therefore, most groundwater discharge from the area around the mine will be by evapo-transpiration during the summer months, rather than by district-scale down-gradient groundwater flow. Although there is a groundwater gradient to the south and southwest, towards the Drish and Suir rivers, this is mostly a function of the regional topographical control, and its influence on the depth of evapo-transpiration, rather than because of any widespread regional groundwater flow. Because of this, there is virtually no risk to any downgradient groundwater receptor, including the local rivers and streams.

Based on the lateral groundwater gradients in the area down-gradient to the south and southwest of the mine area, the calculated natural groundwater flow rate in this direction is about 19 l/s (1.7 MLD). Calculated groundwater velocities were between 90 and 125 m per year. However, as discussed above, much of the down-gradient groundwater flux from the mine area would be lost by evapo-transpiration, and the actual groundwater velocities and rate of mass transport would be significantly less than predicted by the model.

4.3 Closure monitoring plan

Closure of the Lisheen mine site will require a monitoring plan to ensure that actual conditions and potential impacts are roughly as predicted.

Details of the monitoring plan will be prepared once the timing and exact conditions for closure are known with more certainty that at present. However, it is likely that the closure plan will include the following elements:

- **Monitoring of recovering water levels in workings.** This may include water level measurements in the Fresh Air Shaft and in one drill hole in each orebody. Monitoring of the F2/F3 inflows would also be carried out for as long as access allows.

- **Monitoring of recovering regional groundwater levels.** This would be carried out in available shallow boreholes, and also in TMF piezometers and monitoring wells. The monitoring of regional wells would also be continued for a reasonable period of time following shut down of the dewatering system.

- **Monitoring of the chemistry as the workings flood.** This would be carried out by sampling the available drill holes into the ore horizon. A selection of shallow holes would also be monitored to ensure upward mixing of the water was not occurring.

- **Establishment of downgradient compliance point.** This is yet to be determined, but could potentially be the existing Colleeny well or a new purpose-drilled well to the south of the Killoran fault zone. Actual water quality compliance levels would be established following more detailed modelling nearer to the time of closure. The establishment of compliance levels would also use the available baseline monitoring data as a reference.
Potential hydrogeological impacts and closure monitoring

- **Post-closure monitoring of Drish and Rossestown rivers.** This would be carried out as per the current schedule for the first 12 months, decreasing to an annual low flow sample at the downstream bridges following full recovery of the groundwater system.