THE LISHEEN MINE

ANALYSIS OF GROUNDWATER AND SURFACE WATER RESPONSE FOLLOWING COMPLETION OF MINING

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Prepared for

THE LISHEEN MINE

Kiloran, Moyne, Thurles, Co. Tipperary

1st May 2019

PROJECT 3747-R1

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1. INTRODUCTION

1.1 OVERVIEW OF OPERATIONS AND CLOSURE

The Lisheen Mine is located some 12 km to the northeast of Thurles, and some 4 km to the southeast of Templetouhy, in Co. Tipperary (Figure 1.1). While operational, the mine exploited 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 site facilities. The mine was operating between 1998 and 2015, producing an average of about 6,000 tonnes per day of zinc and lead ore.

Ore was extracted from five underground mining zones: Main, Derryville, Main Zone North, Bog and Derryville Island (Figure 1.2). As mining ended, dewatering was progressively stopped, and bulkheads built as the underground operation retreated to the main decline. Ventilation shafts were backfilled with coarse inert rock and capped with a reinforced concrete lintel. The last dewatering pumps (on the main decline) were switched off on 31st December 2015. By January 2018, the groundwater table had recovered to baseline levels as recorded in the pre-mining hydrogeological studies.

Surface infrastructure during operations included a tailings management facility (TMF), an ore stockpile area, a paste tailings plant, two water treatment plants, a main conditioning pond for the mine water, other ponds and infrastructure for mine water management, maintenance areas, an administration/office building and a large borrow pit (Figure 1.2). For closure, a cover was placed on the TMF, starting in August 2014 and completing in February 2018 (Phase 1 'demonstration' was covered in 2008). As groundwater levels have recovered, the Carrick Hill borrow pit flooded (with groundwater) so is now a lake. The remaining infrastructure has been removed or demolished with the exception of the warehouses, sewage treatment plant and administration/office building

Piteau Associates has been retained by Lisheen to assess the groundwater and surface water responses to mine closure.

This report was drafted based on the data available up to September 2018. It does not include any data from the works and monitoring undertaken on the TMF in late 2018 and early 2019.

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Figure 1.1 Lisheen Mine location map

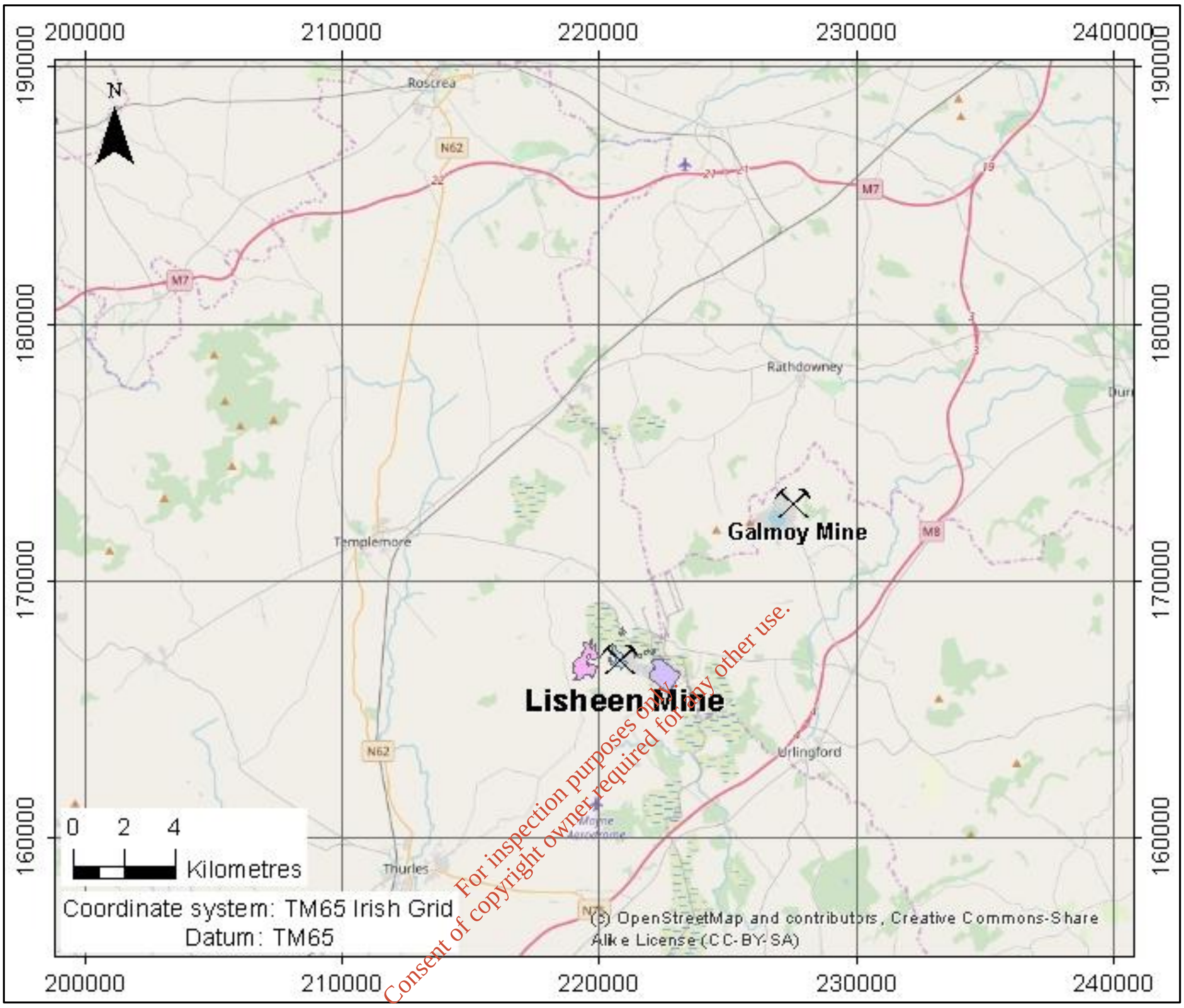

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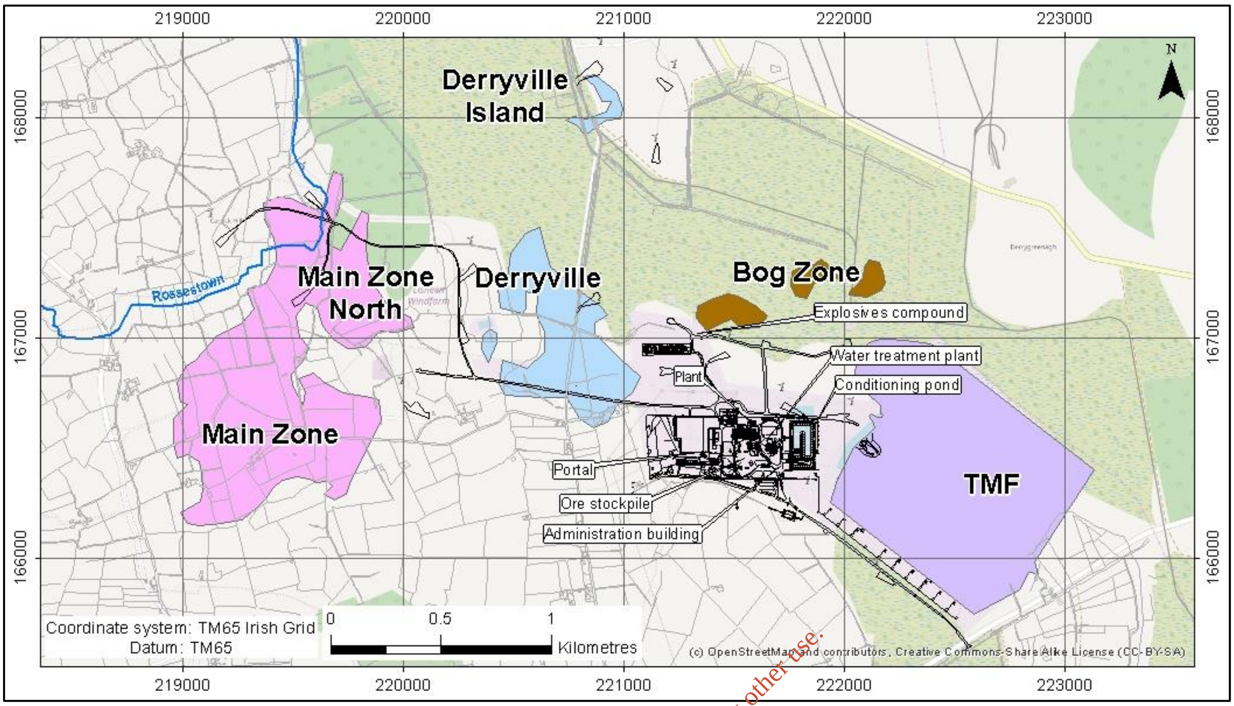
Figure 1.2 Operational mine layout and orebodies



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1.2 REPORT OBJECTIVES

The aim of this report is to review the current database (water levels, surface water and groundwater quality), focusing on the active closure and immediate post-closure periods, to determine the current status of groundwater and surface water conditions in the mining district and any potential impacts on downgradient receptors. Reference is made to the following SWS reports: 50785R5 'Lisheen Mine: hydrogeological review for the Environmental Protection Agency' (SWS, 2015a) and 50785R4 'Lisheen Mine: updated hydrology model to support mine closure' (SWS, 2015b) to review the predicted outcomes with the actual monitoring data. This provides a robust appraisal of the conceptual groundwater model and provides a mechanism for identifying any deficiencies.

Groundwater-associated objectives of the Closure, Restoration and Aftercare Management Plan (CRAMP) have not been reviewed as part of this report.

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2. HYDROGEOLOGY

2.1 GEOLOGY

2.1.1 General geological setting

The bedrock throughout the entire Lisheen district consists of Lower Carboniferous limestone units (Figure 2.1). The most dominant unit locally is the Waulsortian Formation (the Waulsortian mud bank complex). Virtually all the production mining occurred within the Waulsortian. 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.

2.1.2 Waulsortian

The Waulsortian Formation outcrops throughout the local mine area or occurs at a shallow depth beneath Cross Patrick. Regionally, the unit shows variable fracturing controlled mostly by the presence of geological structures.

Typically, the Waulsortian has a zone of increased weathering (oxidation and dissolution) known as epikarst and extending to about 30 to 50 m below topography. This zone usually includes more weathered, fractured and cavernous rock. It is therefore expected that, under natural conditions, most groundwater flow occurs in this upper epikarst zone. The intensity of fracturing below 50 m is observed to decrease significantly.

Except for the main decline, and the extreme southern part of Main Zone (to the south of the Killoran fault), all underground mine workings are located within the Waulsortian.

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2.1.3 Argillaceous Bioclastic Limestone (ABL).

The ABL is a massive limestone and is generally unfractured. Typically, it does not yield any groundwater. It forms a flow barrier between the overlying Waulsortian and the underlying Lisduff Oolite Member.

The main decline is driven through the ABL. As shown in Figure 2.2, in the area of the F2 and F3 fault zones, the contact between the ABL and the top of the underlying oolite occurs within 5 to 12 m below the floor of the decline. It is thought that the upthrown block of oolite caused the initial flooding of the decline as it was being driven, and caused the sustained flow from the F2/F3 feature throughout the entire period of mine operations.

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 Cooleeney area (Figure 2.3). The main outcrop areas of the ABL are to the northwest of Lisheen, and also between Lisheen and Galmoy to the northeast.

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The ABL forms an important unit for mine closure because it occurs in the footwall of the Derryville and Killoran faults. It is expected that the unit will act to form a low permeability barrier, reducing any potential for groundwater flow at depth from the mine area to the south or southwest. A similar situation has been observed across the G-zone fault at the Galmoy Mine.

2.1.4 Lisduff Oolite Member

The oolite occurs stratigraphically within the ABL, as shown in Figure 2.2. Beneath the area of both the Main Zone and Derryville, it occurs at a depth over 250 m below ground level. However, along the footwall (south) side of the Derryville and Killoran Faults, it occurs within about 120 to 150 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 oolite dips to the south with the ABL.

Locally, little is known about the hydrogeology of the oolite. It is evident from the available data that it provided the main conduit for the inflows to the F2/F3 zone 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 into the oolite encountered no major groundwater inflows.

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2.1.5 Superficial deposits

The entire Lisheen area is masked by a veneer of glacial deposits of varying thickness. Most of the glacial material is boulder clay, but there are important sand and gravel lenses that can form sources of domestic and agricultural water supply. The sand and gravel lenses tend to be discontinuous and limited in extent. These lenses are typically shallow, which makes them naturally prone to reduced yields during drier years and/or when the recharge during the preceding winter and spring is low.

When the area of drawdown was at its maximum extent (during operations), it had a seasonally-variable area of between 90 and 95 km². Around 25% of this area (23 km²) was in areas of peat cover. The Bog and Derryville Island mining zones occur wholly beneath peat cover. Peat deposits are formed from vegetation that is inhibited from decaying fully as a result of acidic and anaerobic conditions. Significant dissolved inorganic nitrogen concentrations are known to be leeched from peat land environments (Daniels et al, 2012). Large scale peat harvesting is practiced within the larger bog areas. This may create enhanced runoff and therefore rapid loading of ammonia to surface water and potentially also groundwater because of the artificial drains.

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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.

- **North northwest-south southeast** structural set forms the dominant local structural trend and can be clearly seen in a series of faults south of the mine and to the northwest of the Templetouhy area. It is also evident from regional aeromagnetic data. The F2/F3 feature, together with most of the main faulting in the vicinity of the orebodies, is aligned along this trend. At least 10 prominent structures of this orientation have been identified in the Lisheen area. A similar structural orientation is observed to be a strong control on the groundwater flow system around the Galmoy mine.
- **East northeast-west southwest** structural set associated with the regional Rathdowney trend is 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. The G-zone fault at the Galmoy mine is also oriented along this trend.
- **Subsidiary east-west** structural sets also occur regionally. Locally, this is somewhat less defined, but structures of this orientation are apparent to the west and southwest of the Lisheen area.

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Figure 2.1 Bedrock geology

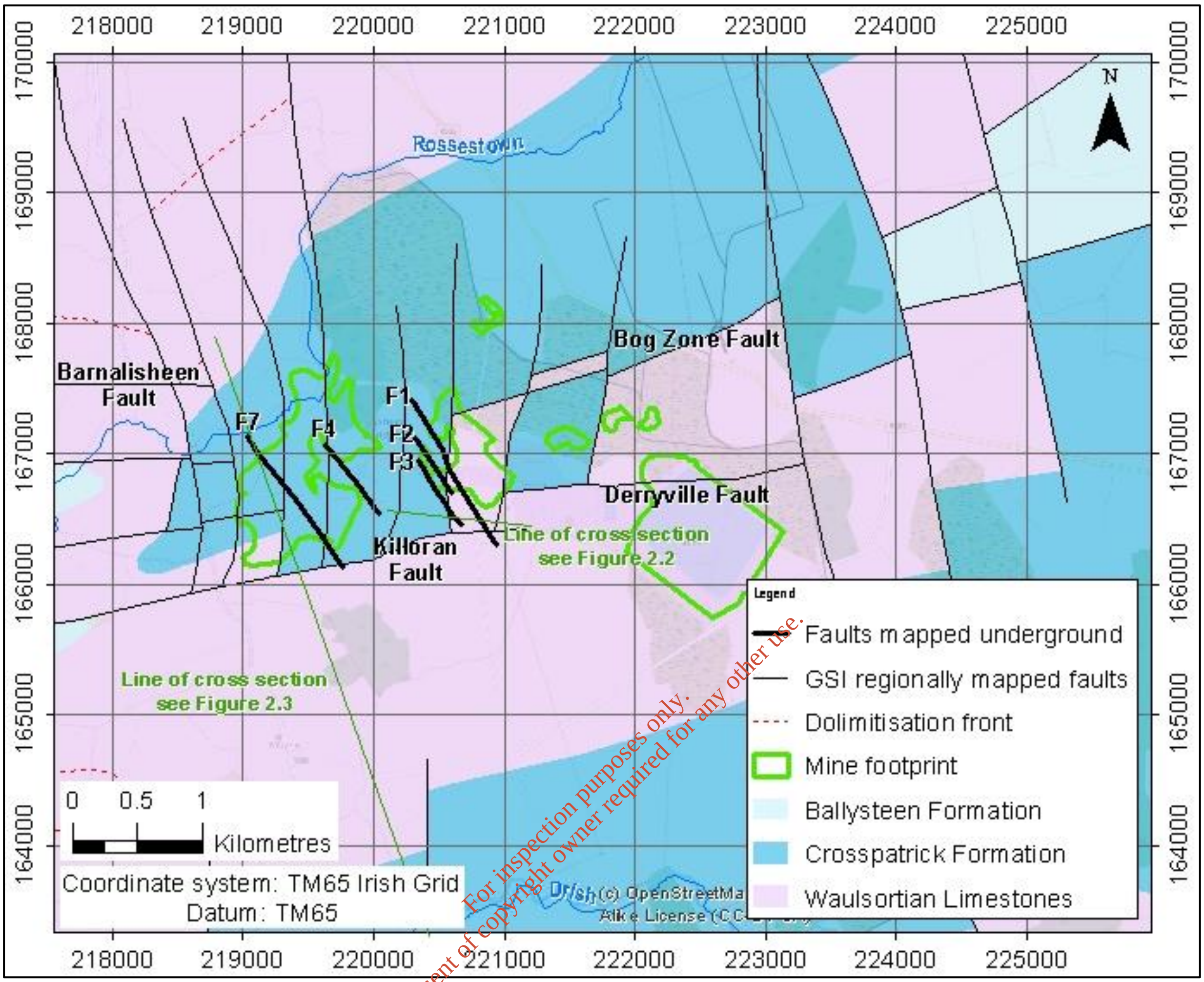

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Figure 2.2 Geological cross section along the decline

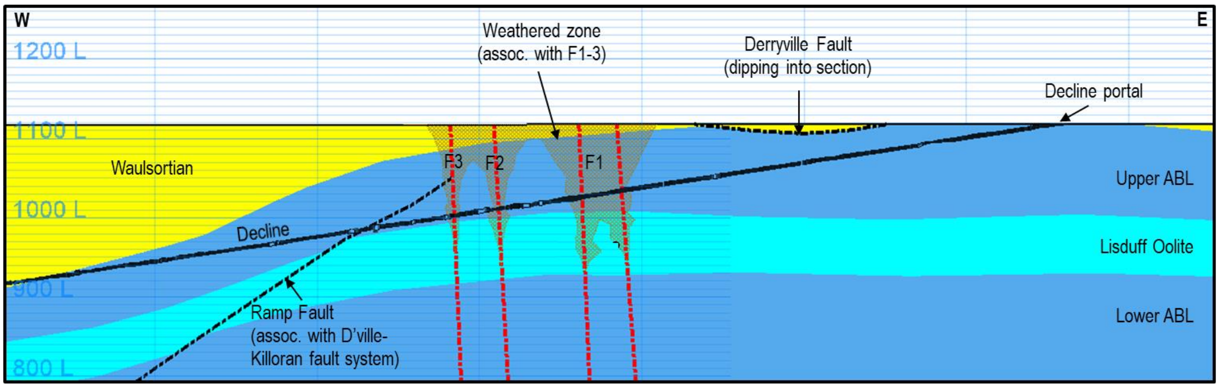

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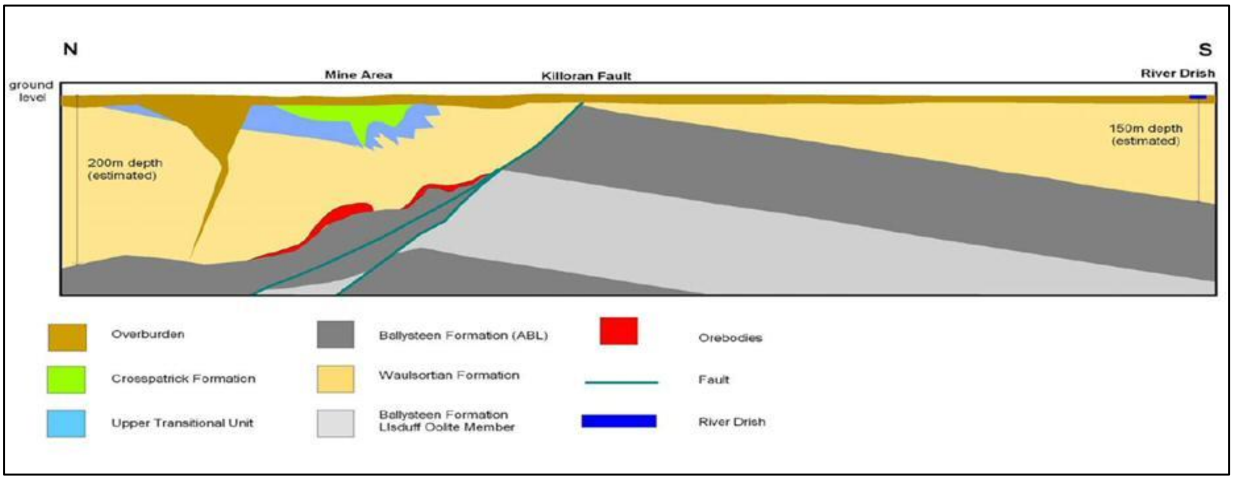
Figure 2.3 Geological cross section north-south



2.2 PRE-MINING GROUNDWATER CONDITIONS

2.2.1 Groundwater levels and flow

Figure 2.4 shows a pre-mining groundwater contour map of the Lisheen area. Groundwater level elevations in the mine area were generally within the range 123-127 mOD. In general, the groundwater table occurred within 3 to 8 m below the ground surface. In most places, the groundwater table occurs within the glacial soils and peat deposits that overlie the limestone units. Around the main streams and ditches in the area, this is often within the zone of evapotranspiration. Plants with roots within this zone take up groundwater for transpiration. This is a form of groundwater discharge.

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As a result, much of the groundwater flux is very localised, and most of the groundwater does not flow laterally for any significant distance. Where groundwater flow occurs within the limestone units, movement is dominated by fracture flow. The structural geology exerts a prominent influence on the regional and local-scale hydrogeology of the Waulsortian.

The pre-mining water level data also indicate that a groundwater divide occurred beneath the Derryville bog immediately to the east and northeast of Lisheen.

2.2.2 Groundwater recharge

All groundwater recharge to the limestone units in the Lisheen area occurs due to infiltration of incident rainfall and runoff. 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 150 and 250 mm per year, which is about 15-30% of the mean annual precipitation.

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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 2 and 5 m. In the winter, the water table rises close to the surface and stays with the capillary zone, where is it removed by evapotranspiration the following summer.

2.2.4 Lateral flow and groundwater discharge

Figure 2.4 shows that the overall district-scale groundwater gradient in the Lisheen area was to the south and southwest, towards the Drish River and regionally towards the River Suir. The pre-mining groundwater head difference between the mine area and the Drish River to the south was only about 5 m, which is only marginally more than the natural seasonal water level fluctuation. The groundwater gradient was a broad reflection of topography, thus suggesting there was little natural flux and transport over large distances.

A small amount of groundwater discharge also occurred locally to the local drainage ditches that feed the Rossestown River. The pre-mining groundwater discharge (as springs and seepages) 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.

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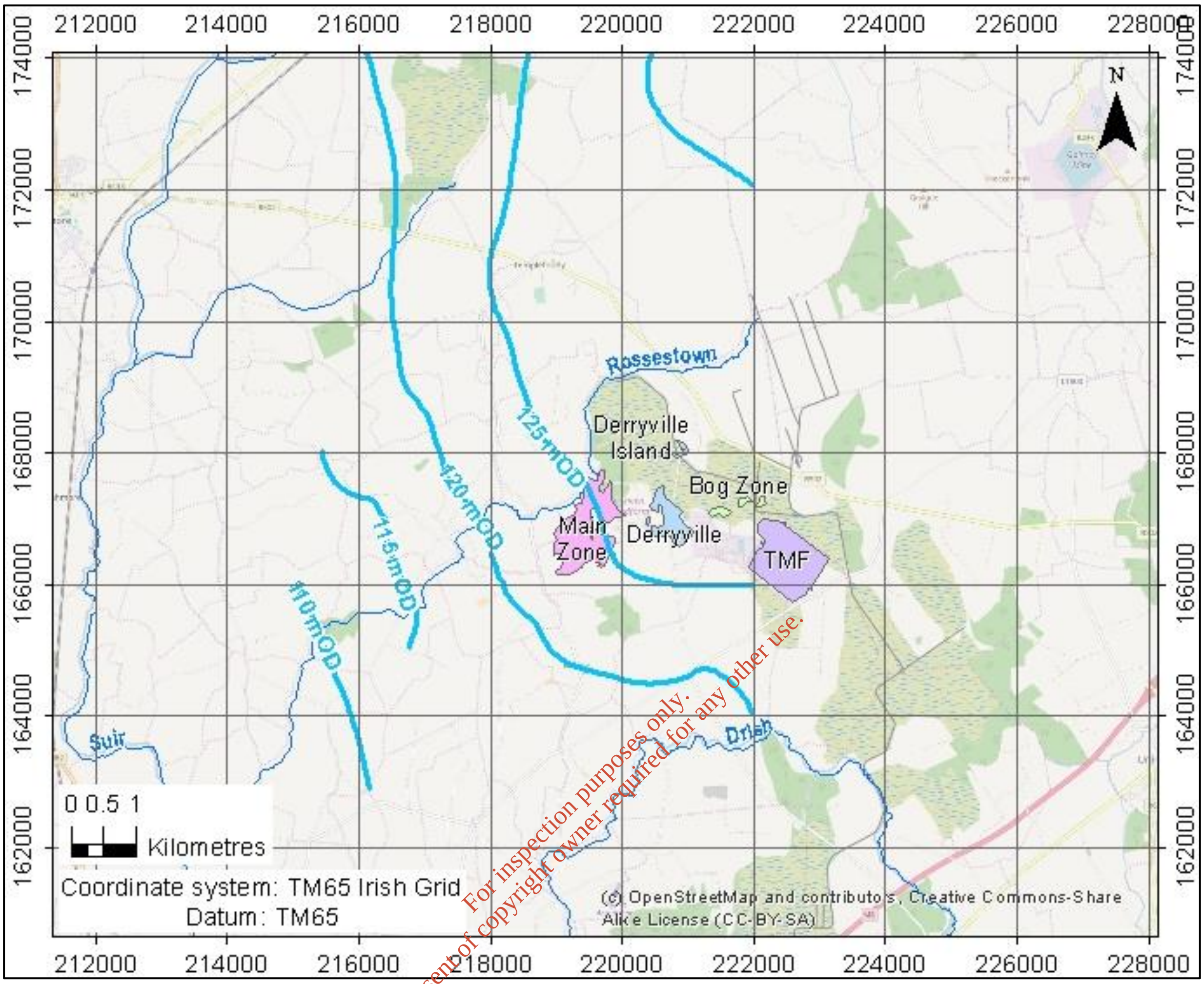
Figure 2.4 Pre-mining groundwater contours



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2.3 OPERATIONAL PERIOD MINE DEWATERING

2.3.1 Dewatering rates

During operations, groundwater inflows to the mine were derived from: i) storage removal in the limestone units; and ii) recharge from rainfall and infiltration over the area of drawdown created by the dewatering system. Storage removal was the main component of the groundwater inflows during the early years of dewatering. The amount of required groundwater storage removal progressively decreased, and groundwater recharge to the area of drawdown gradually became the main source of the sustained inflows.

Significant groundwater inflow was encountered as the decline was driven through the NNW-SSE trending F2 and F3 fault zones. This area provided a steady inflow to the decline throughout mine life, (although reducing slowly since it was first encountered in 1997). The

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F2/F3 water was derived from the Lisduff Oolite Member (part of the ABL) to the south of the mining area; whereas all other inflows to the mine were from the Waulsortian Formation.

Figure 2.5 shows the total pumping reached a peak of 93 MLD in the April 2001 reducing to around 60 MLD by mid-2006 when 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 to close to the top of the workings.

Since 2007, additional mining areas were opened up (Bog Zone and Derryville Island), and there were periods of high winter rainfall together with a number of very dry summers. These factors caused a greater seasonal fluctuation in the mine inflow rate. Following the opening up of Bog Zone, the mine inflow rate peaked at 95 MLD in March 2007, the average Bog Zone inflow rate for early 2007 was 17 MLD.

From 2008 to the end of mine life (December 2015), groundwater storage removal was a minor contributor to dewatering, with almost all inflow due to groundwater recharge over the area of drawdown. This was demonstrated in the winter of 2013/14. The mine pumping rate in November 2013 was at an all-time low of 55 MLD as a result of the very dry summer and autumn. Between 28th December and 19th February, the rate increased from 56 MLD to an all-time high of 106 MLD following exceptional rainfall in January and February (the same period that Galmoy was undergoing active flooding).

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2.3.2 Area of drawdown

As dewatering has progressed, it has become clear that the main structural geology influence on the hydrogeological system was the north northwest-south southeast regional faults. This was reflected by the area of drawdown surrounding the mine being elongated in a north northwest-east southeast direction.

At its maximum extent, the estimated area of drawdown was between 90 and 95 km², as shown in is shown in Figure 2.6. This area represents a “zone of capture” for recharge to the mine workings. The natural seasonal fluctuation in groundwater levels of up to 5 m made it difficult to determine the exact area of the drawdown. Regional monitoring of wells (mostly domestic and agricultural wells) during operations showed the drawdown to be within the bounds of seasonal variation.

During operations, groundwater levels in the superficial deposits became decoupled from those in the underlying bedrock units. As a result, drawdown in the underlying bedrock occurred generally without causing any significant impact to the soil moisture balance or the groundwater levels within the superficial deposits. For example, groundwater levels in all of the monitored

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regional (domestic) wells monitored as part of the closure programme (see Section 3.4) were largely unaffected by the mine dewatering operation.

There are minor, non-connected areas of saturated alluvium along parts of both the Drish and the Rossestown rivers. There was no evidence of any significant leakage from surface waters over the area of the Lisheen drawdown influence, including the Drish River which has significant exposures of weathered bedrock in its bed.

Figure 2.5 Dewatering rates over time

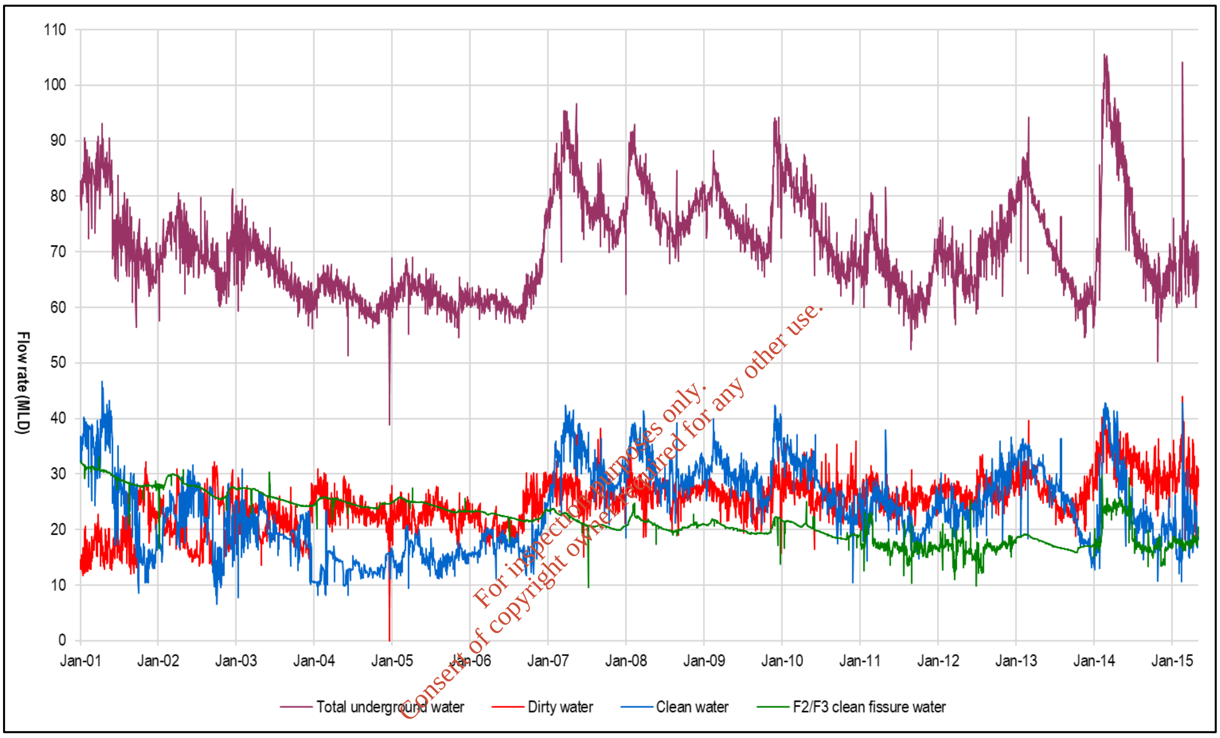

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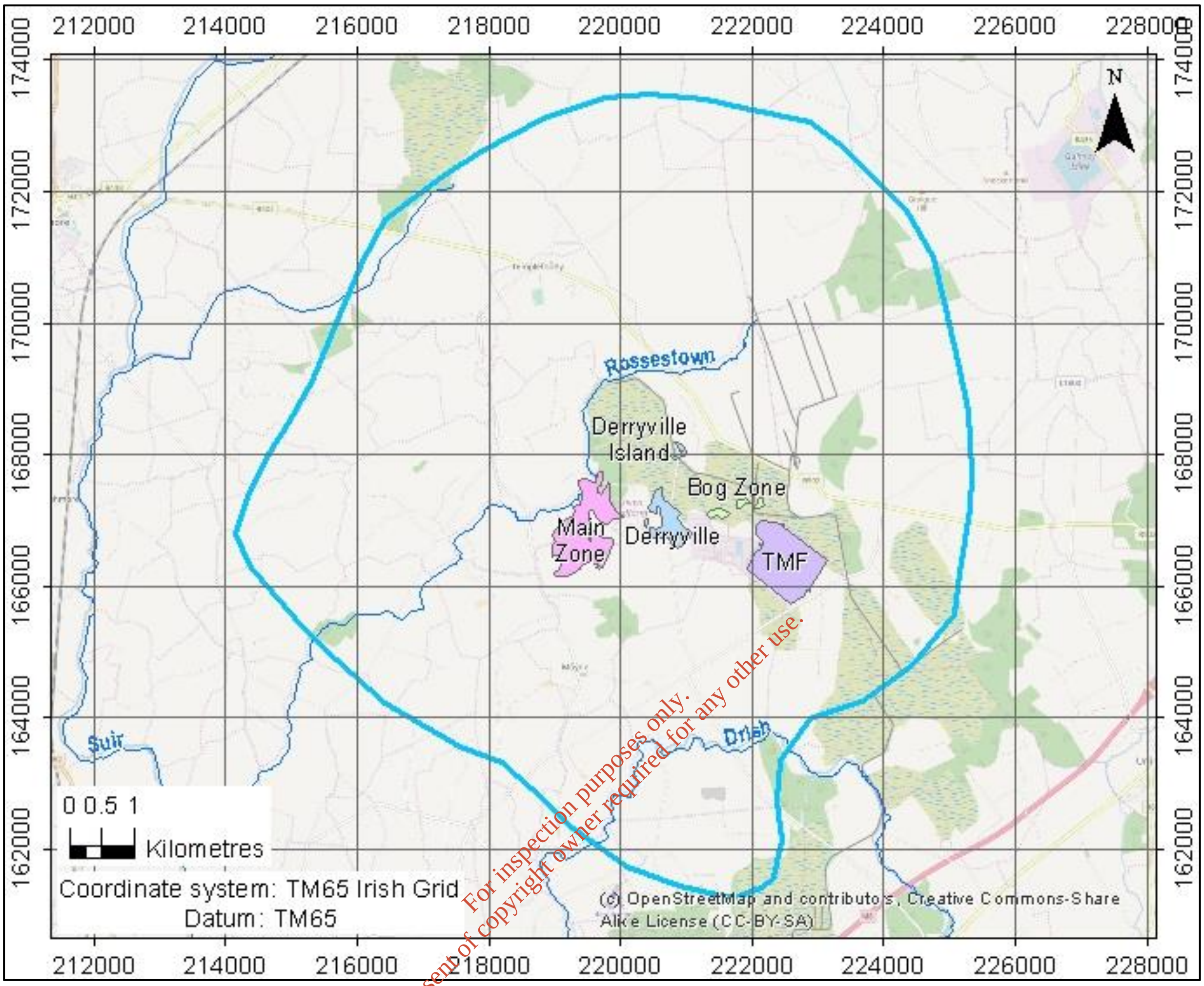
Figure 2.6 Approximate area of drawdown at the peak of operations



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2.4 CLOSURE PERIOD

2.4.1 Mine workings

The final dewatering pumps were switched off on 31st December 2015. Groundwater levels in the mine workings rose over 120 m over the first three months, for example in MW15 levels rose from -63.75 mOD on 22nd December 2015 to 66.27 mOD on 23rd March 2016. This initial response to dewatering was higher than predicted by SWS (2015b) due to the lower porosity of the bedrock and backfill at depth. The recovery model was updated in April 2016 to include this initial response and, since that time, the monitoring data have remained within the predicted envelope, fluctuating seasonally between being above the 'base case' to below it, as shown in Figure 2.7.

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Full recovery of the workings was confirmed in early 2018 when the groundwater level reached between 123.6 mOD and 125.3 mOD, compared with a pre-mining elevation of about 125 mOD. Following that time, a reduction in groundwater levels was observed, indicating that the natural seasonal variation in groundwater levels has become re-established.

2.4.2 Regional groundwater

The regional groundwater level data show that water levels have recovered and returned to the natural baseline condition whereby there is a hydraulic gradient to the south and southwest, as shown in Figure 2.8 for January 2018 water level data. As predicted by SWS (2015b), the hydraulic gradient appears to have flattened in the vicinity of the mine workings due to the greater connectivity of the groundwater system in the old workings. This is expressed as a widening of the space between the 120 mOD and 125 mOD contours in Figure 2.8. Away from the mine workings (including in the vicinity of the TMF), the baseline and post-recovery contours are almost identical, and any differences are within typical seasonal variation (2 to 5 m).

Natural groundwater discharge to the Rossestown became re-established by 21st December 2017 when the Lisheen ended the compensation flow.

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Figure 2.7 Post-closure groundwater level recovery predicted and observed

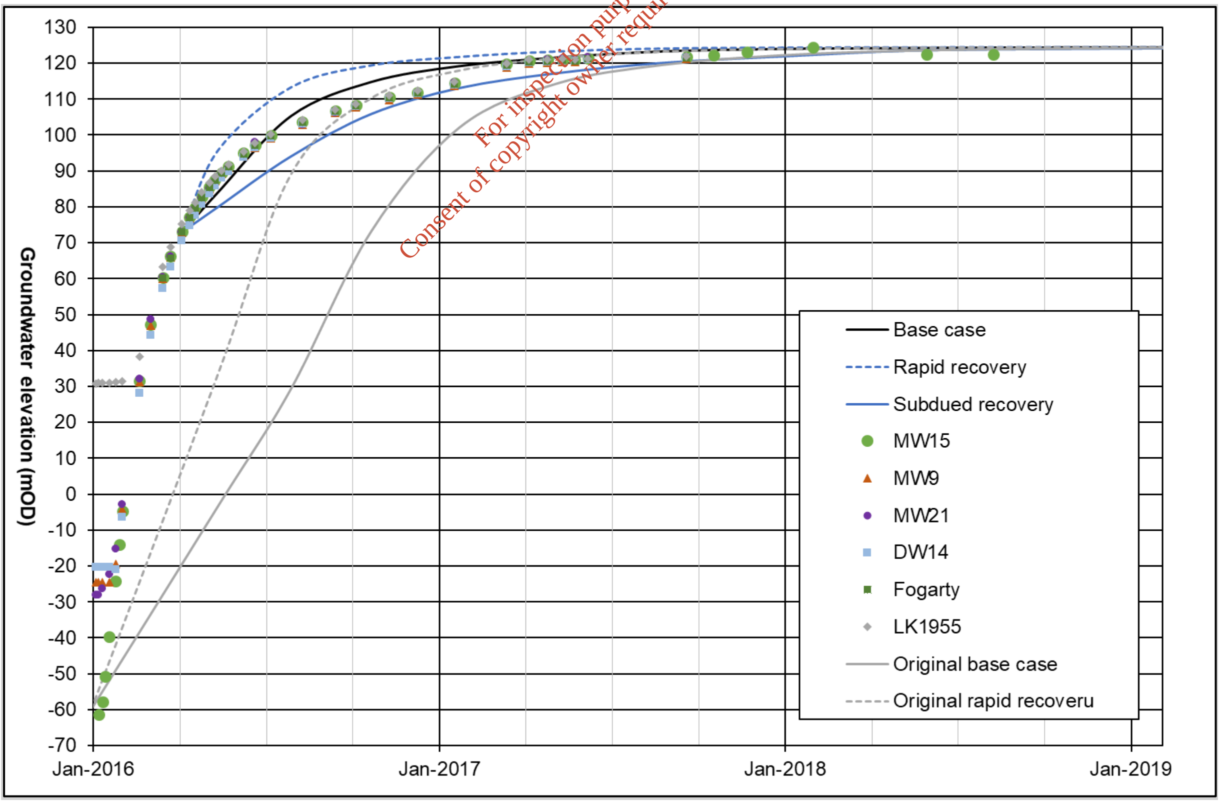

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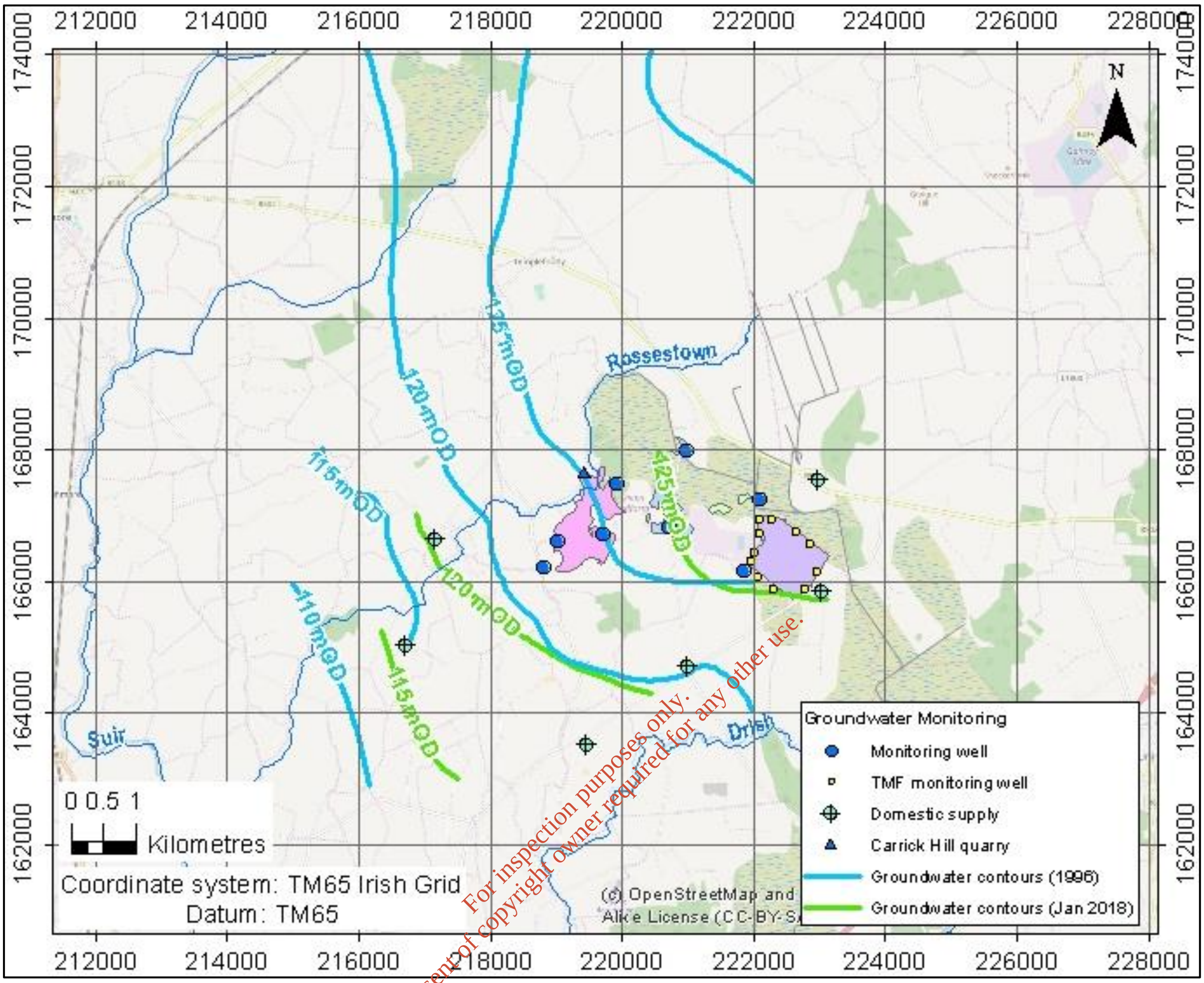
Figure 2.8 Post closure groundwater contours (January 2018)



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3. GROUNDWATER CHEMISTRY

3.1 OVERALL CHARACTERISATION

The following sections discuss the regional groundwater chemistry and impacts of the mine workings and their flooding. Groundwater quality relating to the TMF is discussed in Section 4.3.

As part of the baseline study, 77 domestic wells, monitoring wells and exploration boreholes were sampled between June 1991 and November 1992. Most of the samples taken were from shallow wells, so the results represent groundwater within the upper zone of epikarst. Parameter concentrations at depth around the mineralisation are likely to have been higher.

The data (Table 3.1) show that, with the exception of ammonia, groundwater quality was generally good in the area of the mine. However, the naturally mineralised nature of the area is evident by some locally elevated metals, most notably lead, zinc and arsenic. Baseline ammonia concentration was naturally elevated due to the extensive peat bogs in the area; this appears to be exacerbated in some areas due to agricultural landspreading. The average concentration over the 14-month monitoring period was 0.28 mg/L N; groundwater regulations are 0.065 mg/L N.

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All bedrock groundwaters in the Lisheen area are calcium-bicarbonate dominant, with high bicarbonate values, typically within the range 280-450 mg/l. All waters have a very high natural buffering potential. The pH remained above 6 throughout the operational period, even when the most reactive high sulphide ore was exposed to the inflowing water under oxygenating conditions.

The early monitoring data indicated that higher magnesium values were associated with groundwaters in the more dolomitised areas to the north and northwest of the mine area. They also indicate higher potassium and nitrate concentrations in many of the shallower district wells associated with the upper weathered epikarst zone of the Waulsortian. Bedrock groundwaters beneath the areas of peat bog have naturally high ammonia values.

3.2 REGIONAL WELLS

A total of 42 regional wells have been periodically sampled (this has been reduced to six for closure monitoring). The wells are located at a distance of up to 8 km from the mine. These mainly comprise local domestic and/or agricultural wells. The regional wells can be split into two main groups based on potassium content. Group 1 had elevated potassium concentrations and the waters were K-Ca-HCO_3. The high potassium concentrations are associated with high nitrate (6-55 mg/l) and likely reflect a strong agricultural influence. Group 2 has potassium concentrations below 20 mg/l (usually much lower), and the waters were Ca-HCO_3 to Ca-Mg-

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HCO_3 dominant. Trace metal concentrations are typically low (similar to those seen in river water samples).

The district groundwater samples can generally be described as recent recharge waters with agricultural influence, which is represented by high potassium and nitrate. Calcium and magnesium are replaced by potassium in the samples with agriculture-derived contaminants. It is likely that the samples reflect shallow groundwater. Prior to mining, it is expected the deeper groundwaters in the Waulsortian would have been of low mobility and therefore much older.

3.3 CONTAMINANTS OF POTENTIAL CONCERN (COPC)

The *Lisheen Mine hydrogeological review for the Environmental Protection Agency* (EPA) report (SWS, 2015a) requires the identification of COPC. The report identified that the mine workings and TMF have the same COPC associated with them: dissolved metals, nitrogen species and sulphate.

Based upon these monitoring data, ‘general compliance values’ were proposed to, and accepted by, the EPA for dissolved metals (arsenic, lead, nickel and zinc), sulphate and ammonia. The agreed compliance values are provided in Table 3.1 with typical water quality values at the end of mine operations and baseline values for reference.

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Table 3.1 Typical water chemistry values

	Arsenic (mg/L)	**Lead (mg/L)**	**Nickel (mg/L)**	**Zinc (mg/L)**	**Sulphate (mg/L)**	**Ammonia (mg/L)**
F2/F3 water (Lisduff Oolite)	<0.05	0.008	-	0.2-0.3	30	<0.01
Clean water (Waulsortian)	0.1	0.01-0.2	-	1-2	70-90	1-2
Dirty water (Waulsortian in workings)	5-20	2-20	-	6-30	220-330	2-3
Tailings (in tailings mass)	0.18-0.33	1.3-5.1	0.14-1.0	1.5-34	1100-2100	-
TMF wells (groundwater below TMF)	0.004-0.01	0.001-0.02	0.002-0.08	0.002-0.06	50-90	0.1-0.4
1991 to 1992 baseline	*0.001-0.03*	*0.006-0.2*	0.002-0.007	*0.01-2*	*10-50*	*<0.01-5*
Compliance Value	***0.01***	***0.01875***	***0.02***	***1***	***250***	***0.23 (N)***
GW Regulation (S.I. 9 of 2010)	*0.0075*	*0.01875*	*0.0075*	-	*187.5*	*0.084 (0.065 N)*
DW Standards (S.I 122 of 2014)	*0.01*	*0.01*	*0.01*	-	*250*	*0.3 (0.23 N)*

Note, all metals values expressed as total concentration

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3.4 CLOSURE PERIOD

3.4.1 Monitoring network

The closure groundwater monitoring network comprises the following locations (Figure 3.1):

- compliance wells – CW1 (TMF) and CW2 (flooded workings);
- wells close to the flooded workings – Fogarty, MW15, DW14, MW9, MW21 and LK1955;
- TMF – regular sampling of 20 wells (from a total of 42), MW6, MW14, MW32, MW35 and MW42A are presented in this report; and
- regional (domestic) wells – J Maher, S Hennessy, M Moore, F Cleere, P Fogarty and P Healy.

The data are presented in Appendices A and B, and summarised in Table 3.2. Interpretation of the TMF groundwater monitoring results are provided in Section 4.3.

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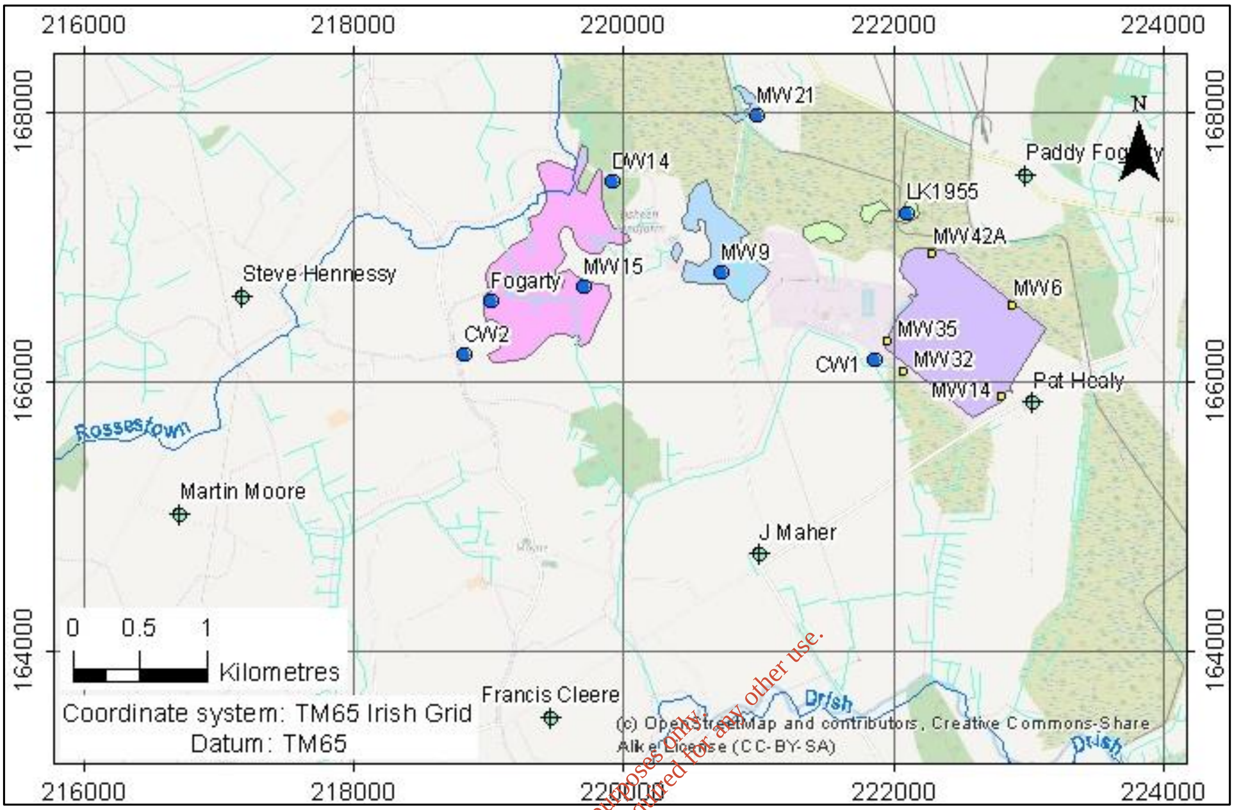
Figure 3.1 Closure groundwater monitoring locations



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3.4.2 Monitoring wells close to the flooded workings

Water quality data from monitoring wells close to the mine workings and the downgradient compliance well (CW2) are generally compliant with the groundwater regulations and below the COPC general compliance values as shown in Table 3.2 and Appendix A. The exception is ammonia; however, baseline data show that ammonia was elevated in the groundwater system pre-mining (see Section 3.1) due to the extensive cover of bog. Monitoring of LK1955 ended in June 2017 when the headworks were accidentally damaged by an excavator.

During 2016, early in the recovery period, some exceedances were seen in wells close to the workings and in compliance wells (for example, arsenic and mercury in all wells, lead in MW9 and MW15 and sulphate in MW9). These were due to the groundwater re-establishing old flow paths and remobilising fracture networks which have been unsaturated for nearly 20 years. Once this 'first flush' had occurred and reducing (low oxygen) conditions were established in the workings, the water quality has stabilised and become more consistent between sampling campaigns.

Water quality at DW14 is generally consistent over time, within a seasonal fluctuation. Sulphate and ammonia both peak in late-winter, causing exceedances, but become compliant again through the spring and summer.

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Since late 2017, a step-change in some parameters (including arsenic, iron, mercury and nickel) has occurred at all locations. This is due to a change in analytical laboratory (from onsite to outsourcing). A review of the outsourcing laboratory's standard operating procedures was initiated in 2018 to improve the consistency with earlier sampling campaigns.

3.4.3 Regional wells

Regional (domestic) well water quality is presented in Appendix B. All locations are generally compliant with groundwater regulations and COPC general compliance values. Some wells show elevated ammonia and nitrate. These locations had elevated values even during mining when the workings formed a groundwater sink (so no contamination could migrate into the regional groundwater system). As discussed above, ammonia is naturally elevated in the Lisheen area due to the extensive peat bogs; nitrate is associated with agriculture.

P Healy has elevated arsenic and nickel (associated with high iron) and J Maher has elevated mercury. In both cases, these parameters were elevated prior to mine closure so are assumed to be due to naturally occurring sources close to the two wells. There has been no significant change or trend in the post-closure monitoring period.

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Table 3.2 Groundwater chemistry in monitoring wells close to the flooded workings and downgradient

Parameter	Unit	Fogarty	MW15	DW14	MW9	MW21	Compliance Well 2	Groundwater Regs SI 9 of 2010
pH	pH units	7.1-7.4	7.3-7.8	6.8-7.1	6.8-7.1	6.9-7.2	6.9-7.0	-
Conductivity	µS/cm	890-1000	390-620	1100-1200	1000-1500	720-770	900-1000	1875
Alkalinity	mg/L	360-430	150-310	450-480	390-520	350-350	450-510	
Ammonia	mg/L	0.031-0.078	0.031-0.084	0.2-0.43	0.03-0.48	0.03-0.075	0.074-2.0	0.23*
Nitrate	mg/L	1.2-2.3	2.2-6.4	1.2-2.2	2.9-9.5	1.3-1.5	5.2-8.5	8.5
Nitrite	mg/L	0.0017-0.011	0.0067-0.036	0.0056-0.056	0.0029-0.079	0.0017-0.010	0.0028-0.028	0.11
Aluminium	mg/L	0.0021-0.013	0.0021-0.0088	0.0021-0.014	0.0021-0.014	0.0021-0.013	0.0021-0.014	0.15
Arsenic	mg/L	0.0013-0.0045	0.0013-0.004	0.0015-0.0059	0.0013-0.0068	0.0013-0.0051	0.002-0.0059	0.01*
Cadmium	mg/L	0.0001-0.0003	0.0001-0.00026	0.0001-0.00022	0.0001-0.00046	0.0001-0.0002	0.0001-0.0003	0.00375
Calcium	mg/L	130-150	23-110	200-210	200-260	120-130	170-190	
Chloride	mg/L	16-18	7.7-11	17-18	12-17	13-14	12-24	
Chromium	mg/L	0.0001-0.0001	0.0001-0.0035	0.0001-0.0001	0.0001-0.0027	0.0054-0.0071	0.0001-0.0001	0.0375
Cobalt	mg/L	0.0007-0.0011	0.00032-0.0012	0.001-0.0015	0.00097-0.0032	0.0005-0.0012	0.0007-0.0018	
Copper	mg/L	0.0002-0.0012	0.0002-0.0019	0.0002-0.00063	0.0003-0.0025	0.0017-0.0027	0.0002-0.0006	1.5
Iron	mg/L	0.0018-0.017	0.0018-0.02	0.0018-0.02	0.0018-0.017	0.0018-0.0061	0.0018-0.025	
Lead	mg/L	0.0009-0.0023	0.001-0.032	0.001-0.003	0.0022-0.02	0.0011-0.0096	0.0009-0.0026	0.01875
Magnesium	mg/L	53-57	24-41	55-59	56-71	32-35	35-41	
Manganese	mg/L	0.0001-0.0065	0.0001-0.085	0.2-0.24	0.048-0.25	0.00022-0.010	0.012-0.03	
Nickel	mg/L	0.0037-0.02	0.00042-0.0044	0.016-0.02	0.014-0.025	0.0053-0.02	0.0044-0.0072	0.02*
Potassium	mg/L	2.8-4.6	1.3-2.3	3-3.8	2.8-11	3.4-4.9	1.4-1.9	
Sodium	mg/L	8.9-10	4.9-6.3	11-12	7.7-16	9.2-11	7.7-8.8	
Sulphate	mg/L	110-170	56-90	230-260	78-570	51-96	29-56	250*
Zinc	mg/L	0.014-0.18	0.016-0.066	0.041-0.17	0.064-0.23	0.095-0.17	0.014-0.014	1*

* shows general compliance value where different to groundwater regulations

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4. TAILINGS MANAGEMENT FACILITY

4.1 DESIGN AND CLOSURE OF THE TMF

The TMF was built in 1998 and the first tailings storage started in 1999. Including embankments, it has a footprint area of 88 ha (Figure 4.1) and capacity of 6 million m³. The design includes a fully engineered composite liner, with chimney drains and finger drains in the embankment which report to the perimeter drain.

Closure and reclamation of the TMF was divided into three ‘phases, as follows:

- **Phase 1** – 9 ha ‘demonstration cell’ constructed along the southwest margin of the Main Cell in 2008, used to trial the closure cover;
- **Phase 2** – remaining 55 ha of the main cell; and
- **Phase 3** – 6 ha extension cell constructed in 2013.

The concept of the closure design for the TMF was to: (i) optimise the post-closure water balance to minimise the potential for downward seepage; (ii) prevent any long term upwards migration of tailings pore water to the cover soils; (iii) allow storm water runoff to shed from the cover as rapidly as possible; and (iv) prevent erosion of the cover or embankments. The reclamation plan was to:

- install a cover on the whole TMF, the design of which would prevent long term upward migration of tailings pore water;
- allow surface water runoff to discharge from the TMF via spillways (one per phase) to reduce the potential for erosion;
- convey water from the spillways and spilling basins via engineered channels to a transfer box and then to a storm water attenuation basin;
- use the storm water attenuation basin to attenuate peak flows and to polish waters prior to off-site discharge; and
- route water from the storm water attenuation basin to the Cloheen pond discharge point (SW1) via an engineered channel, and from there to the Drish in existing surface drains and ditches.

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All three phases used the same cover design for closure: a 700 mm thick rock fill layer and an overlying 300 mm growth medium layer. Phase 1 was covered in 2008 (to demonstrate the closure concept). Cover installation on Main Cell started in mid-2013 (while tailings were still being spigotted) and finished in February 2018. Phase 3 was covered in 2016.

Construction of all surface water conveyance channels and ponds was completed in early 2018 (Figure 4.1). In addition to these works, the perimeter drain was backfilled with compacted peat to prevent any post-mining standing water or flow within the drain.

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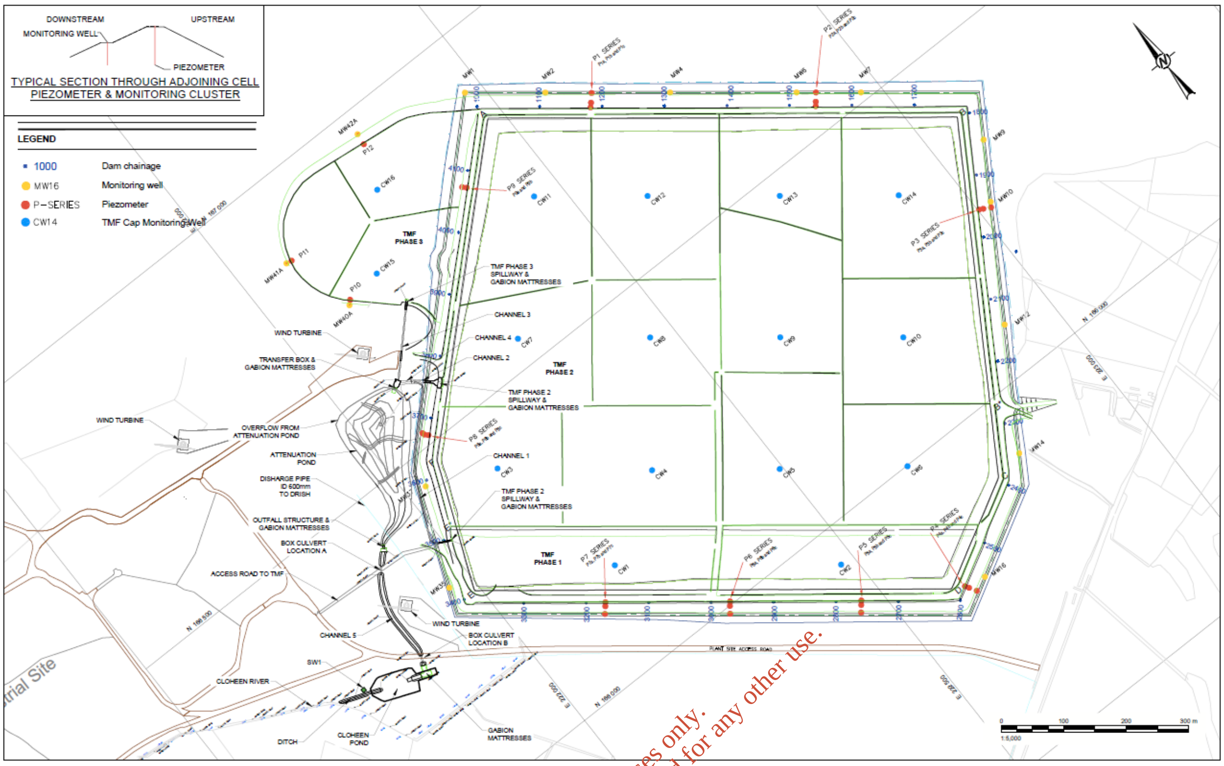
Figure 4.1 As built plan of the TMF closure works (after Golder, 2018)



4.2 TAILINGS PORE WATER CHEMISTRY

The pore water quality within the deposited tailings will broadly reflect that quality of any seepage from the TMF. Seepage may potentially occur either downwards from the base or upwards to the rock fill layer as the tailings mass consolidates. Regular sampling of the tailings pore water was undertaken on Phase 1 between 2010 and 2013, these data have been summarised in Table 4.1. The tailings pore water has elevated metals and sulphate, as expected for a lead-zinc sulphide orebody, but also high alkalinity (and associated calcium) reflecting the naturally high bicarbonate content of the water used for ore processing.

4.3 CLOSURE PERIOD WATER QUALITY

Groundwater samples have been taken from monitoring wells around the perimeter of the TMF on a quarterly basis since 1999. Most samples are not filtered prior to analysis so represent total concentration (as opposed to the dissolved component only). Plots for a representative selection if TMF wells are provided in Appendix C.

Sulphate is usually considered to be a suitable indicator parameter to identify the performance of the TMF because it is not readily precipitated or attenuated in shallow groundwater conditions. Although most sulphate concentrations are slightly elevated, since 2012 and before

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groundwater level recovery, all wells had sulphate values below the groundwater standard (187.5 mg/L). The exceptions were MW35 and MW37 which are located on the western flank of the facility and show average reported concentrations between 270 and 420 mg/L and are associated with known areas where the liner has been damaged. Since groundwater level recovery, some wells have shown an increase in sulphate, although most values remain below the groundwater standard.

There has been a small amount of seepage observed from the southwest embankment of the TMF. It is an area of previous seepage that has started to make water, potentially as a result of tailings consolidation or as a result of temporary standing water on the surface of the cover. An investigation of the seepage area is ongoing, to include: (i) installation of a number of shallow monitoring points on the section of Phase 1 that is wet; and (ii) survey work on the embankment to demonstrate there is no movement or erosion.

Typical ranges of values for monitored parameters are presented in Table 4.1. The data show that concentrations in groundwater adjacent to the TMF are generally at least one order of magnitude lower than those recorded in the tailings pore water and, in almost call cases, the COPCs are below the general compliance values.

Compliance Well 1 (CW1) was installed to monitor groundwater downgradient of the TMF. The data from CW1 indicate that, although some there is some variation in the chemistry, the effects are limited. The only parameter consistently exceeding the general compliance value for COPC is nickel with a typical range of 0.03 to 0.034 mg/L and maximum of 0.059 mg/L at CW1. Typical TMF monitoring well values are 0.0038 to 0.038 mg/L, which suggests that the source of nickel in CW1 is unlikely to be the TMF.

An apparent spike in cadmium also occurs in late-2017. However, this is most likely due to the limit of detection at the laboratory being too high.

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Table 4.1 Typical tailings water and associated groundwater chemistry

Parameter	Unit	Tailings Mass	TMF Groundwater Quality	Compliance Well 1	Groundwater Regs SI 9 of 2010
pH	pH units	6.7-7.4	6.6-7.1	6.7-7	-
Conductivity	µS/cm	2100-3300	710-1000	990-1100	1875
Alkalinity	mg/L	160-510	-	400-420	
Ammonia	mg/L N	-	0.13-0.68	0.09-0.18	0.23*
Nitrate	mg/L N	-	0.097-0.90	0.52-0.23	8.5
Nitrite	mg/L N	-	0.0021-0.010	0.0091-0.020	0.11
Aluminium	mg/L	0.41-2.6	-	0.0021-0.006	0.15
Arsenic	mg/L	0.18-0.33	0.003-0.0084	0.0018-0.0071	0.01*
Cadmium	mg/L	0.0076-0.035	0.0001-0.0006	0.0001-0.0004	0.00375
Calcium	mg/L	530-980	110-210	200-200	
Chloride	mg/L	-	10-18	20-22	
Chromium	mg/L	0.0034-0.0096	0.0001-0.0004	0.0001-0.0001	0.0375
Cobalt	mg/L	0.036-0.36	0.00048-0.0026	0.0048-0.0056	
Copper	mg/L	0.037-0.16	0.0008-0.0034	0.0002-0.0003	1.5
Iron	mg/L	4.3-12	0.054-0.71	0.0018-0.89	
Lead	mg/L	1.3-5.1	0.001-0.019	0.0009-0.0009	0.01875
Magnesium	mg/L	94-310	18-31	32-34	
Manganese	mg/L	0.44-2.2	0.04-0.4	1.3-1.4	
Nickel	mg/L	0.14-1	0.0038-0.038	0.03-0.034	0.02*
Potassium	mg/L	9.4-28	1.6-3.8	1.3-1.6	
Sodium	mg/L	9.9-41	8.2-15	12-14	
Sulphate	mg/L	1100-2100	52-100	160-180	187.5
Zinc	mg/L	1.5-34	0.0043-0.074	0.009-0.014	1*

* shows general compliance value where different to groundwater regulations

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5. SURFACE WATER

5.1 SURFACE WATER NETWORK

During the operational period, Lisheen had four licensed surface water discharge points, two each to the Drish (PWE1 pipeline and SW1 Cloheen pond) and Rossestown (PWE2 pipeline and SW2 Carrick Hill wetland). The PWE2 pipeline was primarily to provide compensation flows to the Rossestown. This was required because mine dewatering reduced the upstream baseflow rates. Three of the four discharges have now been decommissioned as follows:

- discharge from PWE1 to the Drish ended in May 2017;
- discharge from PWE2 to the Rossestown ended in December 2017 once the natural baseflow conditions in the upper catchment had recovered; and
- discharge from SW2 via the Carrick Hill wetland to the Rossestown ended in September 2016 and the land remediated to remove any metals in the soils.

SW1 discharge from the Cloheen pond is now the only discharge point from the site. It receives runoff from the TMF and locally to the pond, as well as a small amount of treated waste water via the storm water attenuation basin. Runoff and rock fill outflow from the TMF is discharged via three spillways to the transfer box and then flows into the storm water attenuation basin (Figure 5.1). Discharge from the attenuation basin occurs once the water level reaches the spill way. Water flows through a channel to the Cloheen pond wetland area, from where it discharges to the Cloheen ditch (a field drainage system). The Cloheen ditch is part of a field drainage system and so receives water from the adjacent fields along its 4 km course before discharging to the Drish.

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As part of the closure plan, a surface water drainage model was created for the TMF cover and industrial area contributing to the storm water attenuation basin. The objective was to identify the likely flow variation and magnitude of surface water runoff and discharge through the rock fill layer. The closure works on the TMF were completed in early 2018. Due to the timing of this completion and the relatively dry and warm summer, very little water has been discharged from site. Once flow and chemistry data are available from the TMF, storm water attenuation basin and Cloheen pond, the results should be analyses and compared to the model results to verify the outputs.

Since completion of the TMF cover, there has been: i) almost continuous discharge from Phase 1 (it was dry for a few weeks in the summer of 2018); ii) discharge from Phase 2 for a few weeks in late-spring 2018; and iii) short periods of discharge from Phase 3 (spring 2017 and 2018). The flow from Phase 1 in September 2017 was estimated to be around 2 L/s. During operation, the same flow (pumped to Phase 2) was estimated to be around half of this. The difference in flow may be due to the method of estimation. However, it is also possible that the

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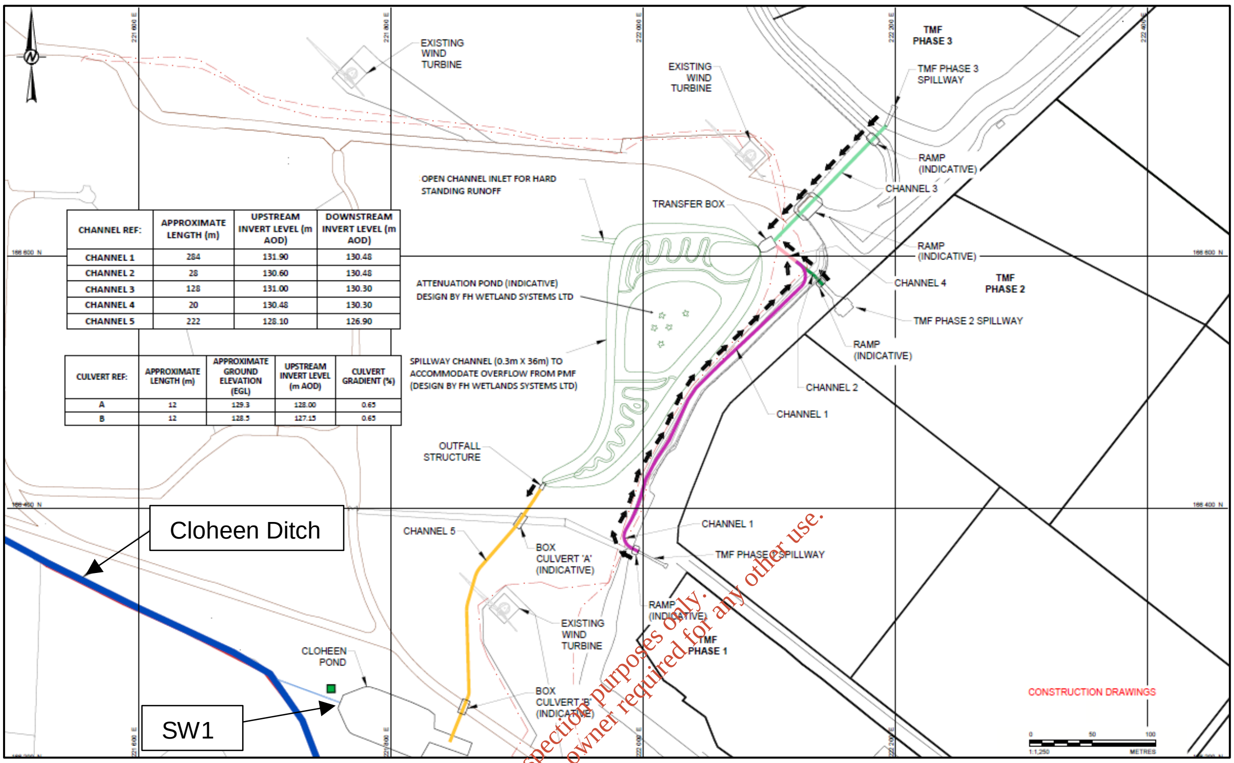
installation of a cover has enhanced the flow through the tailings mass from Phase 2 to Phase 1. This must continue to be monitored as flows from the TMF increase through winter.

Figure 5.1 Plan of the surface water management infrastructure



CHANNEL REF:	APPROXIMATE LENGTH (m)	UPSTREAM INVERT LEVEL (m AOD)	DOWNSTREAM INVERT LEVEL (m AOD)
CHANNEL 1	284	131.90	130.48
CHANNEL 2	28	130.60	130.48
CHANNEL 3	128	131.00	130.30
CHANNEL 4	20	130.48	130.30
CHANNEL 5	222	128.10	126.90

CULVERT REF:	APPROXIMATE LENGTH (m)	APPROXIMATE GROUND ELEVATION (EGL)	UPSTREAM INVERT LEVEL (m AOD)	CULVERT GRADIENT (%)
A	12	129.3	128.00	0.65
B	12	128.5	127.15	0.65

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5.2 CLOSURE SURFACE DISCHARGE PREDICTIONS

Full details of the model inputs and results are included in SWS (2015b) report 50785R4 '*Lisheen Mine: updated hydrology model to support mine closure*'.

The model was constructed in GoldSim™, a graphical, object-oriented software designed for dynamic simulations. The graphical layout is based around 'Elements' which are used to replicate all aspects of the site water system. The model comprises the following elements: the covered TMF, the hardstanding areas, vegetated and reclaimed areas, the storm water attenuation basin and the Cloheen pond.

The model runs on a daily time-step using historic (2003 to 2014) daily rainfall records from Lisheen and monthly potential evapotranspiration from the Met Éireann station at Oak Park, Carlow.

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5.2.1 Model structure and methodology

Rock fill discharge

Within the TMF element, a soil moisture balance simulates water within the TMF cover layer based on the Food and Agriculture Organisation of the United Nations (FAO) Irrigation and Drainage Paper 56. The model calculates infiltration to the rock fill layer by accounting for changes in moisture in the soil layer as follows.

- On a dry day, no additional moisture is added to the balance.
- On a wet day, runoff is calculated first using the SCS Curve Number Method (see below); this is subtracted from the total rainfall and the difference is added to the soil layer as "infiltration".
- Water is removed from the soil layer by actual evapotranspiration. This is a factored version of potential evapotranspiration. The factor used varies over time depending upon the amount of moisture in the soil. When the moisture content is low, the factor is low because water is not readily taken up by the grass cover. When moisture content is high, the factor is high. The factor is calculated using the FAO methodology using the following inputs:
    - Readily available water (RAW) = 50 mm
    - Total available water (TAW) = 100 mm
    - Crop coefficient (Kc) = 1
- When the evapotranspiration demand has been met, any excess water will become stored in the soil zone.
- If the soil moisture deficit has not been satisfied, the water will remain stored in the soil horizon above the capillary break created by the rock fill layer.
- If the soil moisture deficit has been satisfied because of on-going rainfall infiltration, any excess water entering the soil will be available to percolate downward in to the rock fill layer.
- While the soil moisture content is in deficit, no percolation to the rock fill occurs. Once the soil moisture is less than zero, when field capacity has been reached, the surplus moisture becomes infiltration to the rock fill layer.

Flow through the rock fill layer is modelled using a decay curve: breakthrough occurs one day after infiltration and flow decreases to zero over the next 9 days if no additional infiltration occurs in that time.

Surface runoff

Peak runoff was calculated using the Rational Method to provide design criteria for sizing drainage structures and the storm water attenuation basin. Under less extreme conditions, the amount of runoff generated will vary greatly and can be modelled using the SCS Curve Number

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method. Using this method, the proportion of rainfall which becomes runoff adapts depending upon the antecedent moisture conditions and amount of rainfall. Curve numbers were assigned to each of the areas as presented in Table 5.1.

For the TMF, runoff is also linked to the soil moisture balance. The model "rejects" infiltration to the soil layer if the rock fill layer is fully saturated, thereby increasing the amount of runoff.

Table 5.1 Surface water drainage model curve numbers

Cover type	Curve Number	SCS land use description
Capped TMF	78	Meadow: continuous grass.
Hardstanding	98	Impervious areas: paved parking lots, roofs, driveways, etc.
Grassland	78	Meadow: continuous grass.
Open water	N/A	Open water: 100% contribution

Storm water attenuation basin

The storm water attenuation basin was designed to have a maximum capacity of 14,200 m³ to attenuate a 100-year rainfall event. Rainfall contributes directly over the total surface area and evaporation removes water over the same area. If the storm water attenuation basin reaches capacity, it discharges to Cloheen pond.

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5.2.2 Model results

The surface water drainage model results are presented in Table 5.2 with peak flows calculated for infrastructure design for comparison. The model shows that the average rock fill discharge rate is 0.1 MLD, and runoff average of 0.28 MLD. Runoff events produce higher flow rates but for shorter durations than rock fill discharge. Discharge from the rock fill occurs almost all year round, whereas runoff rarely occurs, but is most common from December to February for average weather conditions.

The results also show that discharge from the storm water attenuation basin will only occur when surface runoff enters the basin (i.e. discharge from the TMF rock fill layer alone will not cause discharge). The model predicts that most discharge will occur from November to March, and will only occur infrequently from June to September.

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Table 5.2 Storm water attenuation basin inflow rates

Catchment	Mean annual discharge (MLD)	Peak discharge for 100-year return period design rainfall (MLD)
TMF rock fill discharge	0.1	6.5
Phase 1 runoff	0.02	16
Phase 2 runoff	0.14	88
Phase 3 runoff	0.02	20
Combined TMF discharge*	***0.28***	***152*****
Hardstanding	0.21	188
Vegetated	0.01	146
Storm water attenuation basin rainfall	0.05	244
Total storm water attenuation basin inflow*	***1.16***	***329***

* Virtually all TMF peak discharge is due to runoff from the reclaimed cover
** Not direct total of the contributing catchments due to variations in time of concentration

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5.3 SURFACE WATER QUALITY

The rock fill layer has been identified as the only post-closure water source which will potentially have a negative impact on water quality. This is because the tailings mass will settle slightly soon after closure (within 1 year) releasing some tailings pore water into the rock fill layer. Any settlement after this time is expected to be minimal (although the flushing of the rock fill will take longer).

Based on the assumed downward seepage rates and liner conditions, the tailings pile will remain saturated, so future long-term consolidation will be limited. Using a conservative assumption that all water released by the consolidation process will migrate into the rock fill within one year, the average daily pore water contribution will be 0.5 MLD. After this, the contribution will be significantly reduced and, ultimately, the downward head gradient from the rock fill to the tailings will ensure that no upward seepage occurs.

As the consolidation rate of the tailings reduces, the water quality in the rock fill layer will progressively improve. Any residual tailings pore water in the rock fill layer will be replaced by rainwater-recharge. The chemistry of the water within the rock fill layer will eventually become representative of the pore water in the overlying soil.

In the interim period, the chemistry of the rock fill water will contain elevated sulphate and some metals. Monitoring from Phase 1 suggests that the concentrations of sulphate, nickel and zinc reduce by around 20% a year.

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A water chemistry mixing model was combined with the surface water drainage model to predict the composite chemistry of the mixed water within the storm water attenuation basin and therefore the water that will be discharged to Cloheen pond. It indicates the discharge from rock fill will comply with the Integrated Pollution Control (IPC) Emission Limit Values (ELVs) within 7 years of covering (i.e. by 2025), except for zinc. The storm water attenuation basin has been planted with rhizomes and is expected to have the ability to 'polish' the water. However, the model is conservative and does not include the sequestration of metals, such as zinc, in the storm water attenuation basin. This will be investigated as part of the monitoring programme (Section 7.3).

5.4 CLOSURE PERIOD WATER QUALITY

5.4.1 Cloheen pond

Water quality data are presented in Appendix D. They show that the SW1 discharge (Cloheen pond) is generally compliant with the ELVs, with the following exceptions.

- Nickel and zinc exceed their respective ELVs for every sample. The source is currently unclear. However, the CW1 compliance well is adjacent to the Cloheen pond and this also shows elevated nickel (not seen in the groundwater adjacent to the TMF) and slightly elevated zinc. Therefore, a common source is probable. Further monitoring and review is required.
- Lead appears to spike in early-2018. However, this is most likely due to the limit of detection at the laboratory being too high (which has subsequently been reduced and all data since are compliant).
- Sulphate and ammonia were both elevated in late-2017 (and ammonia in early-2018) but this reduced following completion of the TMF closure works.

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5.4.2 Drish

Water quality upstream (Castletown) and downstream (Boolabeha) of the Cloheen ditch discharge confirm that the SW1 discharge from site is having a negligible impact on the Drish. Water quality in the Drish is generally below the ELVs for Lisheen's IPC licence and, where exceedances are seen, they are associated with upstream water quality as opposed to the SW1/Cloheen ditch discharge. Most notably, ammonia is frequently above the ELV in the upstream (Castletown) sample and, therefore, also elevated in the downstream (Boolabeha) sample. This is because the headwaters of the Drish receive water from peat bogs. Occasional upstream exceedances (and corresponding downstream exceedances) also occur for mercury and cadmium. It is unclear whether these are due to natural conditions or associated with analytical variance.

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5.4.3 Carrick Hill lake

The predominant water source at Carrick Hill lake is groundwater with some localised runoff and direct rainfall. Water quality samples taken in late-2017 and 2018 show a strong similarity with water quality in the Drish upstream of the PWE1 discharge point. This would be expected because both sources would be from shallow groundwater beneath areas of peat bog. The data (Appendix D) show that the water quality is generally below the ELVs, with the exception of:

- nickel since mid-2017 – this is associated with the limit of detection at the laboratory being too high and was rectified in August 2018; and
- cadmium – values are low but typically above the ELV.

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6. COMPARISON TO PREDICTIVE MODELS

6.1 OVERVIEW

The SWS (2015b) report 50785R4 '*Lisheen Mine: updated hydrology model to support mine closure*' made a number of recommendations regarding the active closure phases of groundwater level recovery at Lisheen. These have been revisited here to compare the predicted outcomes with the actual monitoring data. This provides a robust appraisal of the conceptual groundwater model and provides a mechanism for identifying its deficiencies.

The comparison focuses on Section 4.1 of the SWS report, excerpts from which are underlined and italicised in the following sections.

6.2 RECOVERY OF THE GROUNDWATER SYSTEM

6.2.1 Recovery period

The numerical analysis shows that final stabilisation of the groundwater system to pre-mining levels will most likely take between 3 and 7 years, depending on: (i) the actual drained porosity of the limestone units that surround the mine, and (ii) possible variations in the rainfall and recharge pattern during the filling period. If successive wet winters were to occur during the recovery period, then the rise in water level will be significantly quicker, as was the case at the Galmoy mine. Conversely, if there are dry winters and low spring recharge, the time for full recovery will be slower.

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As discussed in Section 2.4, the final dewatering wells were switched off on 31st December 2015 and full recovery was confirmed in April 2018 (Figure 2.7). Water levels took only 2 years and 4 months to recover, faster than the 'rapid recovery' prediction. This was due to lower than estimated porosity of the bedrock and backfill at depth. It confirms that most of the water pumped for dewatering was on-going recharge rather than release of groundwater storage. The recovery data show that the actual groundwater storage at the mining horizon is very low.

6.2.2 Post-recovery groundwater levels

The flooded mine workings themselves will have minimal effect on the post-mining groundwater flow system (assuming there is no residual pumping from the flooded workings). Based on the available pre-mining groundwater level data and the current model results, it is currently estimated that groundwater levels within the mine footprint area will ultimately recover to an elevation within the range 124 to 127 mOD. Because the entire mine footprint area will be interconnected by workings, water levels in the deeper Waulsortian will be flat across the entire mined footprint area.

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Peak groundwater levels observed on 31st January 2018 were: 123.6 mOD in DW14 and Fogarty; 124.3 mOD in MW15; and 125.3 mOD in MW21. The peak water level of 125.2 mOD in MW9 was seen on 31st May. It is likely that the maximum water levels occurred around late-March or early April. The monitoring data indicate the groundwater system has fully recovered.

As predicted, a flattening of the hydraulic gradient appears to have occurred in vicinity of the mine workings due to the greater connectivity of the groundwater system in the old workings. This is expressed as a widening of the space between the 120 mOD and 125 mOD contours in Figure 2.8.

6.3 INSTALLATION OF BULKHEADS

6.3.1 F2/F3 bulkhead

The available pre-mining data set suggests that groundwater heads in F2/F3 were 0.7 m lower than those in Waulsortian on the north side of the Killoran fault zone. If this is the case, there may be some potential for outflow to occur from the decline into the oolite at a very low rate. This is not likely to create any significant impacts to the downgradient groundwater system, particularly because the oolite is overlain by a thick sequence of ABL.

However, to mitigate any possible effects, it is planned that low pressure bulkheads will be installed in the Main decline and in the Derryville decline immediately below the F2/F3 pumping station. The purpose of the bulkheads is to isolate the F2/F3 zone from the main part of the flooded workings.

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A low-pressure bulkhead was installed below the F2/F3 pumping station. There are no monitoring wells in the Lisduff Oolite. However, all monitoring and compliance wells do not show an impact from the mine workings.

6.3.2 Derryville Island and Bog zones bulkheads

A low pressure bulkhead will also be installed to isolate the Derryville Island and Bog zones from the main part of the mined out workings. The purpose is to prevent free movement of water within the flooded workings and to prevent equilibration of heads across the mined out area.

Low pressure bulkheads were installed at Derryville Island and Bog zones.

6.4 GROUNDWATER HYDRAULIC GRADIENT AND FLOW

6.4.1 Hydraulic gradient

Once the groundwater recovery is substantially complete, the drawdown area will cease to represent a groundwater sink. Locally, the pre-mining shallow groundwater gradient towards

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the Rossestown and Drish rivers will become re-established. Regionally, the pre-mining gradient towards the south and southwest will eventually also re-establish.

Pre-mining groundwater gradients to the south and southwest have re-established as discussed in Section 2.4.2 and presented in Figure 2.8.

6.4.2 Groundwater flow

It is expected that post-mining groundwater flow will remain localized. Most of the recharge to Waulsortian above the mine footprint area will discharge locally to the ditches and streams that occur within and surrounding the mine footprint area. It is expected that the pre-mining baseflow to the Rossestown will also become re-established. Although there will be a small overall hydraulic gradient to the southwest, it is expected that minimal regional-scale groundwater flow will occur.

Most active post-mining groundwater flow will occur within the shallow epikarst zone where permeability is higher. It is expected there will be virtually no flow at deeper levels in the bedrock and that the flooded workings will be below the level of (and isolated from) the active groundwater system. The presence of the Killoran and Derryville fault zones, with low permeability ABL rock on the footwall, will tend to further isolate the flooded workings from any active flow at shallow levels.

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Natural groundwater discharge to the Rossestown was re-established by 21st December 2017 when the Lisheen ended the compensation flow.

Monitoring data from the two compliance wells show that any influence from the TMF is minimal and there is no influence of groundwater from the workings (Section 4.3 and 3.4, respectively). Furthermore, water quality data from the Drish also show no evidence of groundwater flow from the workings into the river (Section 5.3).

6.4.3 Shallow wells

Groundwater levels in the overlying glacial deposits are likely to remain decoupled and isolated from the underlying limestone bedrock. Over areas of slightly higher ground, there will be a slight downward gradient between the superficial deposits and the underlying competent Waulsortian. In areas of slightly lower topography, hydrostatic conditions will occur between the units, or there may be a very slight upward gradient. The slight vertical head gradients may be locally strengthened over the mine footprint area because of the interconnected nature of the flooded workings. Groundwater levels in the overlying peat deposits are likely to remain independent of the underlying Waulsortian.

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Groundwater levels in all of the regional (domestic) wells monitored as part of the closure programme (Section 3.4) were largely unaffected by the mine dewatering operation and the post-closure groundwater recovery.

6.5 CARRICK HILL BORROW PIT

The Carrick Hill borrow pit is located to the west of Main Zone. Current plans are for the pit to reach a maximum depth of 107 mOD. Final groundwater level recovery in this area is expected to between 121 and 122 mOD. The recovery model indicates that a lake will start forming within the borrow area from around 1 year after dewatering has stopped. The lake will ultimately be 14-15 m deep and full recovery will take between three and four years, depending on the rainfall patterns. Groundwater levels in the area of Carrick Hill will recover in a shorter time period than some of the mining areas because it is further from the centre of dewatering.

The design maximum water elevation for the lake is 122 mOD (i.e. comparable to groundwater levels), this is controlled by the permeable ‘storm outlet structure’ constructed to allow discharge from the lake to the Rossestown without allowing any fish into the Rossestown.

6.6 TMF

Invert levels in the TMF perimeter drain range from 120 to 128 mOD. In this area, it is predicted that groundwater levels will recover to between 125 and 130 mOD. Backfilling the drain with compacted peat would prevent any post-mining standing water or flow within the drain. Backfilling of the drain will very slightly alter the groundwater conditions within the foundation materials of the TMF embankments, therefore the post-closure stability will be considered before finalising the plan.

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The TMF drain was backfilled and groundwater levels have recovered to over 125 mOD. The TMF is regularly audited as part of the post-closure monitoring programme to ensure that the recovered groundwater levels do not have an impact on embankment stability.

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7. MONITORING

7.1 POTENTIAL HYDROGEOLOGICAL IMPACTS

Most natural groundwater flow in the Lisheen area occurs in the upper epikarst zone of weathering and fracturing, typically 30 to 50 m below ground level. This was indicated by the baseline hydrogeology studies for the project and has been confirmed by the operational monitoring data. Since full recovery was achieved in early 2018, the regional groundwater gradient to the south and southwest has become re-established. However, as demonstrated during the baseline period, the actual groundwater flux rate is very limited. Assuming a hydraulic gradient of 0.003, the natural groundwater flow rate towards the south and southwest can be calculated to be about 1.7 MLD. Calculated groundwater velocities are between 90 and 125 m per year. The downgradient groundwater flux would occur above the level of the mine workings, and much of the flux would remain fairly local to the site and would be lost by evapotranspiration. This has been demonstrated by the relationship between the workings and CW2 (Section 3.3) and between the TMF and CW1 (Section 4.3).

7.2 RECEPTORS

7.2.1 Overview

There are four types of receptor for which potential impacts need to be considered following permanent mine closure. These are as follows:

- domestic and agricultural water supply wells downgradient of the mine workings and TMF to the south and southwest;
- public and group scheme wells in the downgradient area to the south and southwest;
- the Drish and Rossestown rivers and other local streams and ditches, as a result of groundwater discharge from the flooded workings to local drainages
- the drainage system between Cloheen pond and the Drish as a result of outflow from the storm water attenuation basin; either flooding or water quality.

7.2.2 Domestic and agricultural water supply wells

Lisheen maintains a database of water supply wells in the local area. It catalogues ten private wells within a 2.5 km radius of the mine site and underground workings. A further 27 domestic/agricultural wells are located within a 5 km radius. Most private wells are located to the north or east of the mine (upgradient of the mine workings and the TMF) or at considerable distance to the south or west (downgradient). The exceptions shown on Figure 4-3 are:

- Fintan Casey and Sean Hayden located 300 m south of Derryville and 900 m west of the TMF; and

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- Hennessy's, Pat Healy's and Patrick Daly located between 200 m and 900 m south of the TMF.

The available well logs indicate that the wells are completed either in superficial glacial sand and gravel lenses, or in shallow bedrock. As such, it is extremely unlikely they will be affected by water chemistry changes in the workings. There is some small potential they may be partially within the downgradient transport zone from the TMF but monitoring data from CW2 (downgradient of the TMF) shows that the water quality is compliant with the exception of nickel (deemed to be due to a source local to the well) and nitrogen-species (associated with the peat bogs and agriculture).

Water quality sampling of the wells has been undertaken throughout the mine life and will continue at select locations during and after closure as discussed in Section 7.3.1.

7.2.3 Public and group scheme wells

The closest public or group water scheme supply (GWSS) wells to the mine area are Bawnmore and Kilmakill (Moyne GWSS).

The Kilmakill well is about 5 km to the south of the mine site (downgradient). The available well logs indicate that most of the scheme wells are less than 90 m deep, and available inflow data suggest that inflows to the wells are from the upper epikarst zone. As such, there is little potential for any impacts during the closure and post-closure period.

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The Bawnmore group water scheme is it is located about 1.5 km northeast (upgradient) of the TMF. The two wells are shallow and therefore likely to be drawing groundwater supply from sand and gravel lenses contained within glacial till material. It has been demonstrated that the wells are not being impacted by the drawdown area, and they are not likely to be at risk from mine closure or in the long term.

7.2.4 Drish and Rossestown rivers

Under natural conditions, both the Drish and Rossestown rivers include gaining reaches where they flow closest to the mine area. They both receive groundwater from the shallow Waulsortian. The Rossestown received a compensation flow of at least 0.04 m³/s during operations to mitigate the reduction in groundwater baseflow as a result of dewatering. The Drish did not demonstrated any losses to groundwater during the period of mine dewatering but received most of the dewatering discharge water.

Natural groundwater baseflow to the Rossestown became re-established in 2017, before full recovery was complete. This baseflow is derived from the shallow epikarst zone and will be sustained by ongoing recharge and infiltration within the local area, so there is little potential for any impacts from the flooded workings.

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Similarly, the natural groundwater baseflow to the Drish is derived from the shallow epikarst zone; sustained by ongoing recharge and infiltration within the local area. Although the river is downgradient from the mine area, there is little potential for any water chemistry impacts as the predicted flux from the mine area is low. During mine operations, there were no losses from the Drish to drawdown area.

Monitoring data from the Drish in 2018 (post-full groundwater recovery) show no impact from groundwater in mine workings or below the TMF, or from surface water discharges from Cloheen pond (SW1). Ammonia is frequently above the ELV in the Drish upstream (Castletown) sample and, therefore, also elevated in the downstream (Boolabeha) sample. This is because the headwaters of the Drish receive water from peat bogs.

7.2.5 Drainage system between the Cloheen pond and the Drish

Potential impacts below the Cloheen pond may occur because of high flows or elevated water chemistry parameters in the TMF or retention pond discharge.

As described in Section 4, the storm water attenuation basin was constructed so that the maximum discharge to Cloheen pond at SW1 is no greater than flow rates under pre-mining ("greenfield") conditions. Therefore, the potential for flooding will be the same post-closure as it was pre-mining because the storm water attenuation basin has been designed to attenuate peak flows.

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The mass balance analysis for the storm water attenuation basin has been carried out to help ensure that the discharge from the basin to the Cloheen pond complies with the IPC licence limits for water quality and flow. As conditions within the reclaimed TMF stabilise, the potential for any water quality exceedances will reduce with time.

7.3 MONITORING PLAN

7.3.1 Modifications to the plan

A comprehensive monitoring plan was prepared for the closure and post-closure period (see SWS, 2015b for further details). As a result of the data analysis above and liaison with the EPA, the only changes to this plan are: (i) inclusion of some additional parameters in the analysis suites; and (ii) maintaining the frequency of Carrick Hill lake sampling at quarterly (as opposed to bi-annually). Full details are presented in Appendix E and monitoring locations presented in Figure 7.1 and Figure 7.2.

7.3.2 Groundwater

All groundwater monitoring locations (compliance wells, workings, TMF and regional) will be sampled bi-annually through 2019 and 2020. These samples will be analysed in an external

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laboratory for the 'groundwater suite'. In addition to this, the water level in the compliance wells will be monitored monthly and any additional IPC sampling and analysis required by the licence conditions will be completed on the TMF wells.

The groundwater monitoring suite is as follows:

- physicochemical – pH, electrical conductivity, temperature, dissolved oxygen and total dissolved solids (TDS);
- dissolved metals – Ag, Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, Pb, Sn, U and Zn;
- nutrients – NH_3, NO_3, NO_2 and PO_4; and
- anions – Cl, SO_4, hardness and alkalinity.

7.3.3 Surface water

Once discharge is occurring from all three TMF phases, flow and field parameters will be recorded at least on a fortnightly basis at: (i) all three spillways; (ii) the transfer box; and (iii) the storm water attenuation basin spillway. Based on the results, the frequency may be reduced. Sampling for 'surface water suite' analysis will be undertaken at the same locations once a month until the chemistry has stabilised.

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Monthly sampling and 'surface water suite' analysis will also be undertaken at: (i) the Cloheen pond (SW1); (ii) downstream of the Cloheen before meeting the Drish; (iii) upstream of the confluence in the Drish (Castletown); and (iv) downstream in the Drish (Bohlabela). These locations may also be subject to additional IPC sampling and analysis, as required by the licence conditions.

Carrick Hill will continue to be sampled for 'surface water suite' analysis on a quarterly basis through 2019 and, provided that the chemistry has stabilised, reduced to bi-annually in 2020.

Fortnightly field parameters to be monitored are pH, electrical conductivity, temperature and dissolved oxygen.

The surface water monitoring suite is as follows:

- physicochemical – pH, electrical conductivity, temperature, dissolved oxygen, redox, TDS, total suspended solids (TSS), colour and turbidity;
- dissolved metals – Ag, Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, Pb, Sn, U and Zn;
- nutrients – NH_3, NO_3, NO_2, P and TOC; and
- anions – Cl, F, SO_4, hardness and alkalinity.

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Figure 7.1 Monitoring locations

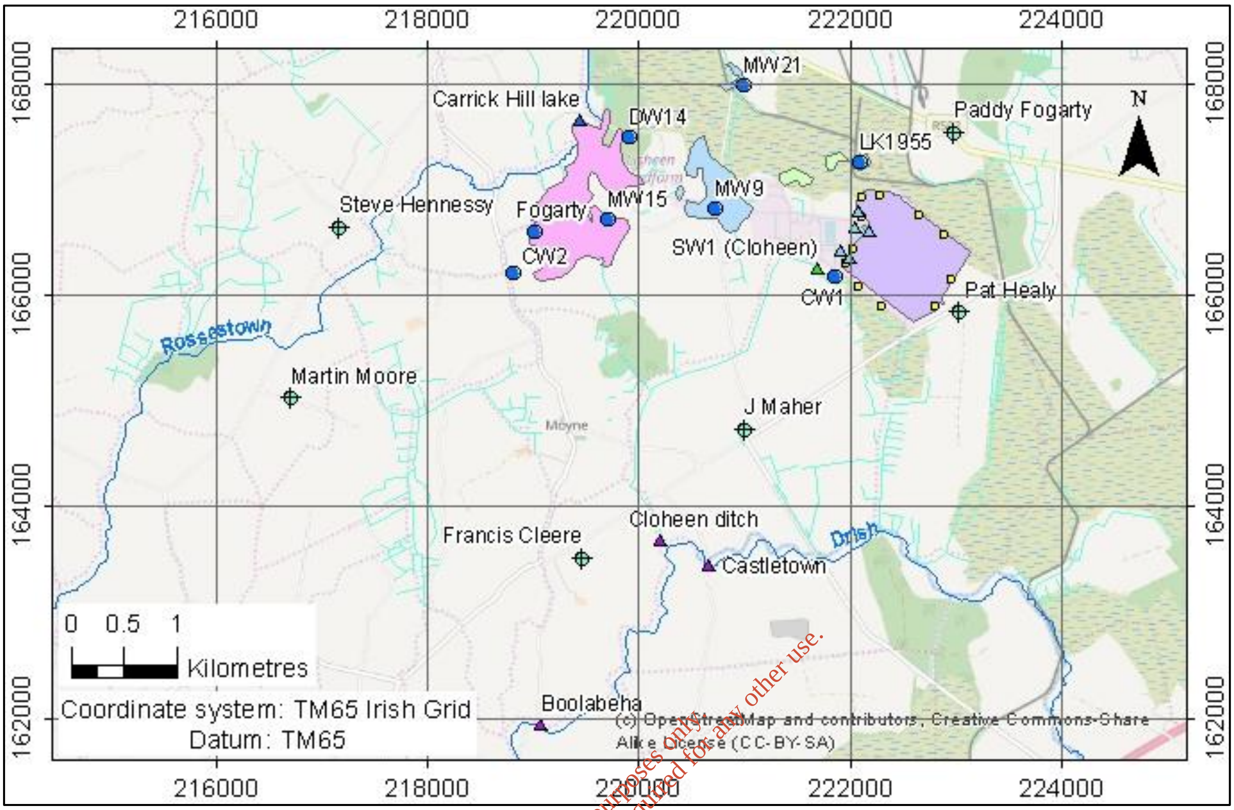
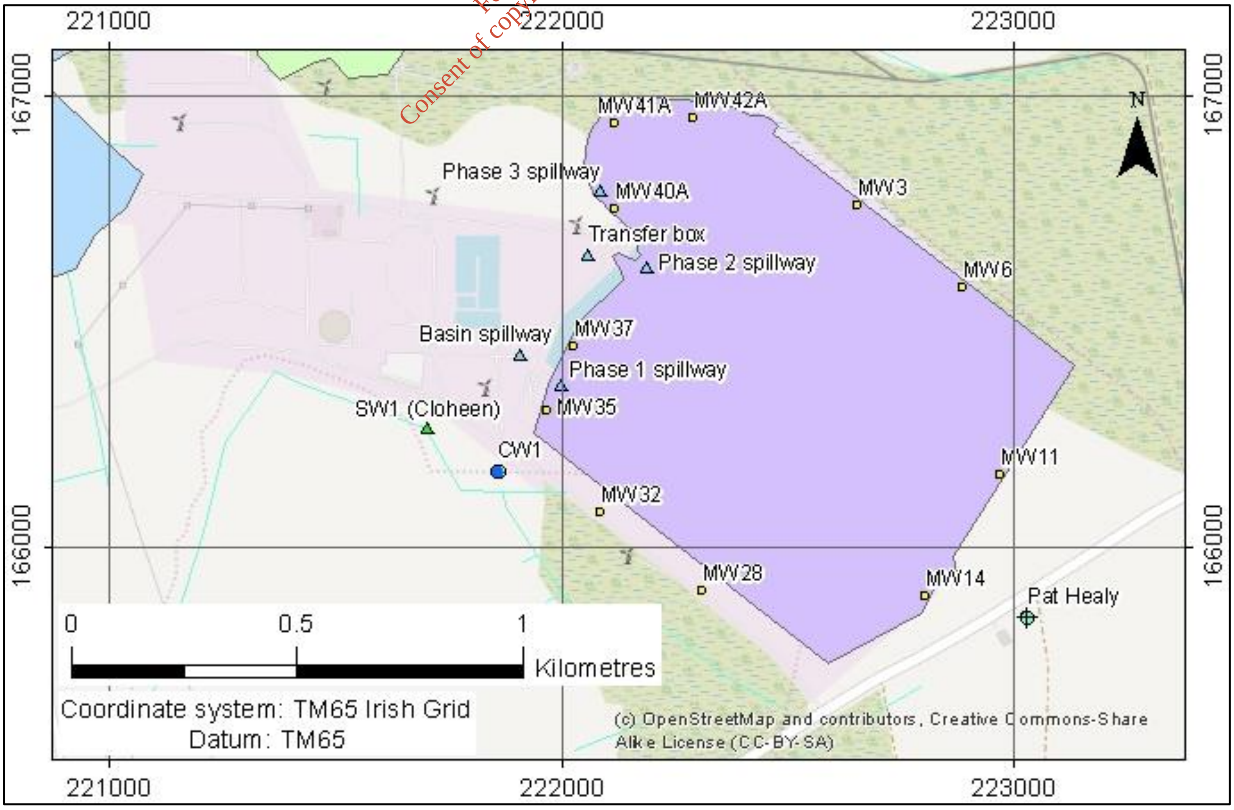


Figure 7.2 TMF monitoring locations



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8. CONCLUSION

Groundwater conditions around the Lisheen mine had full recovered by January 2018, two years after the last dewatering pumps were switched off. Peak groundwater levels observed on 31st January 2018 were between 123 mOD and 125 mOD, compared to a pre-mining groundwater elevation of between 122 and 127 mOD. Pre-mining groundwater gradients to the south and southwest have re-established but, as predicted, a slight flattening of the hydraulic gradient appears to have occurred in vicinity of the mine workings due to the greater connectivity of the groundwater system in the old workings.

Natural groundwater discharge to the Rossestown has become re-established and all surface water discharges have been decommissioned, except for SW1 (Cloheen pond) which is the discharge point of TMF and site runoff.

Monitoring data from the two compliance wells show that any influence from the TMF is minimal and there is no influence of groundwater from the workings. Water quality data from the Drish also show no evidence of groundwater flow from the flooded workings or the TMF.

Groundwater levels and water quality in all of the regional (domestic) wells monitored as part of the closure programme were largely unaffected by the mine dewatering operation and the post-closure groundwater recovery.

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Both groundwater and surface water data show that water quality is generally good and within compliance/regulatory standards. However, there are the following exceptions.

- Nickel is elevated in both SW1 and CW1 (surface water and groundwater at the same location) and zinc in SW1. This is likely to be due to the same source which, currently, is uncertain. Further monitoring and review is required to determine the source or monitor the trend until it is compliant.
- Mercury in Carrick Hill lake also shows elevated values. This appears to be due to the limit of detection being too high, but further investigation should be made to confirm this.

Many groundwater and surface water locations have elevated ammonia (and occasionally nitrate). These are associated with pre-mining conditions (peat bogs) and current agricultural practices (landspreading).

A comprehensive monitoring plan was prepared for the closure and post-closure period (see SWS, 2015b for further details). Only two modifications have been made to this plan as part of this review: (i) inclusion of some additional parameters in the analysis suites (at the request of the EPA); and (ii) maintaining the frequency of Carrick Hill lake sampling at quarterly (as opposed to bi-annually) as the water quality stabilises.

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9. LIMITATIONS

Piteau Associates has exercised reasonable skill, care and diligence in obtaining, reviewing, analysing and interpreting the information acquired during this study, but makes no guarantees or warranties, expressed or implied, as to the completeness of the information contained in this report. Conclusions and recommendations provided in this report are based on the information available at the time of this assessment.

In preparing the recommendations contained herein, Piteau Associates has relied on information and interpretations provided by others. Piteau Associates is not responsible for any errors or omissions in this information. This report is comprised of text, tables, figures, photos and appendices, and all components must be read and interpreted in the context of the whole report. The report has been prepared for the sole use of Lisheen Mine, and no representation of any kind is made to any other party.

Respectfully submitted,

PITEAU ASSOCIATES UK LTD.

SSholl

Simon Sholl
Hydrogeologist

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APPENDIX A

Water quality data for the mine workings

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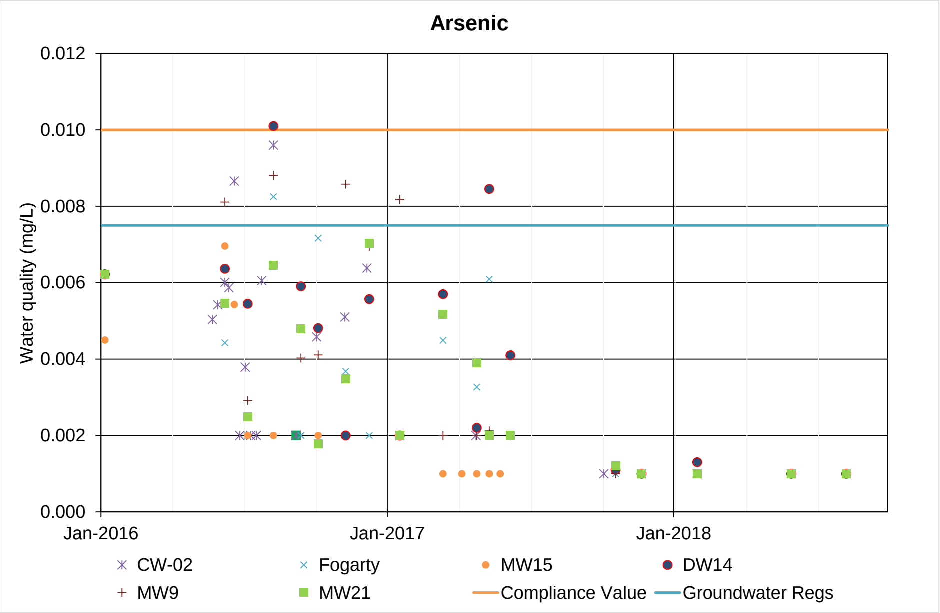
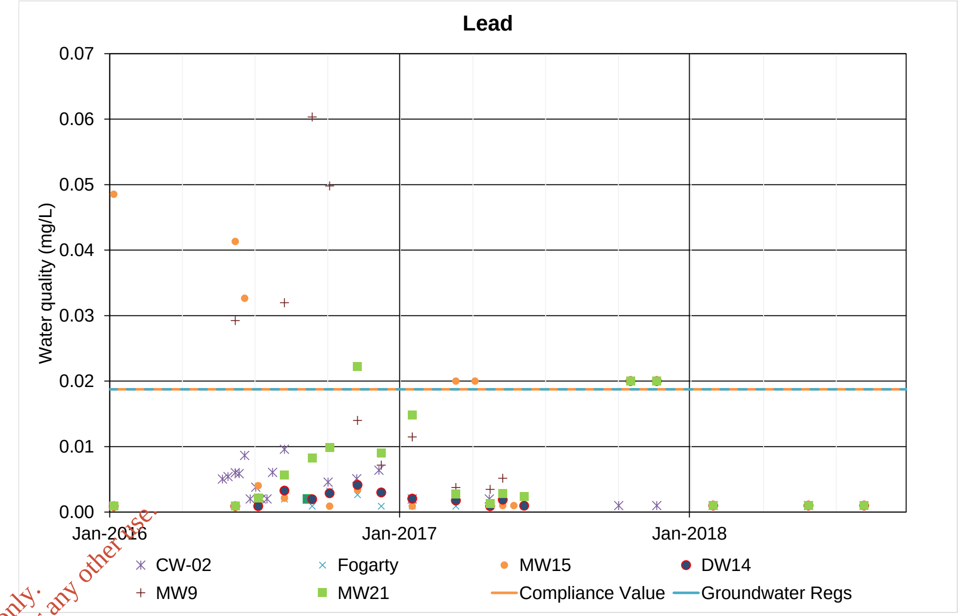
Water quality data for the mine workings





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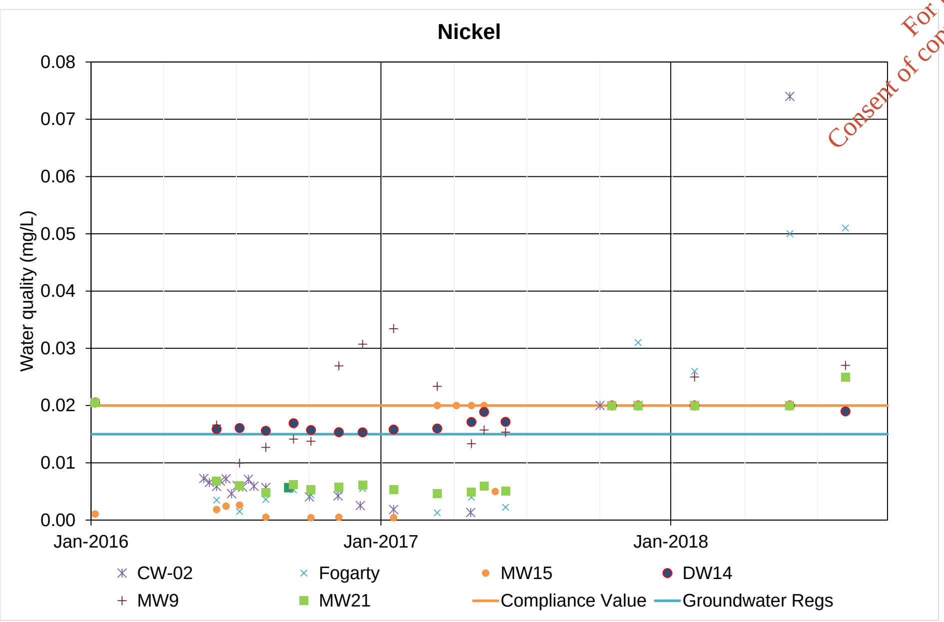

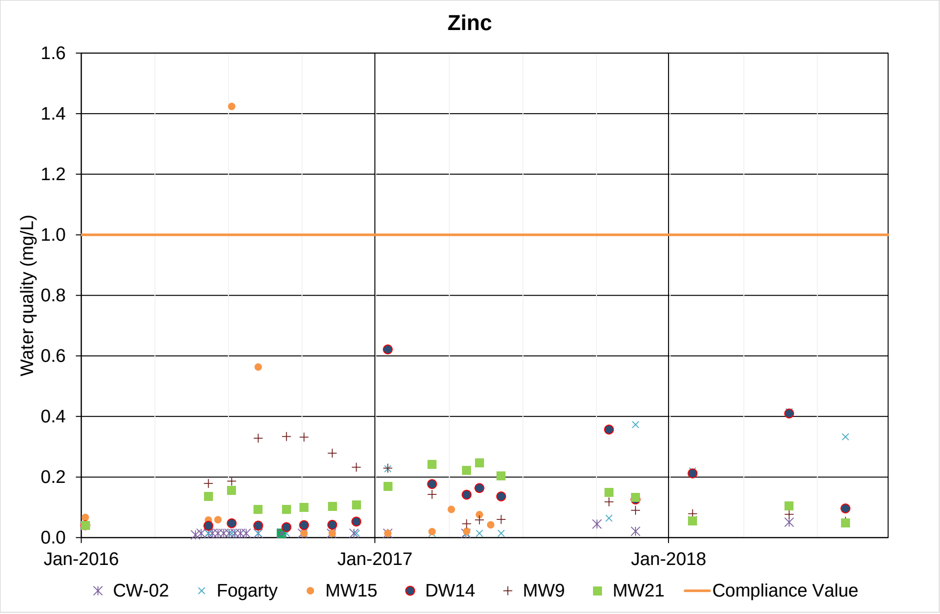

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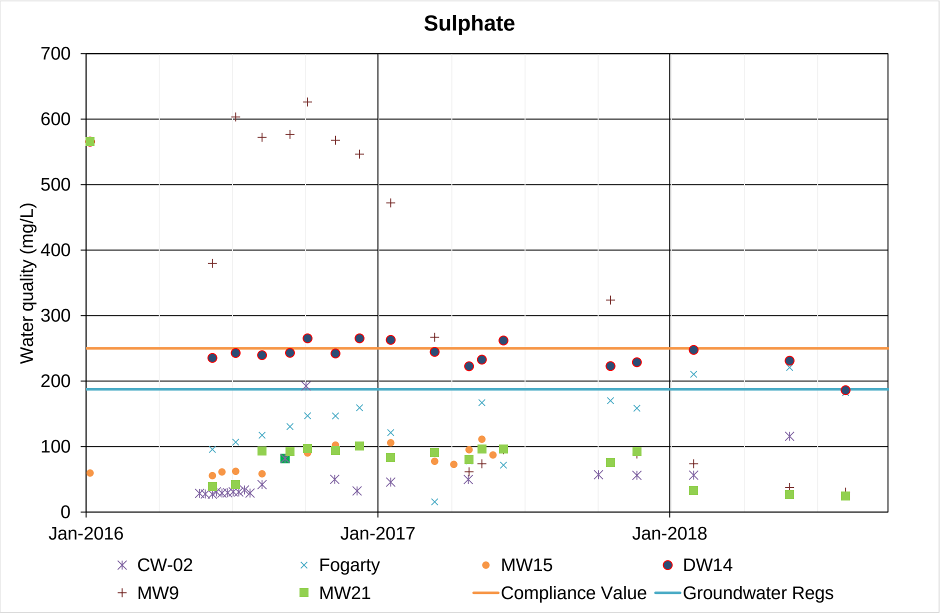

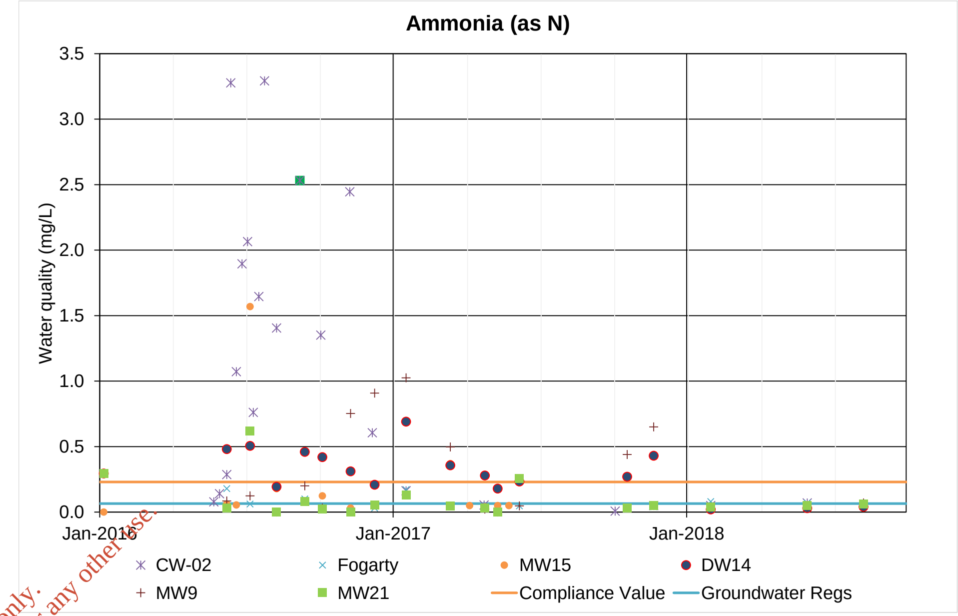

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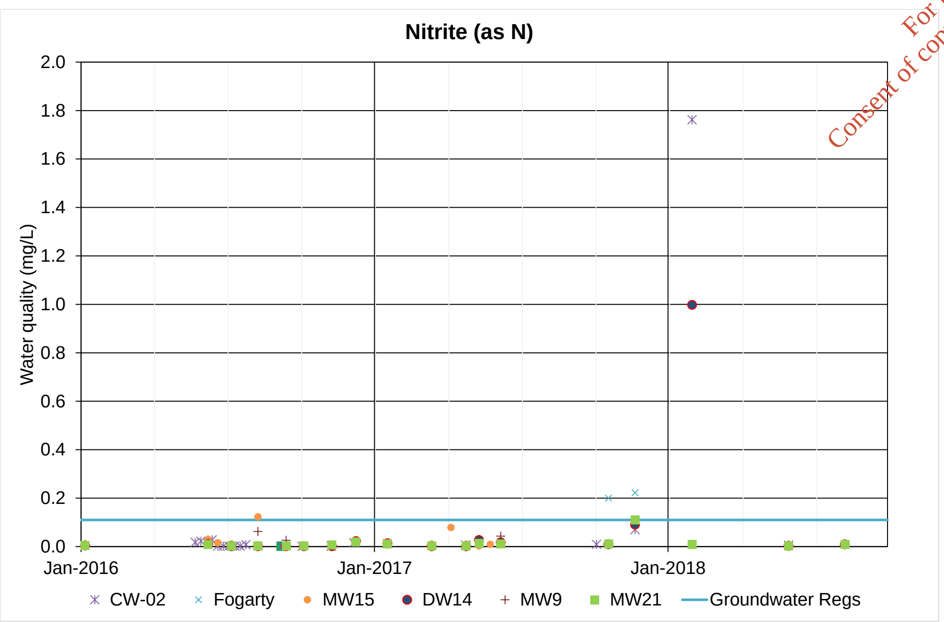

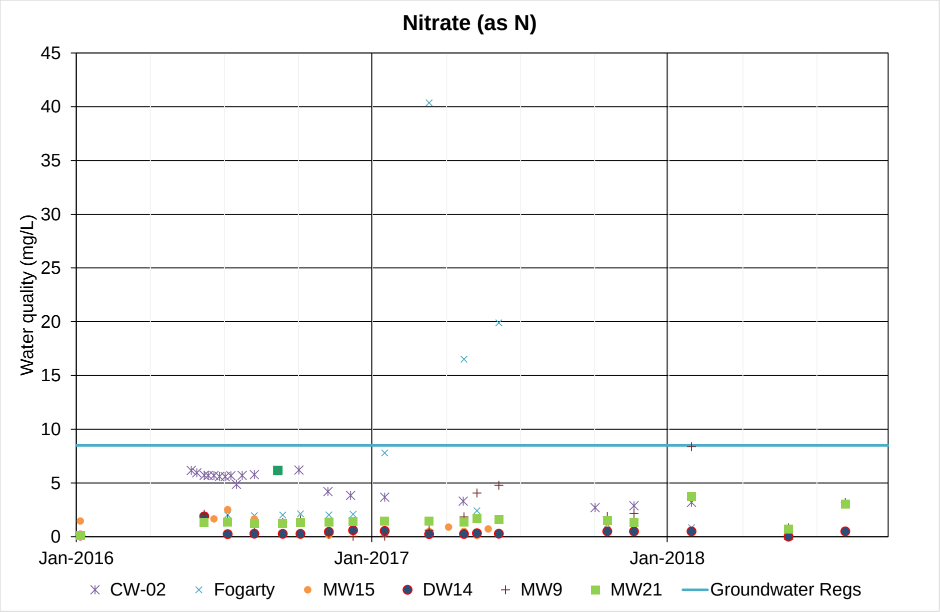

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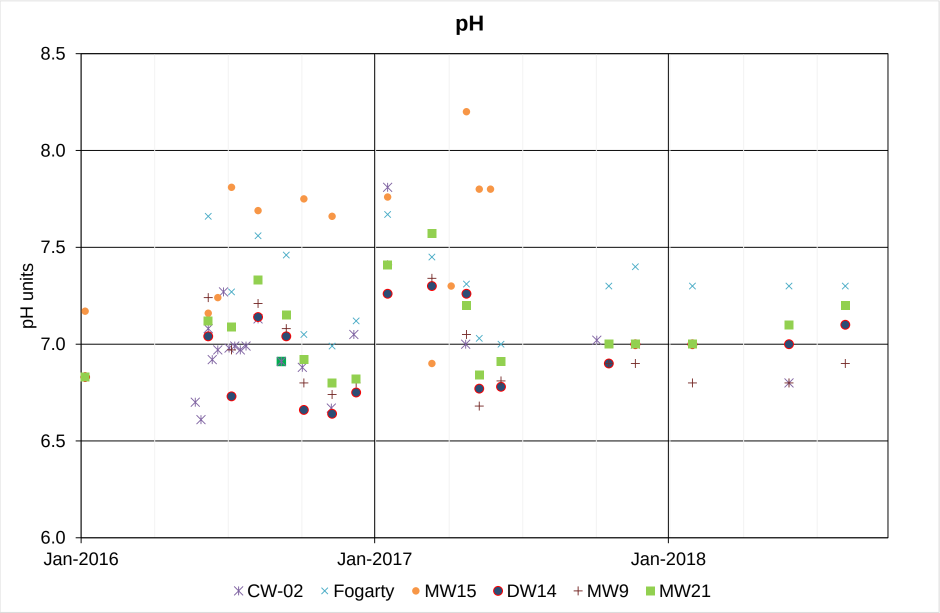

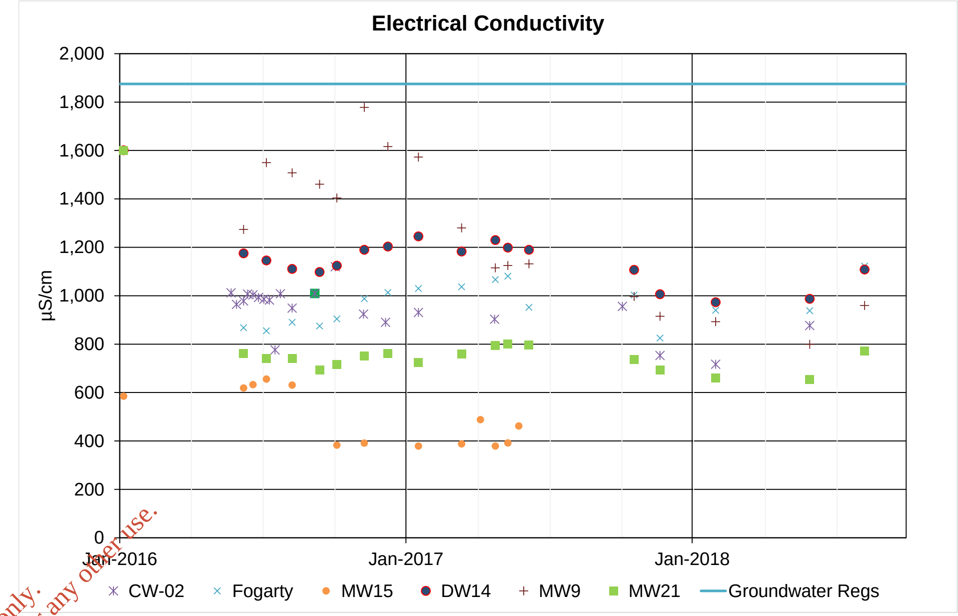

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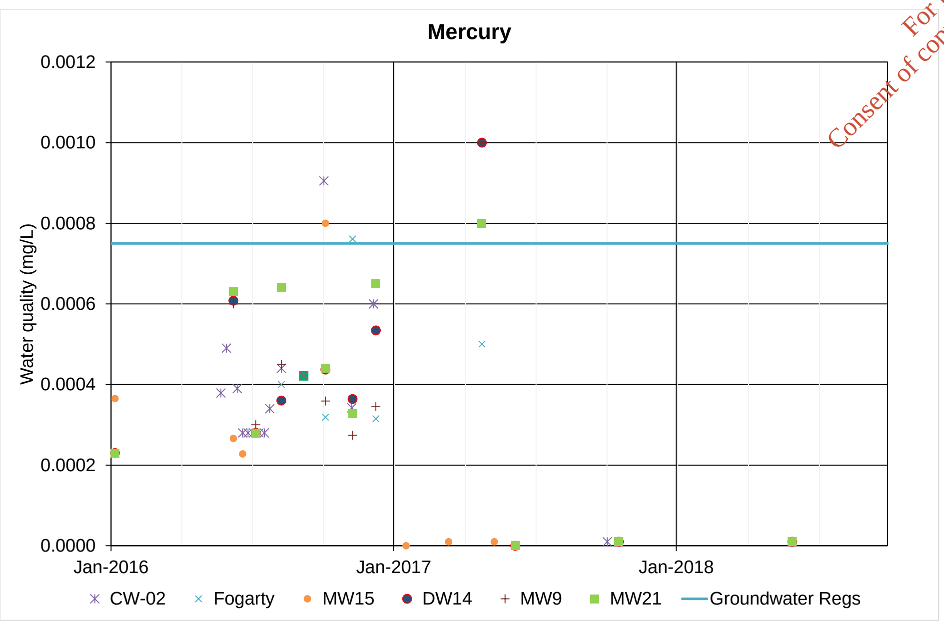

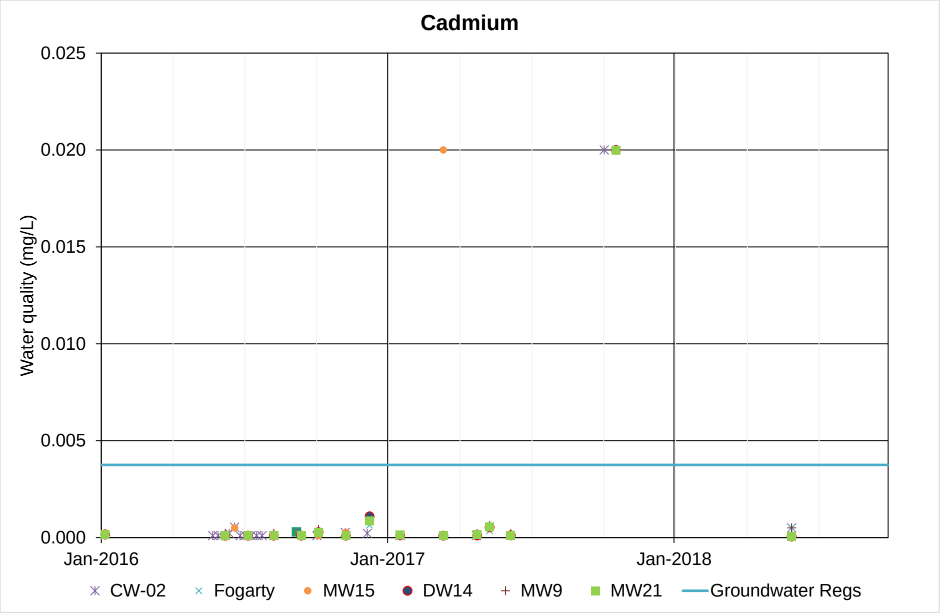

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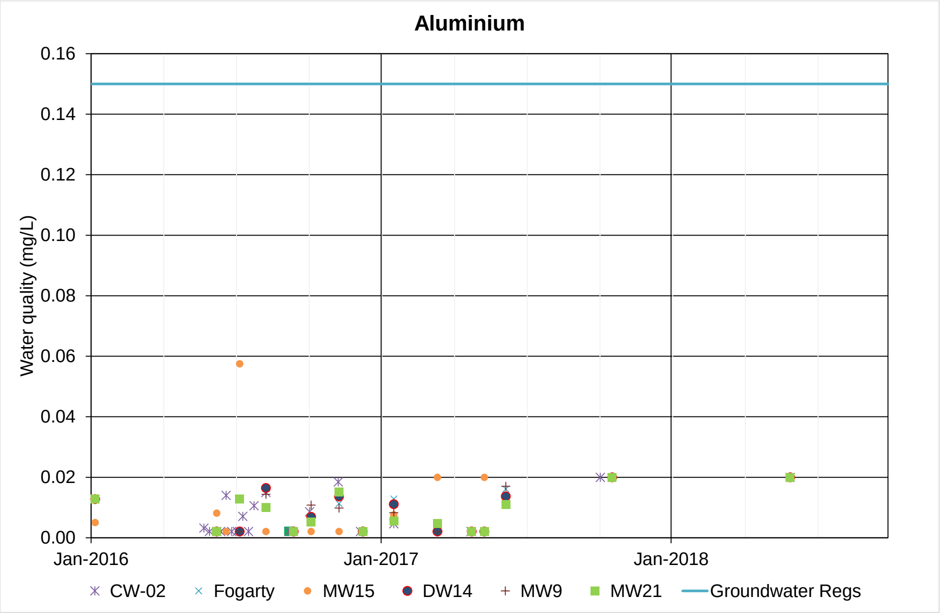

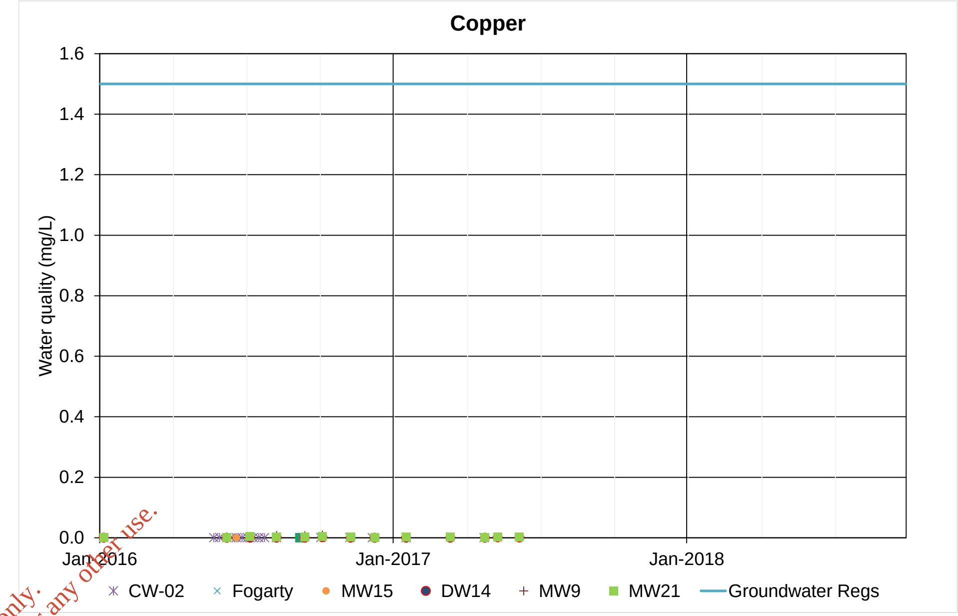

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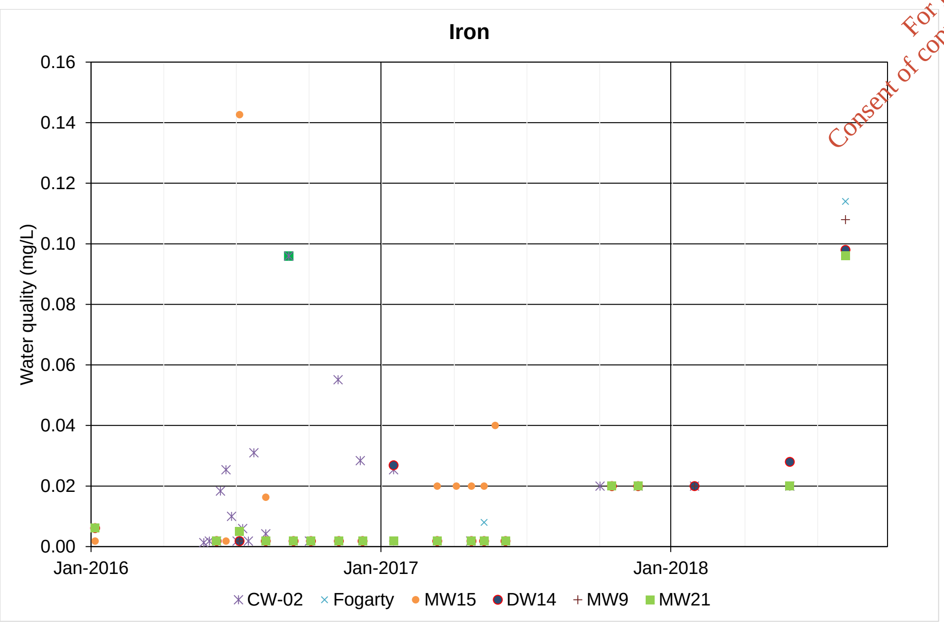

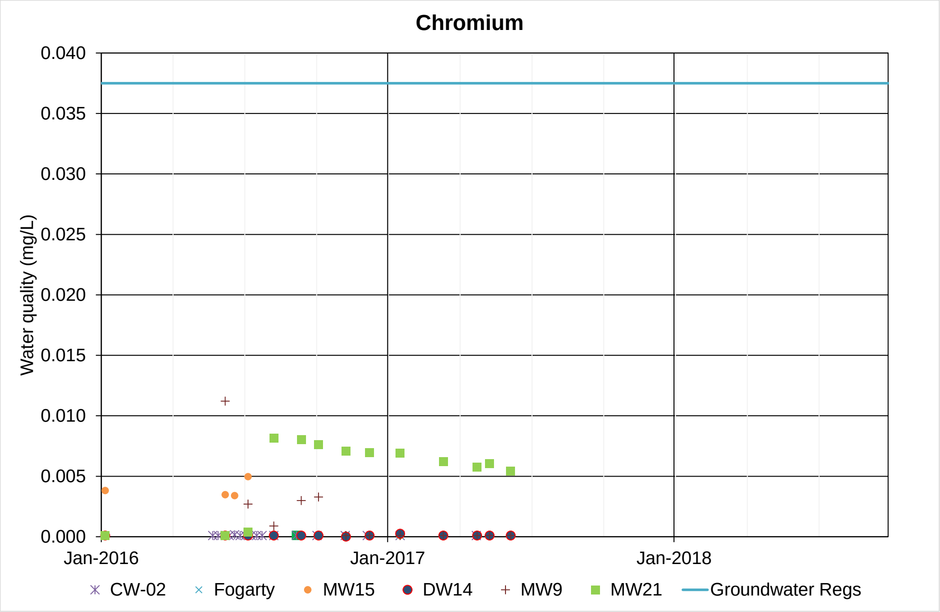

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APPENDIX B

Water quality data for the regional (domestic) wells

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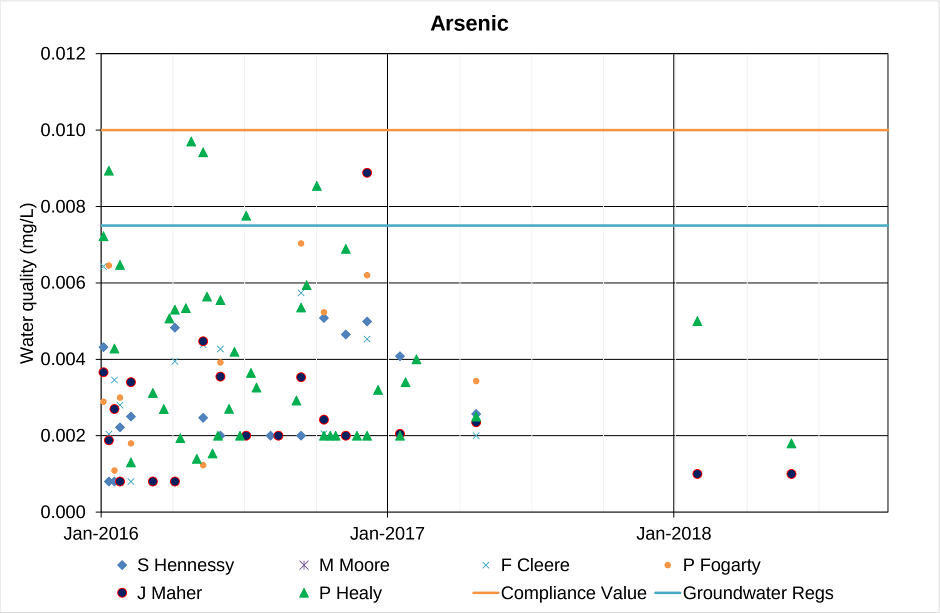
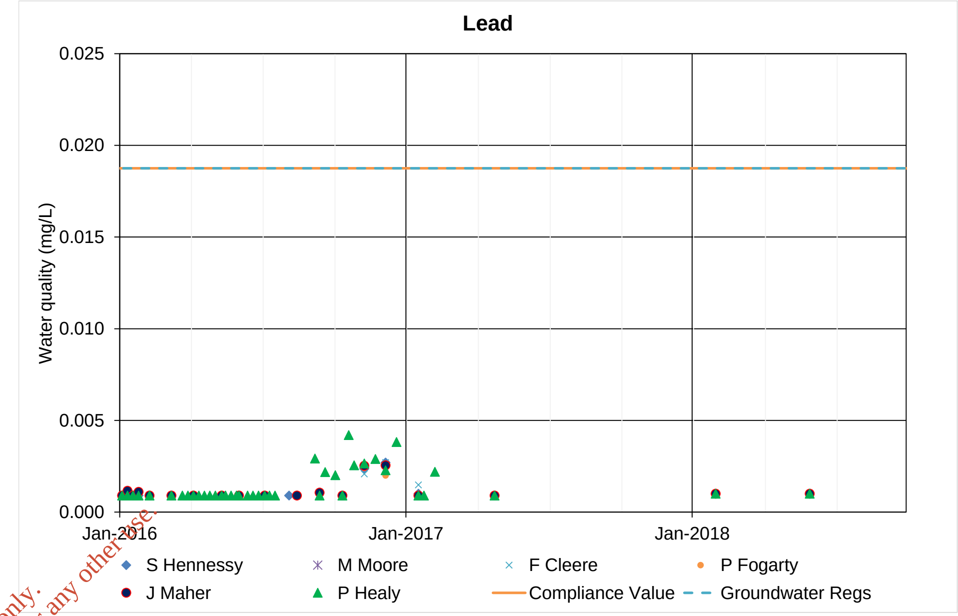
Water quality data for the regional (domestic) wells





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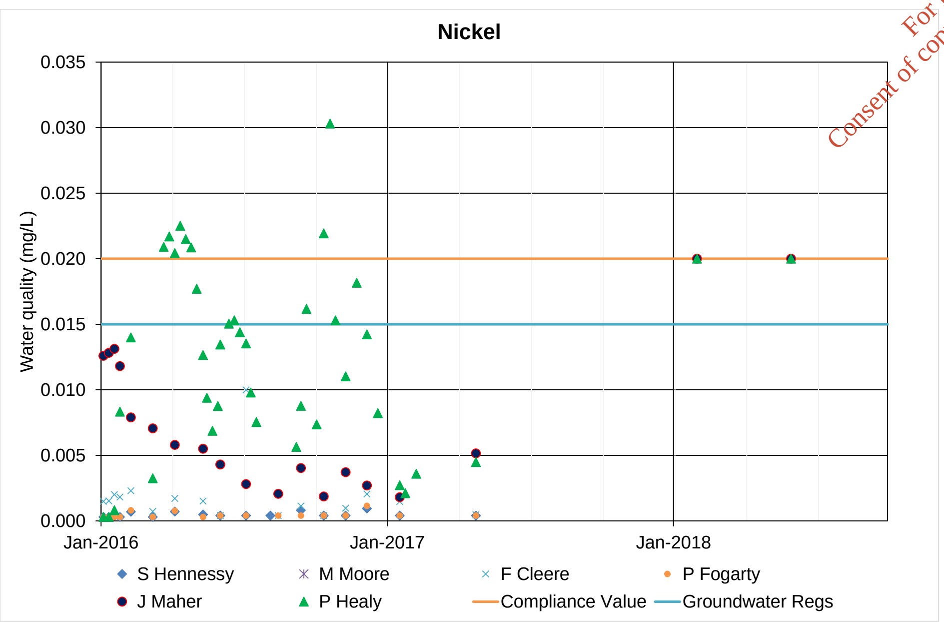

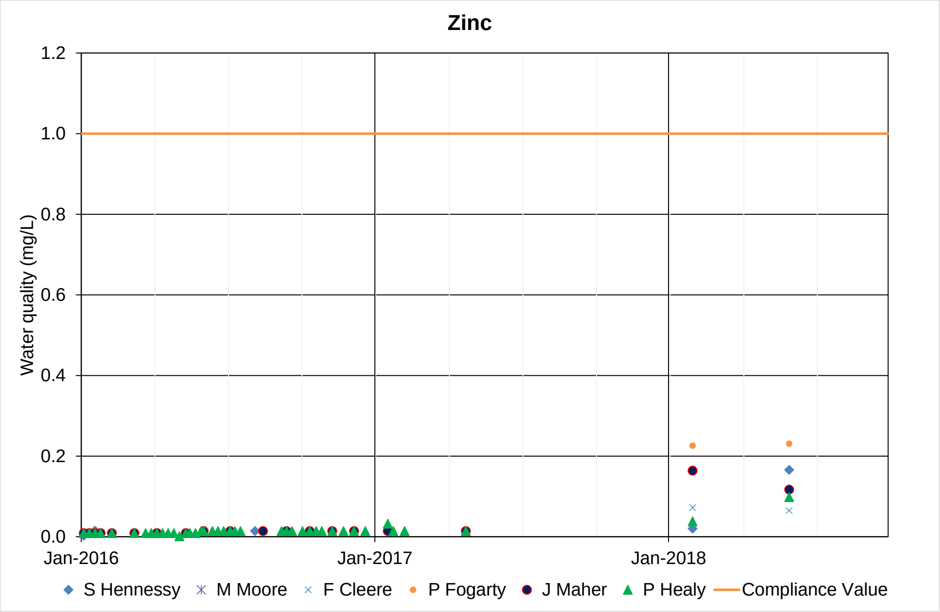

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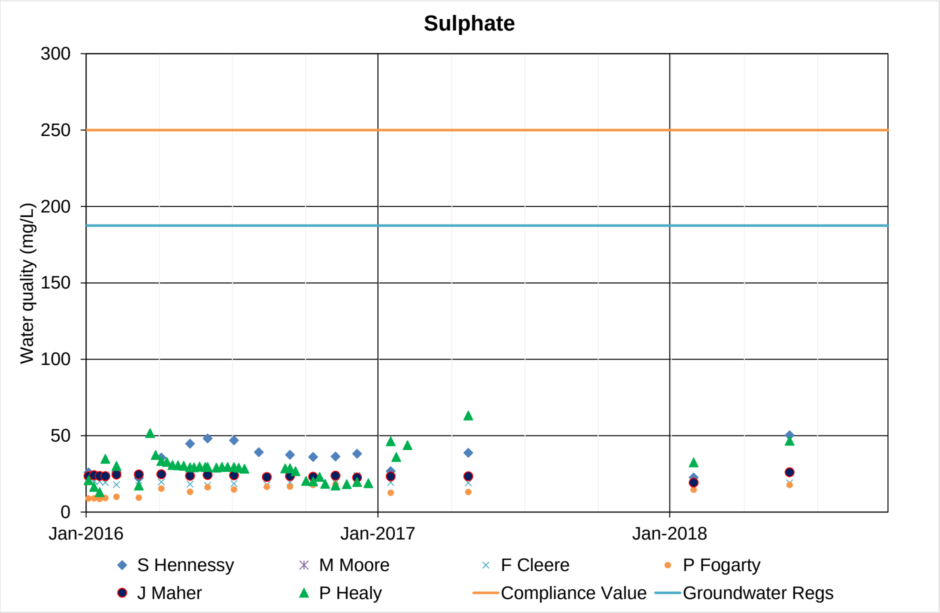
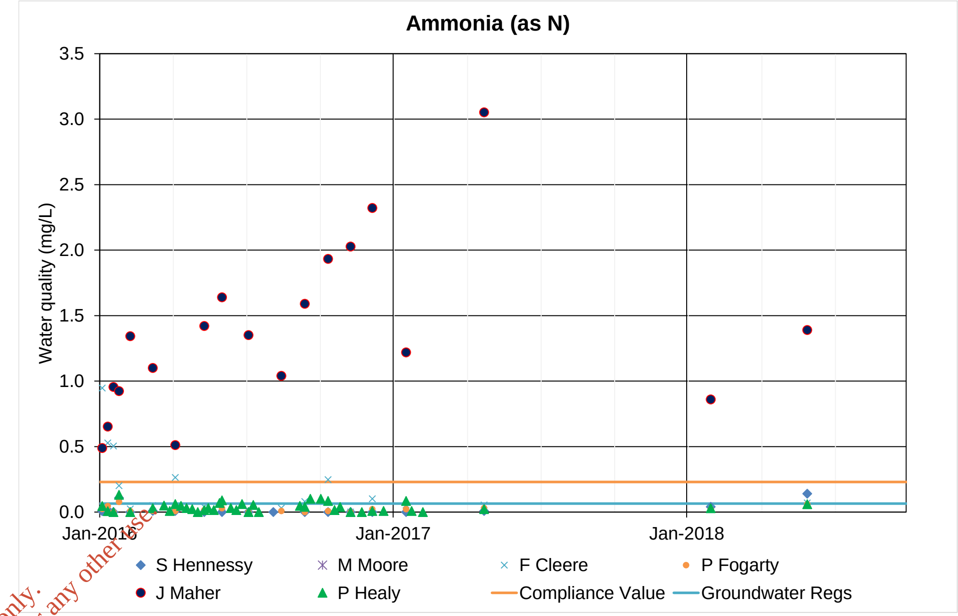
Water quality data for the regional (domestic) wells





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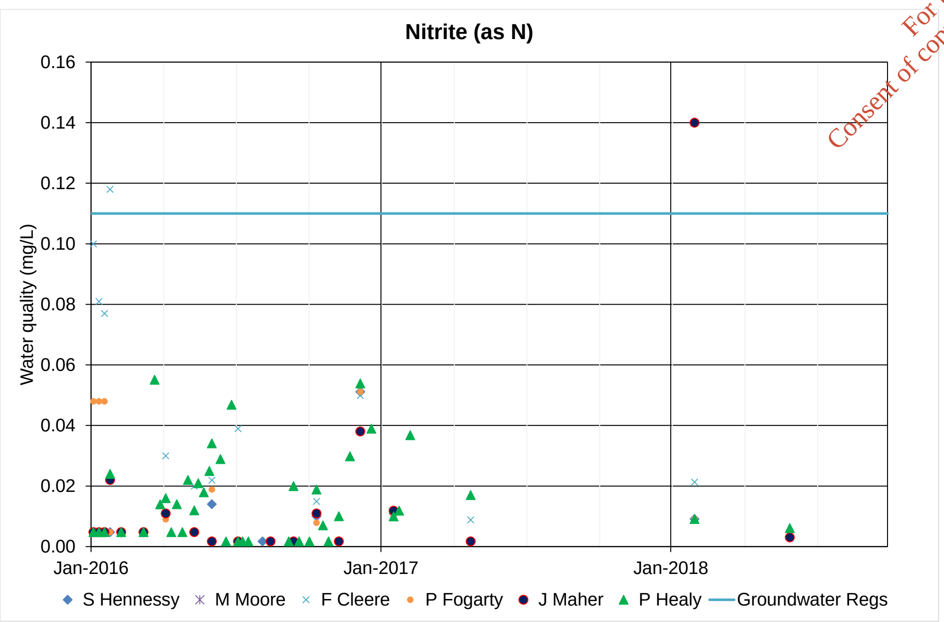

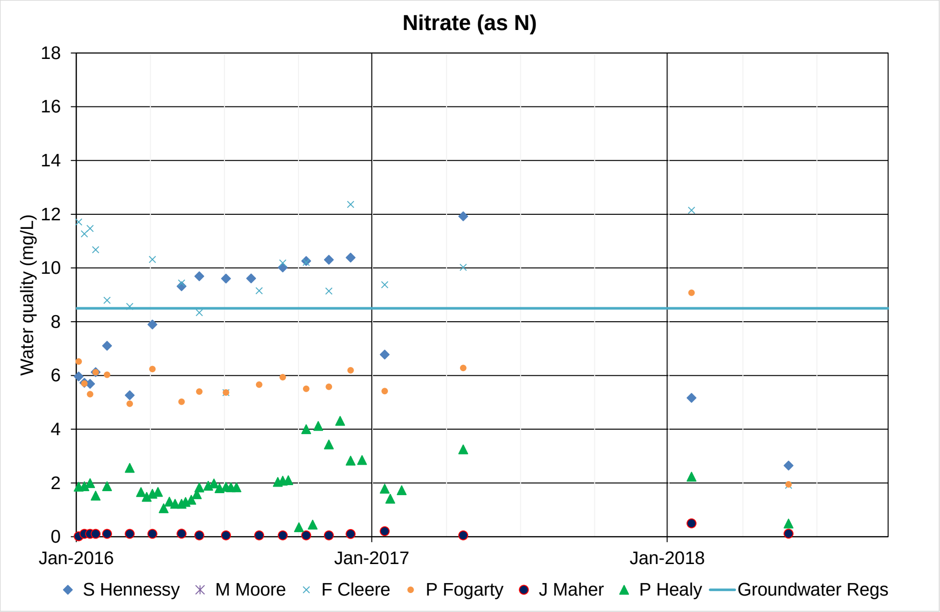

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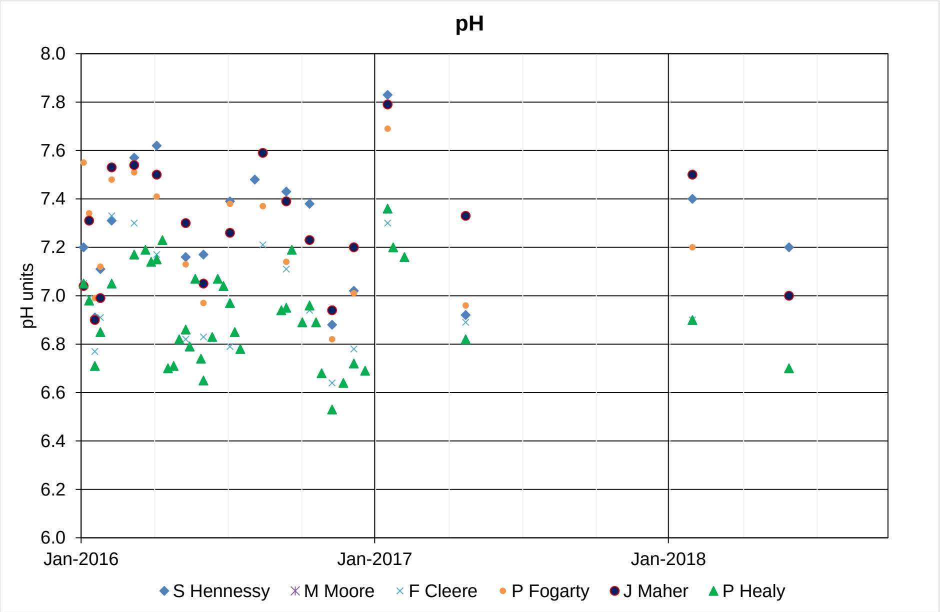
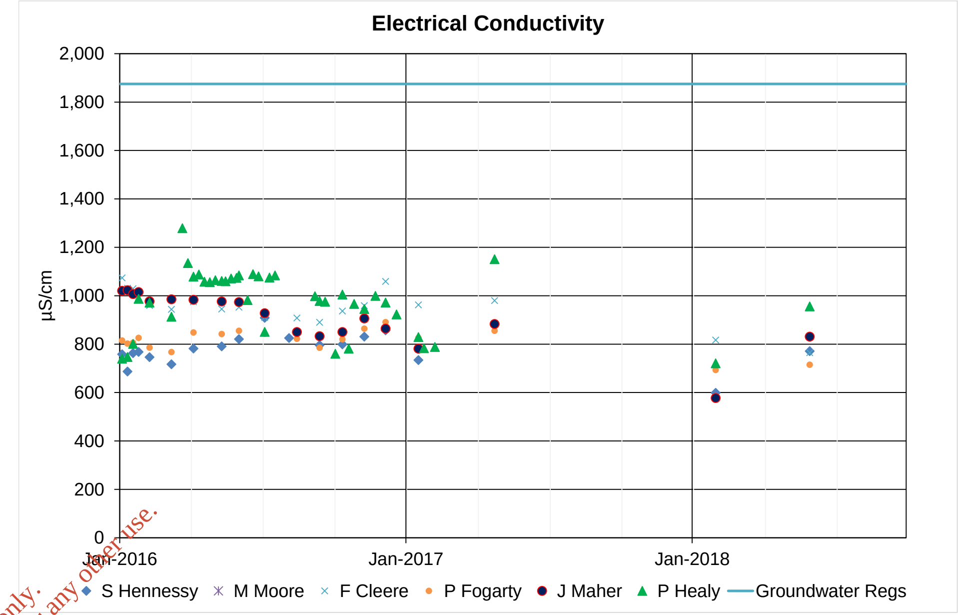
Water quality data for the regional (domestic) wells





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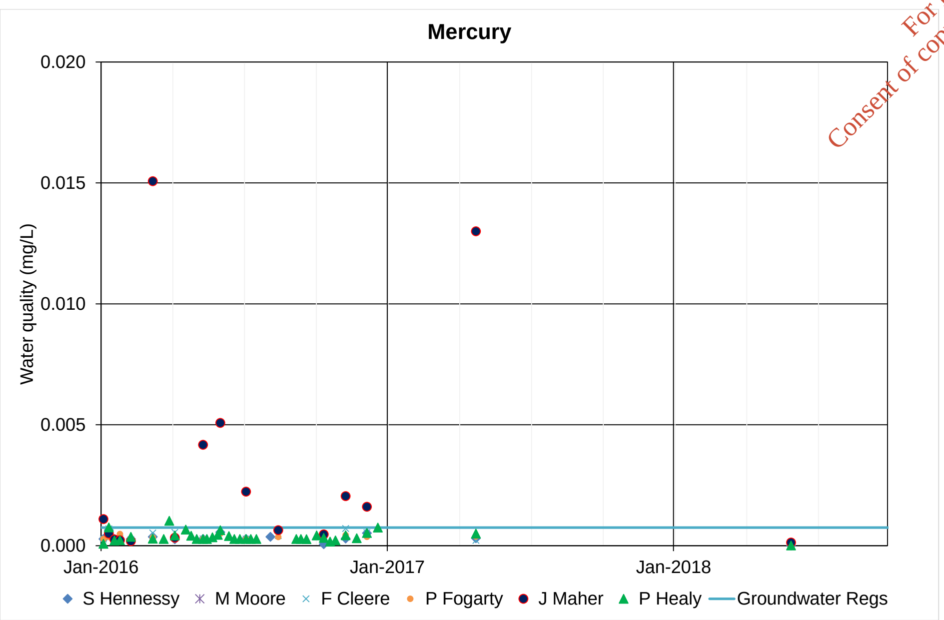

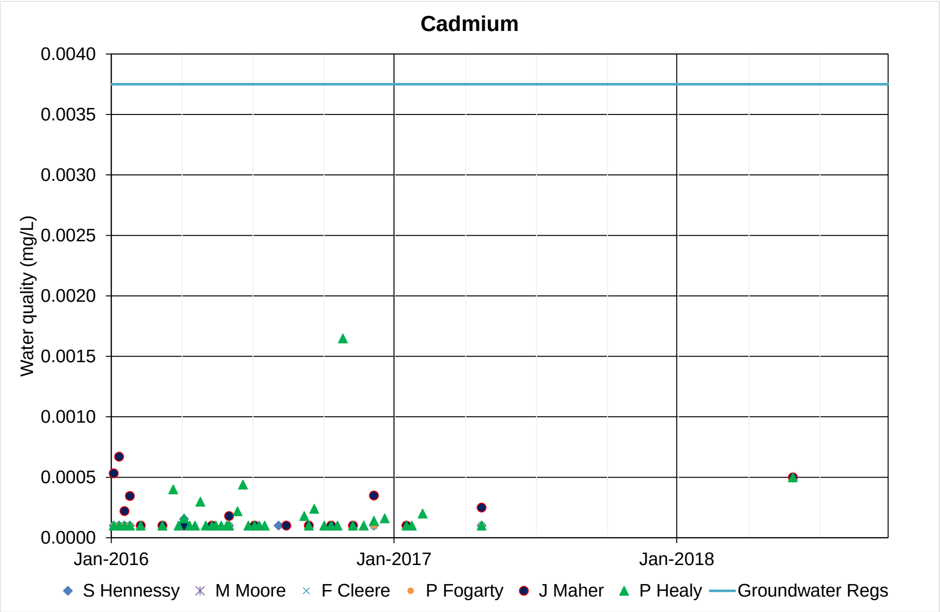

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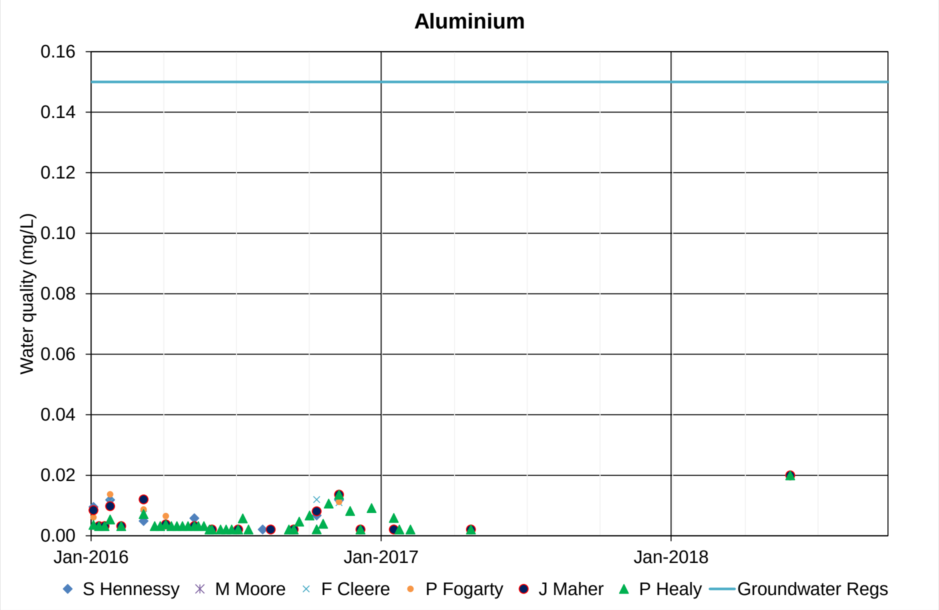

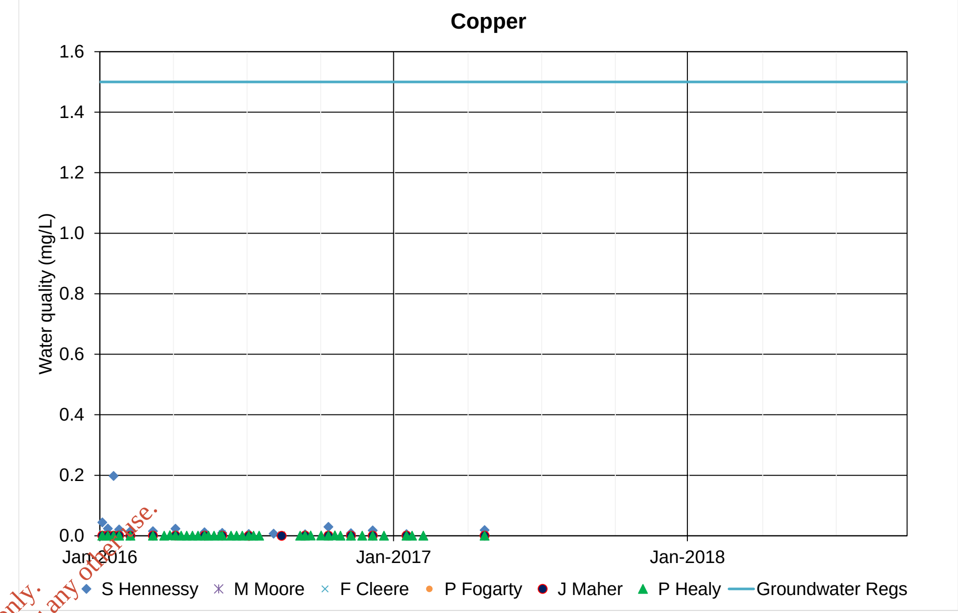

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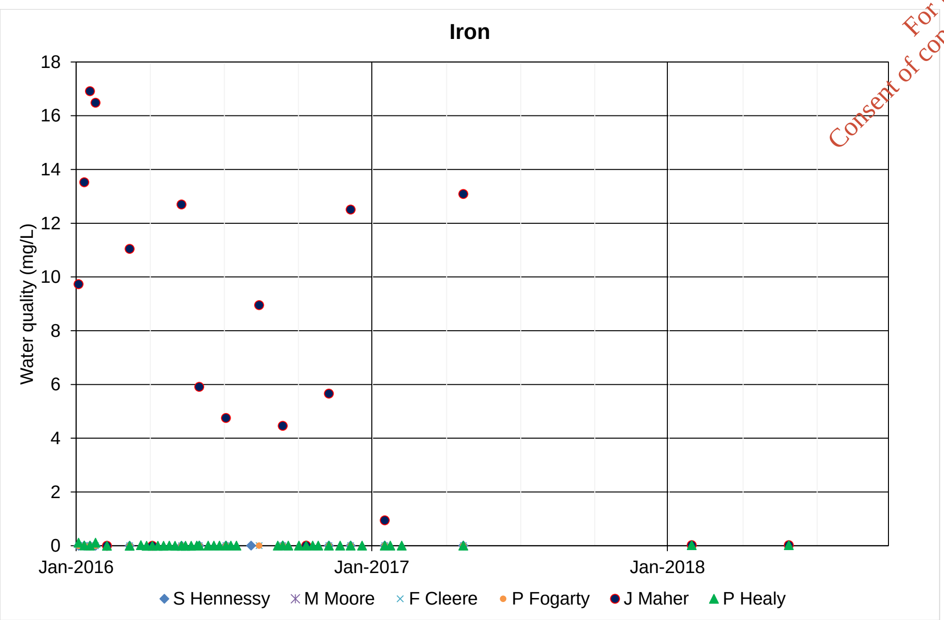

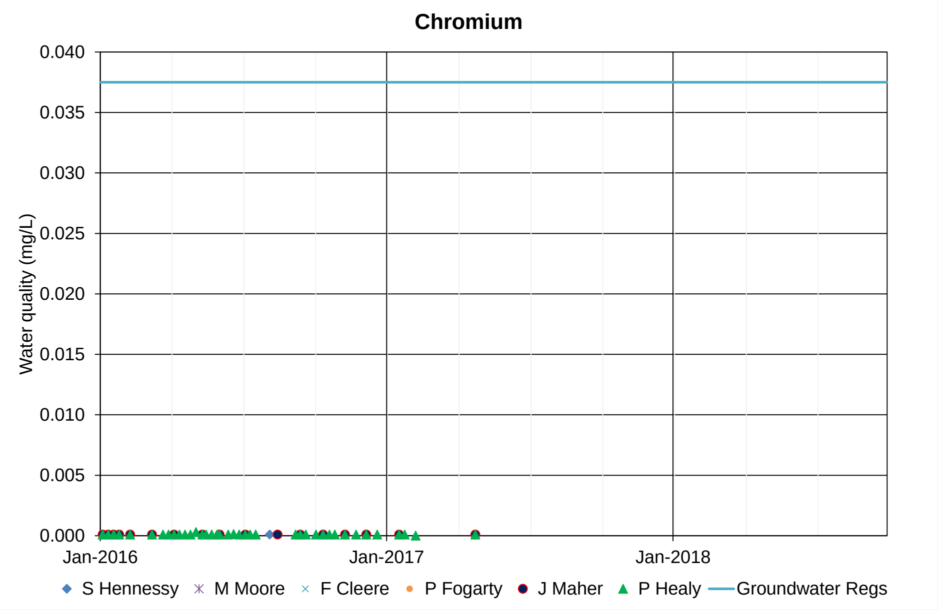

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APPENDIX C

Water quality data for a selection of TMF wells

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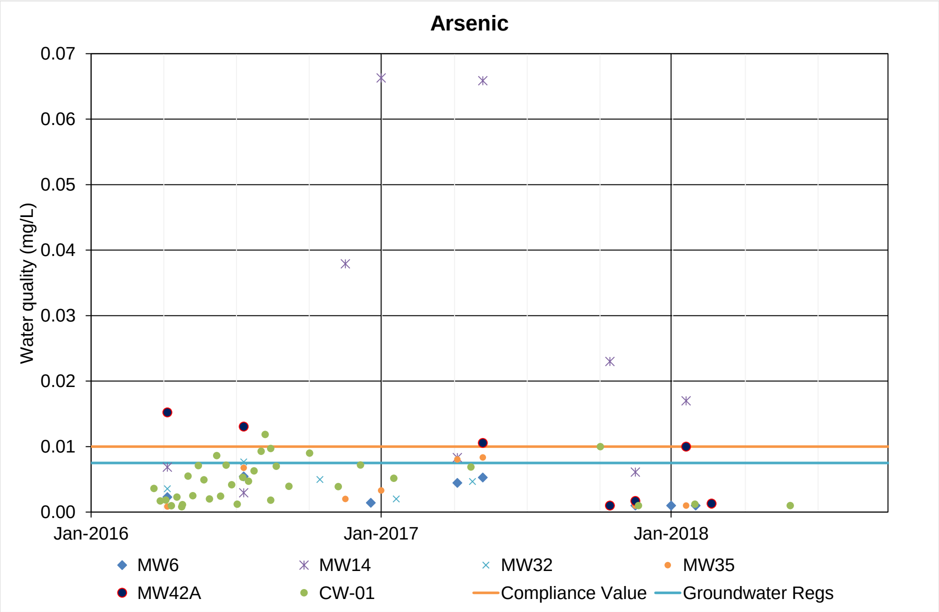
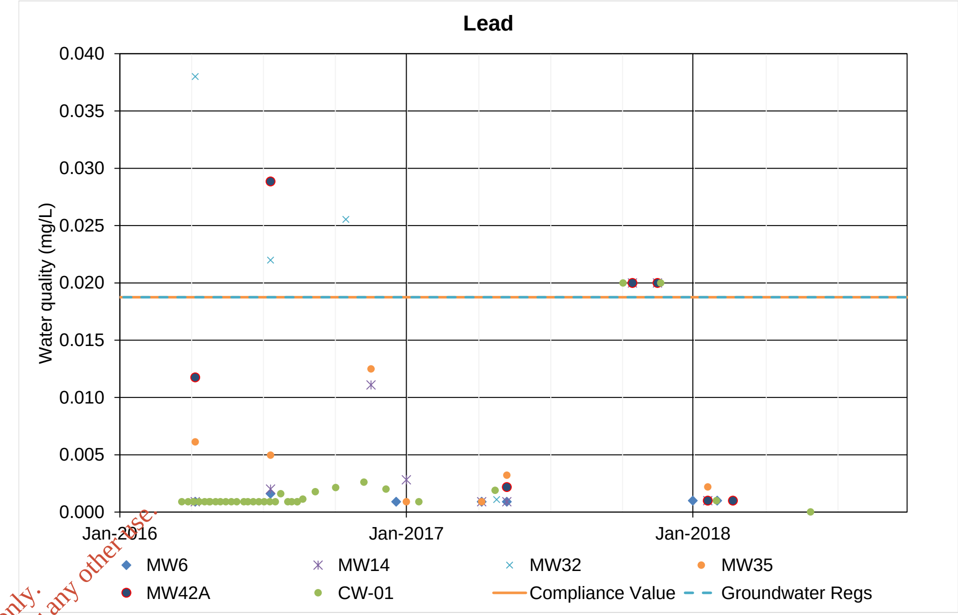
Water quality data for a selection of TMF wells





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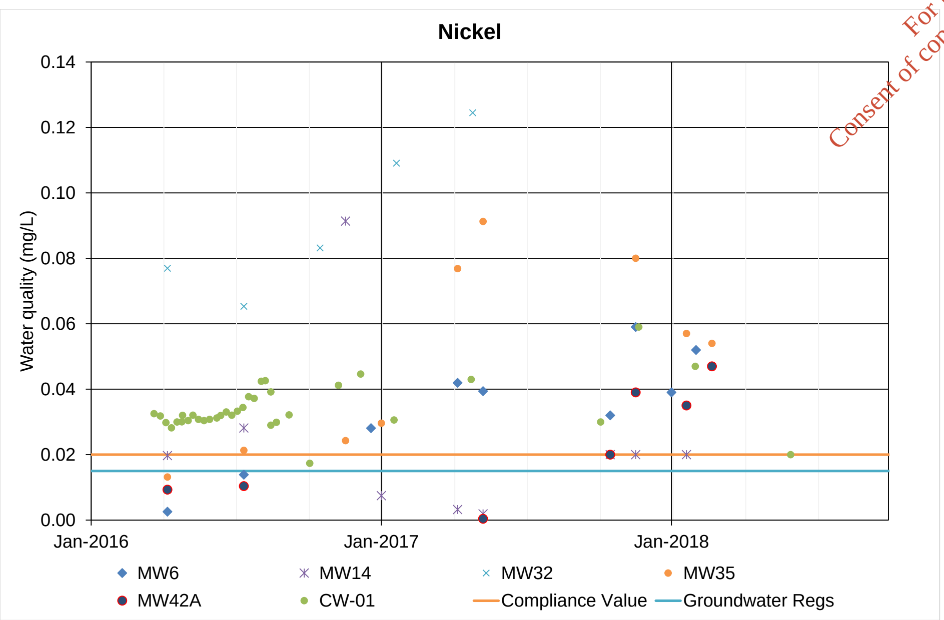

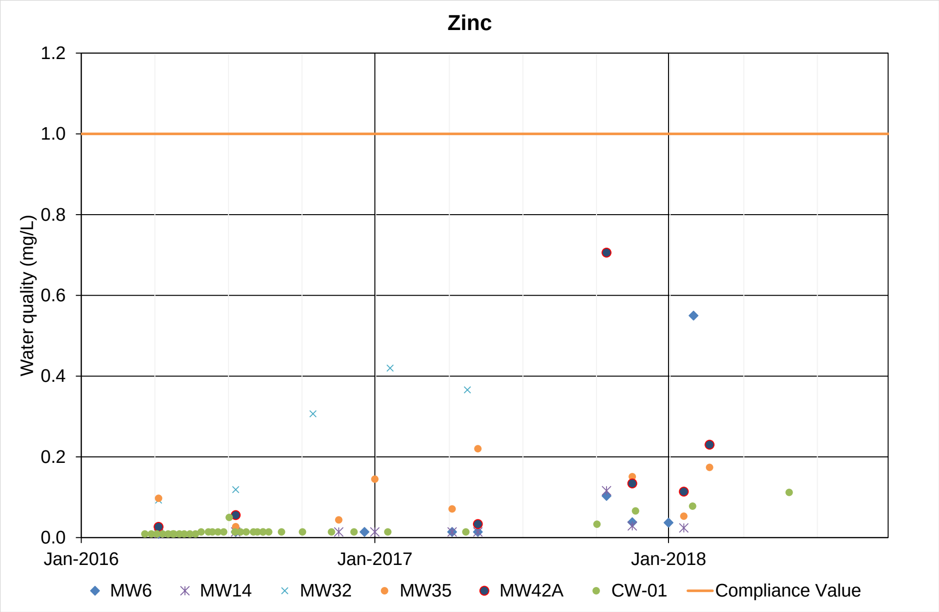

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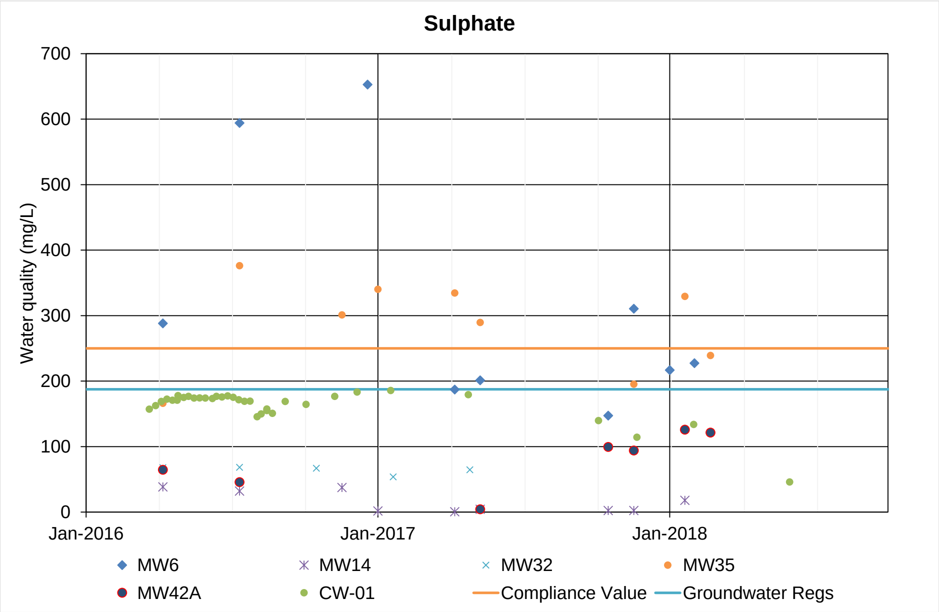

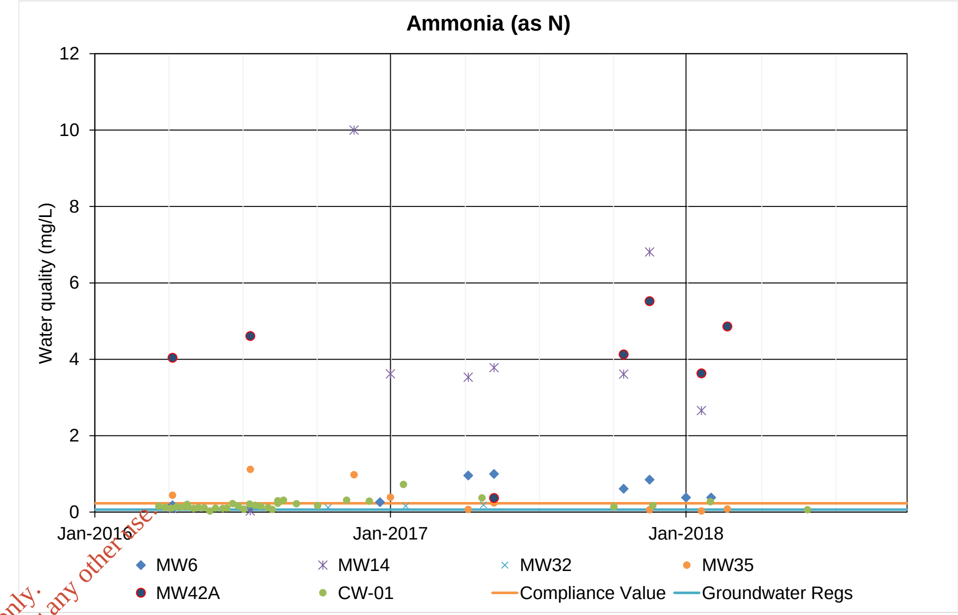

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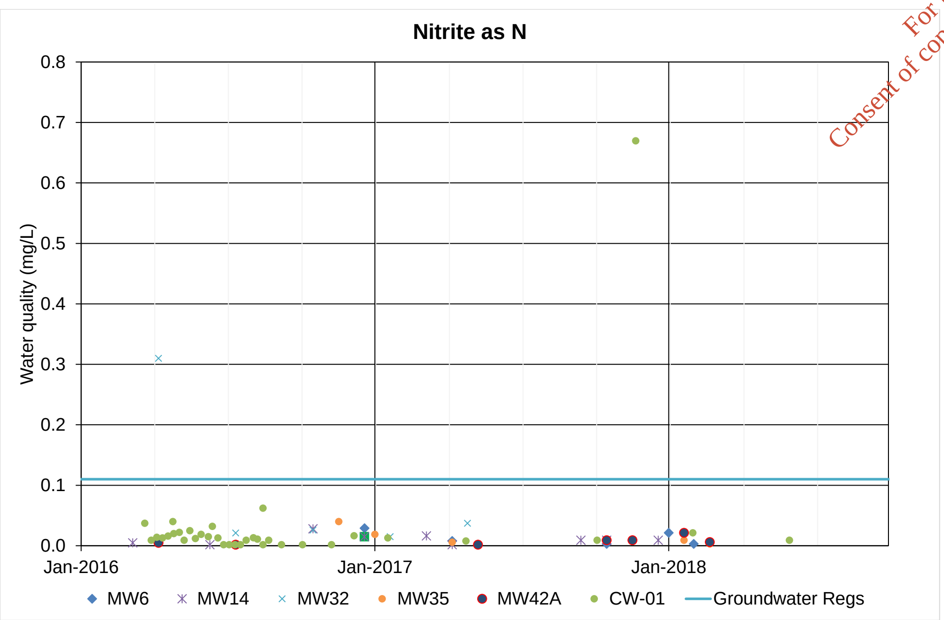

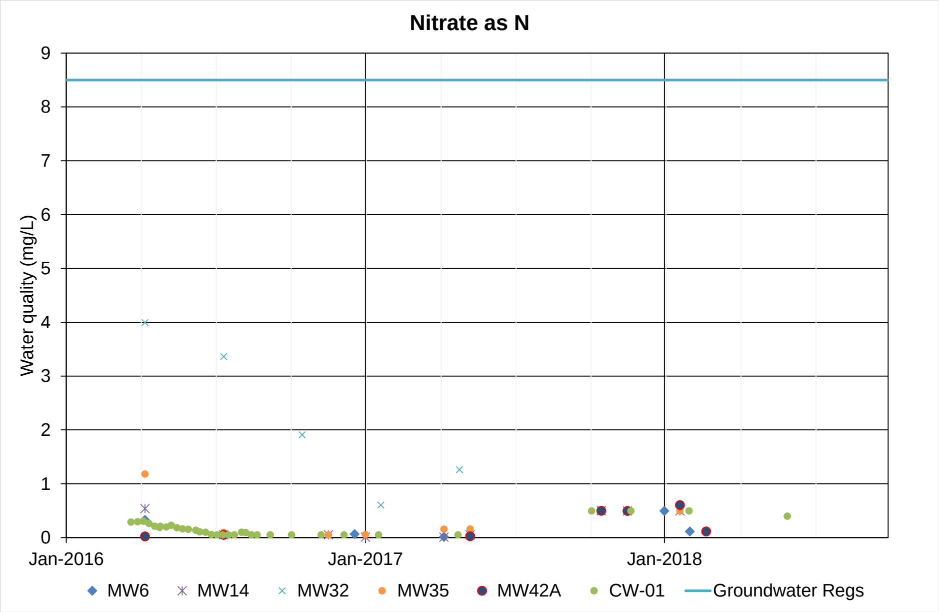

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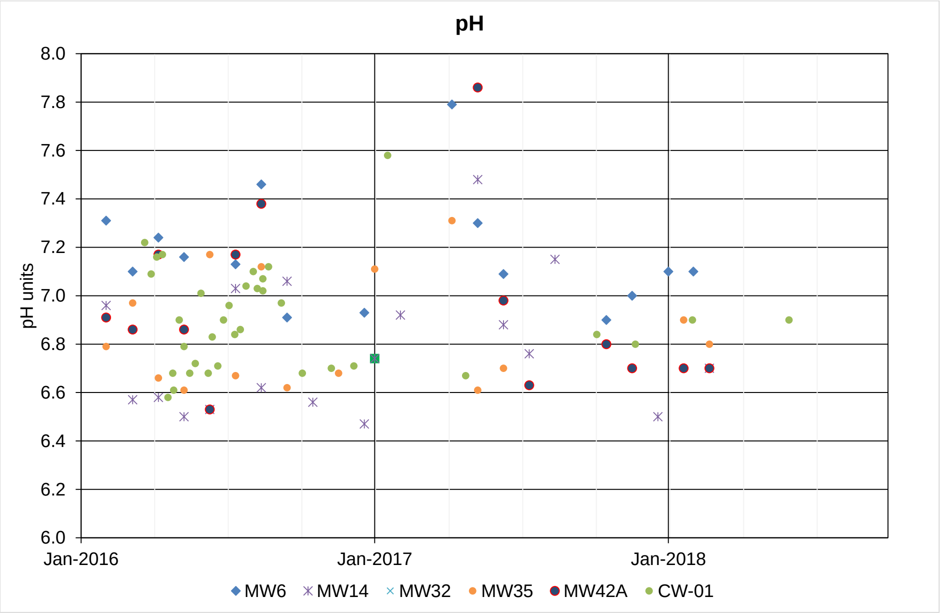
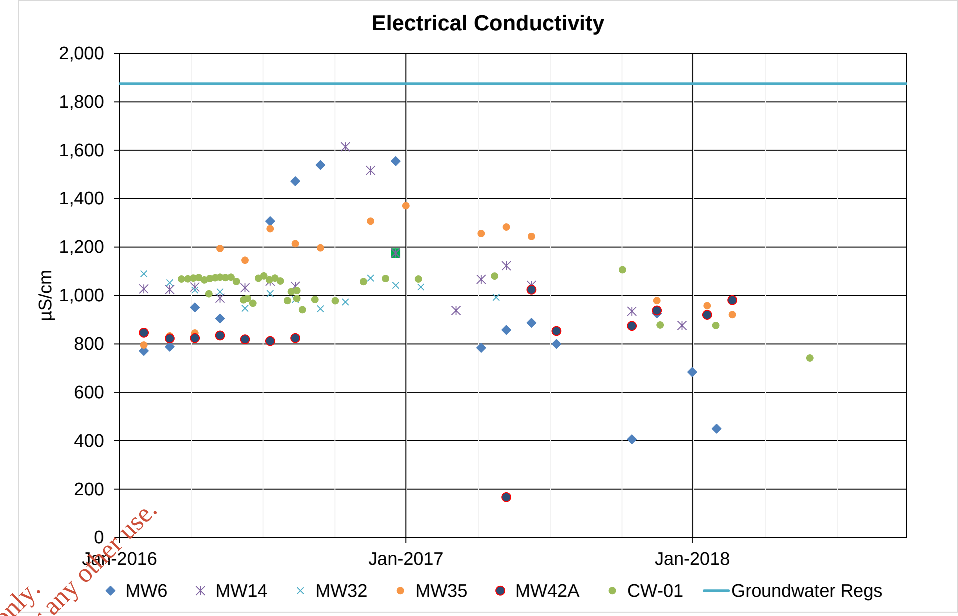
Water quality data for a selection of TMF wells


pH


Electrical Conductivity

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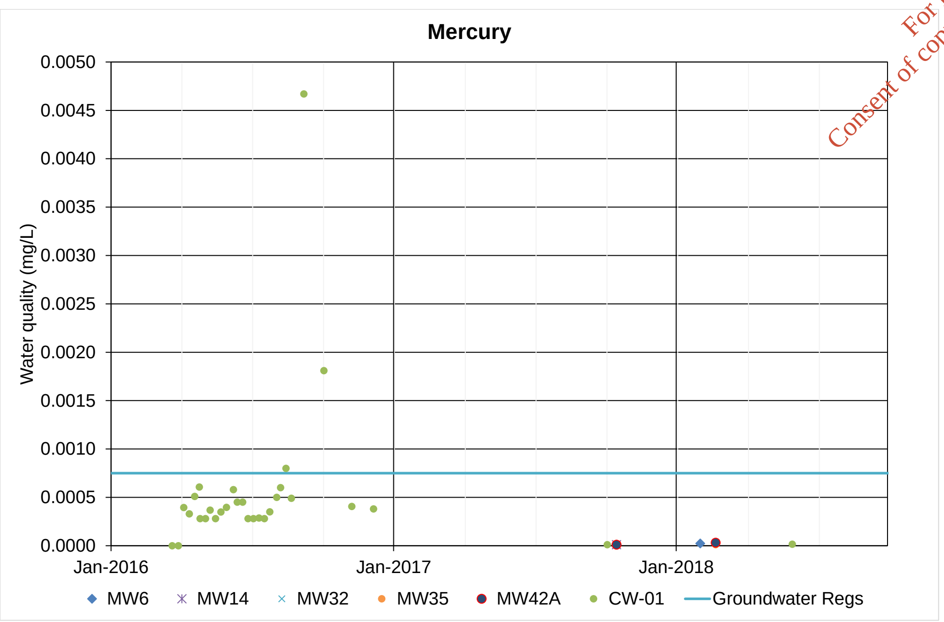
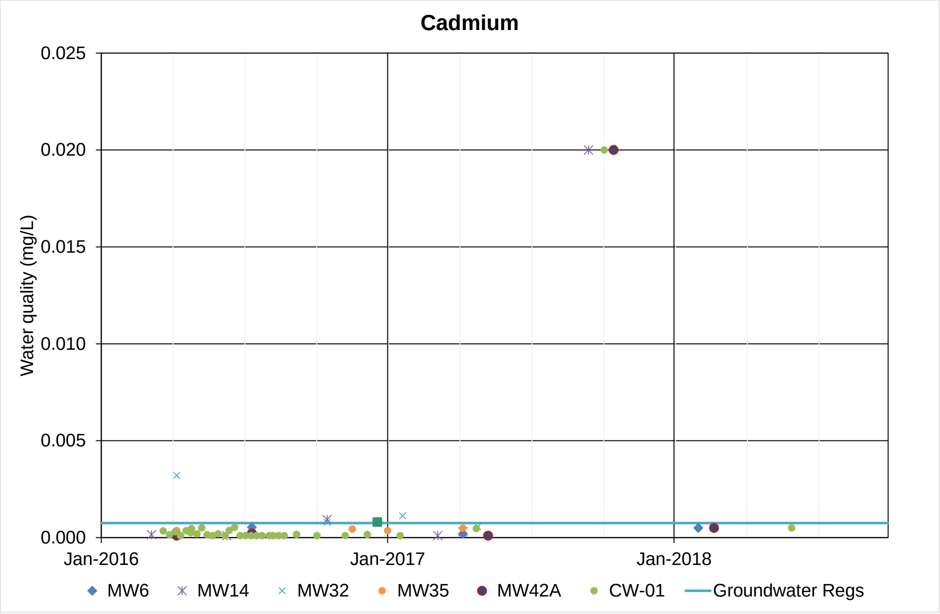
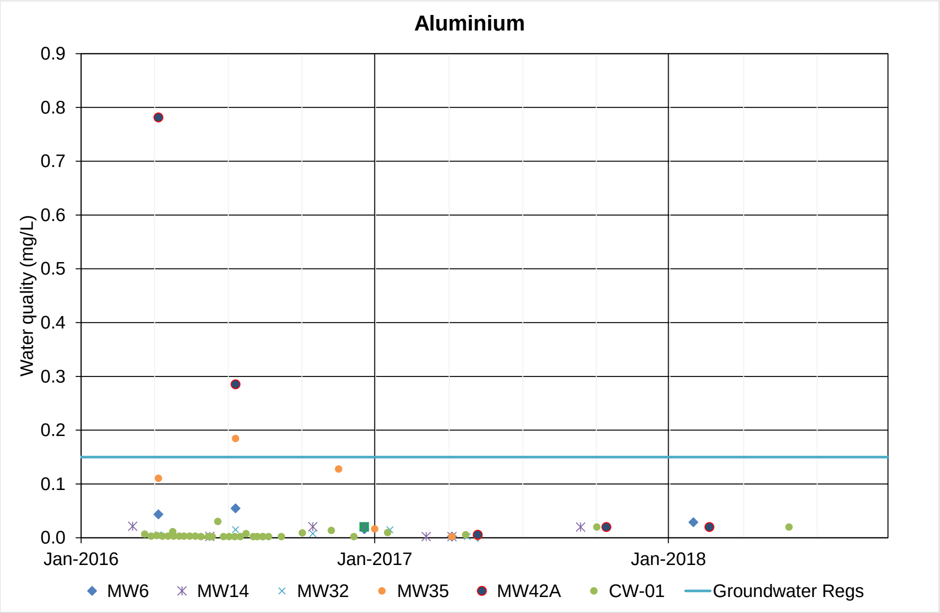
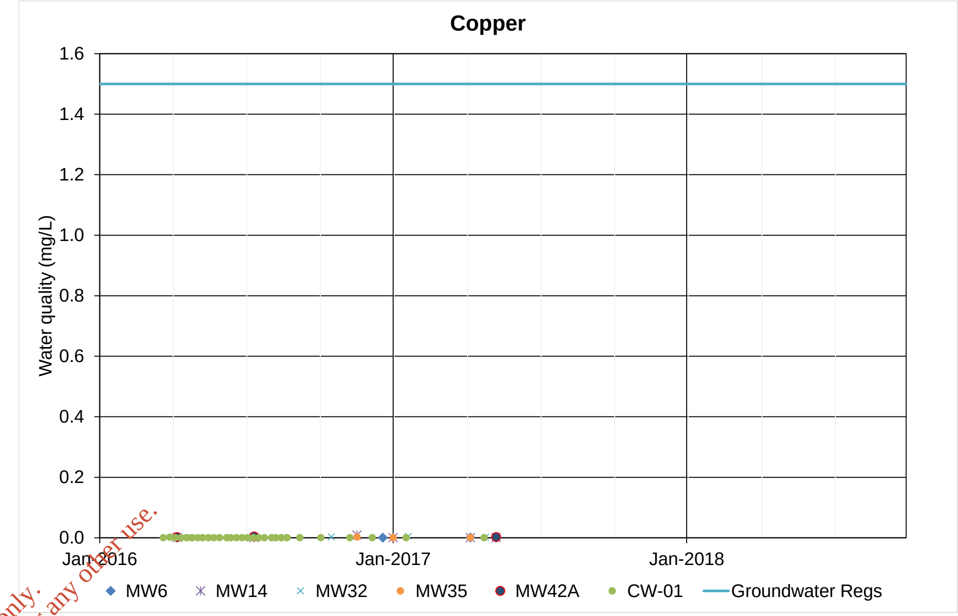

Mercury


Cadmium

Water quality data for a selection of TMF wells





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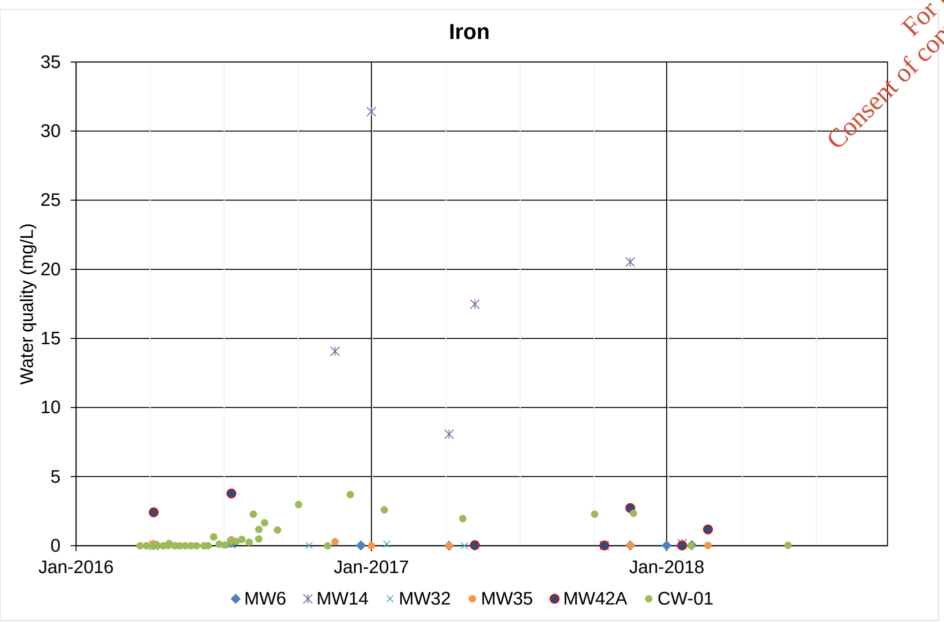

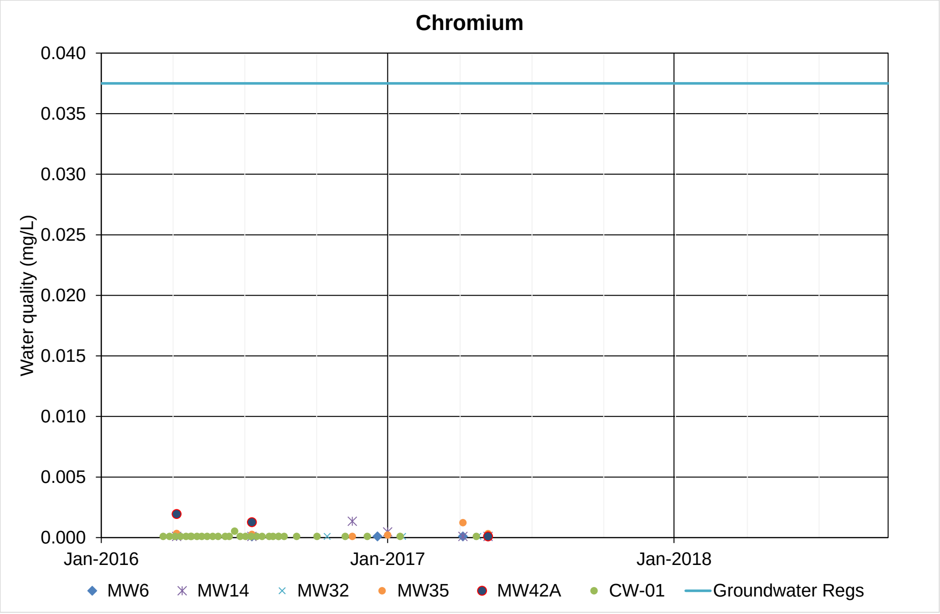

APPENDIX D

Water quality data for surface water monitoring

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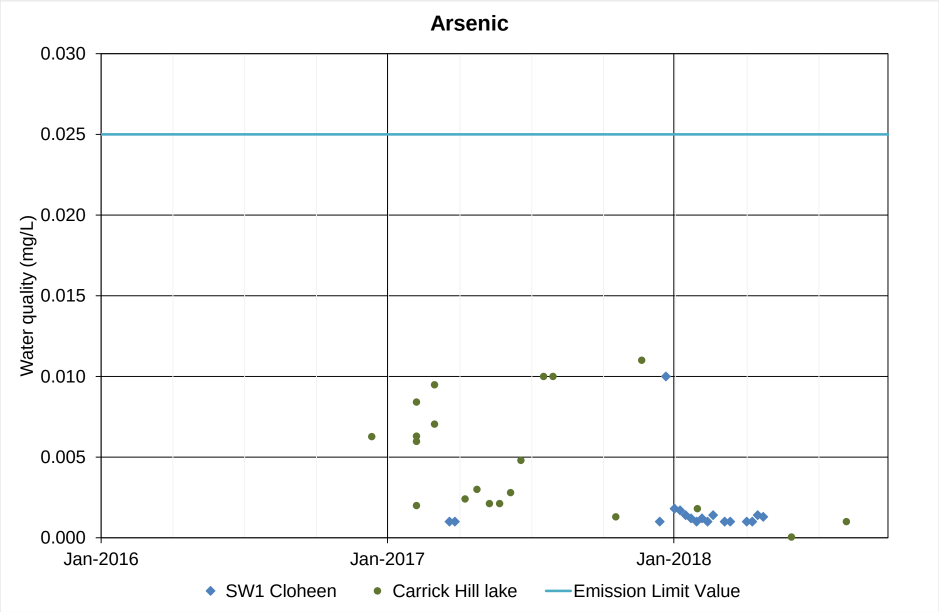
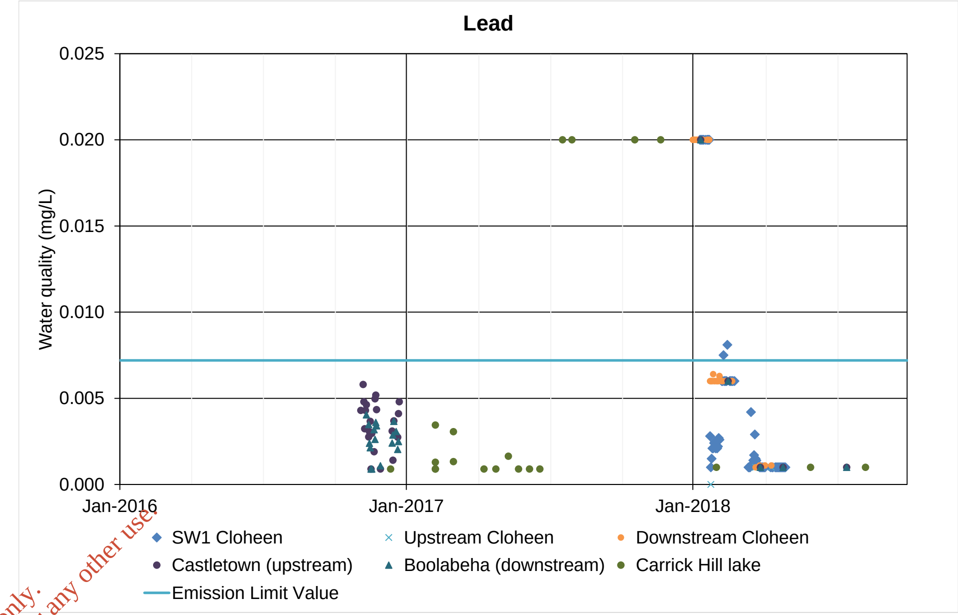
Water quality data for surface water monitoring


Arsenic


Lead

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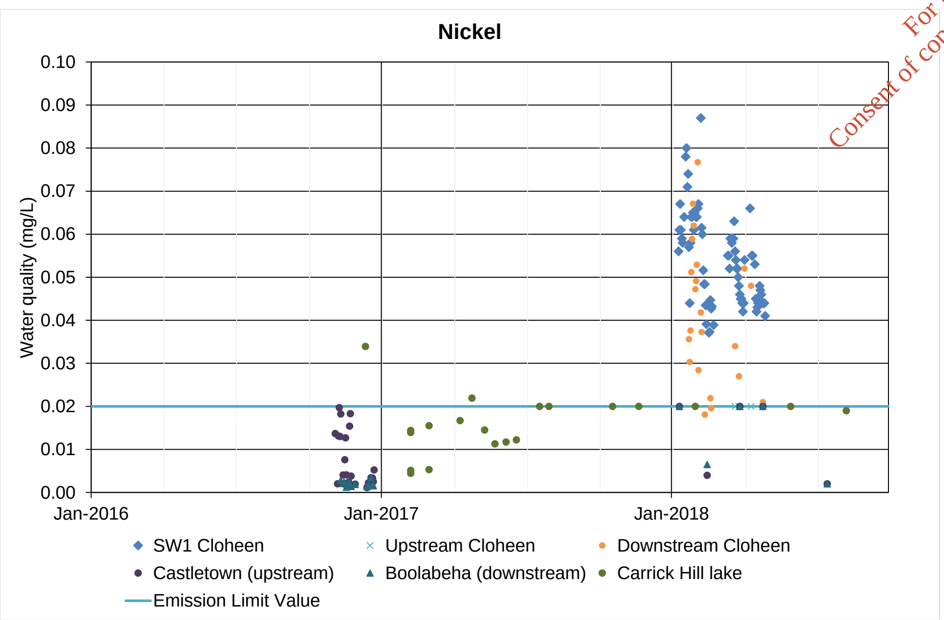
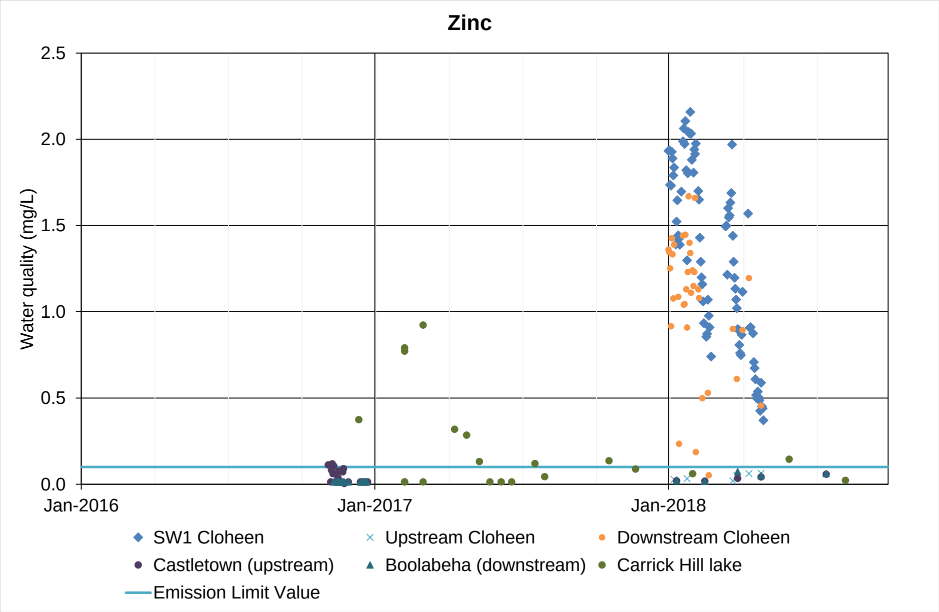
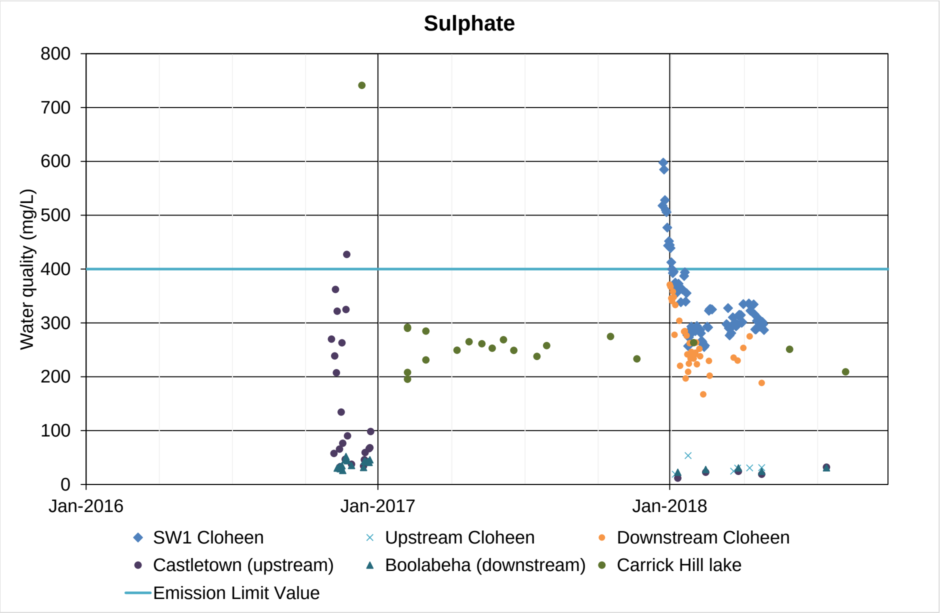
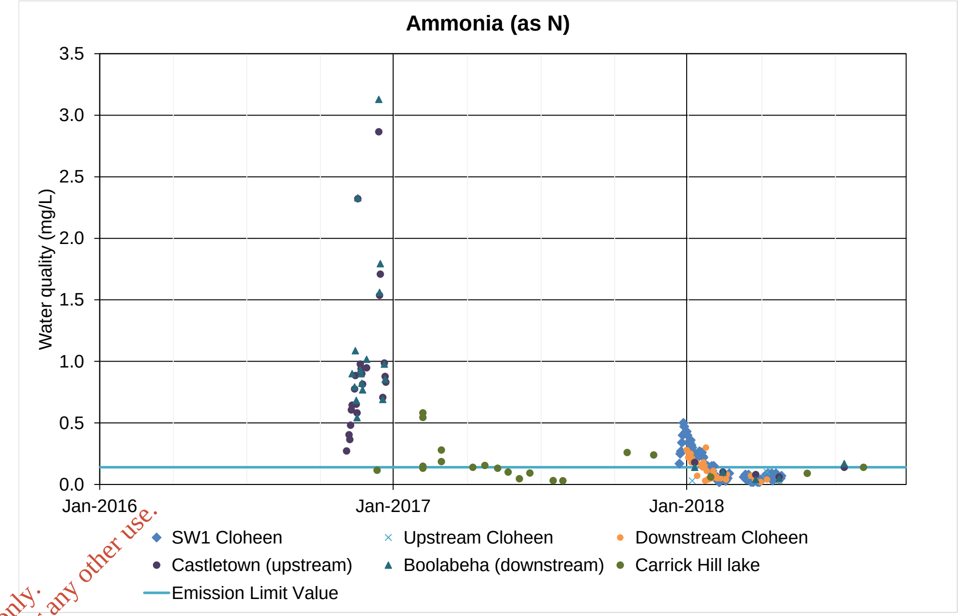

Nickel


Zinc

Water quality data for surface water monitoring





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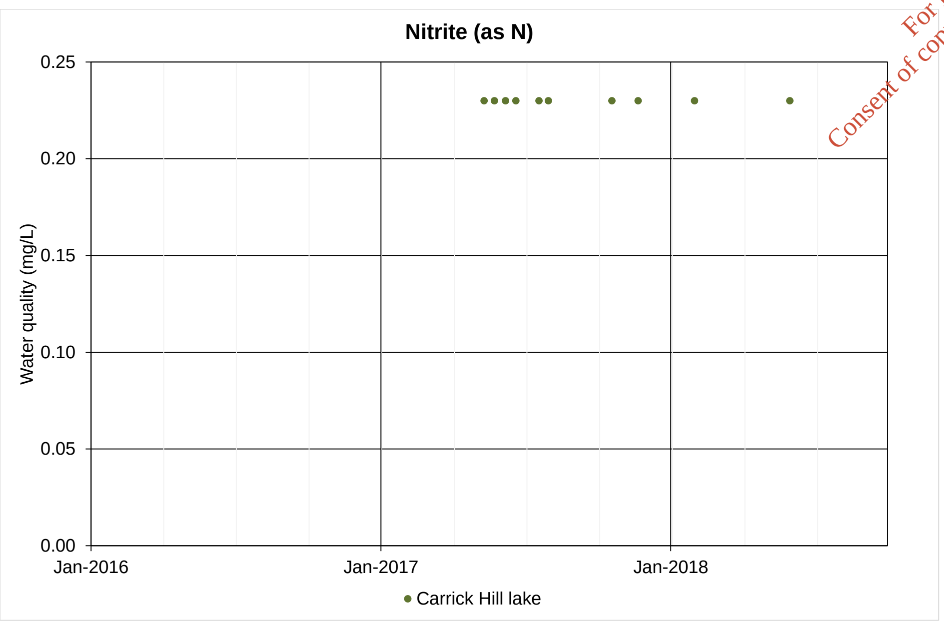

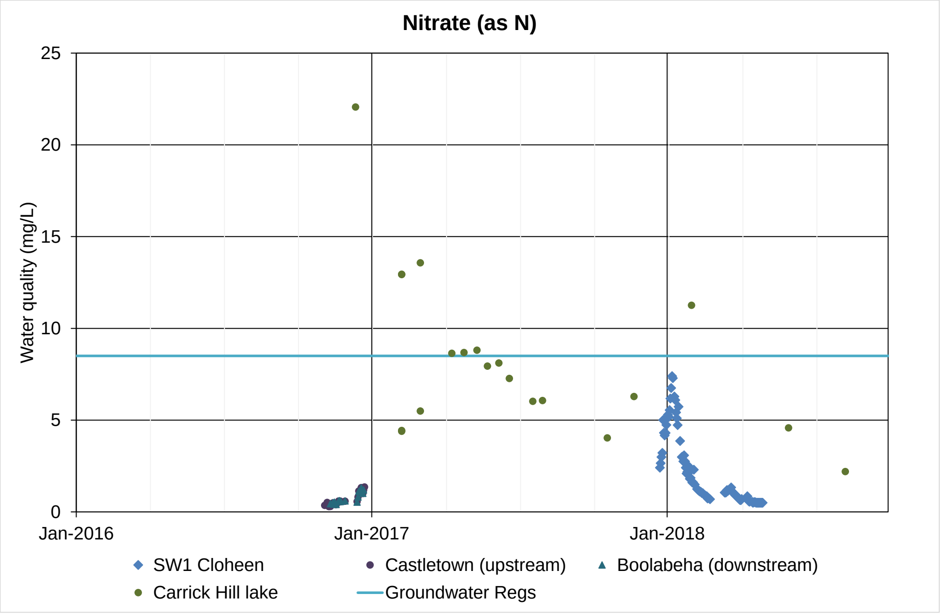

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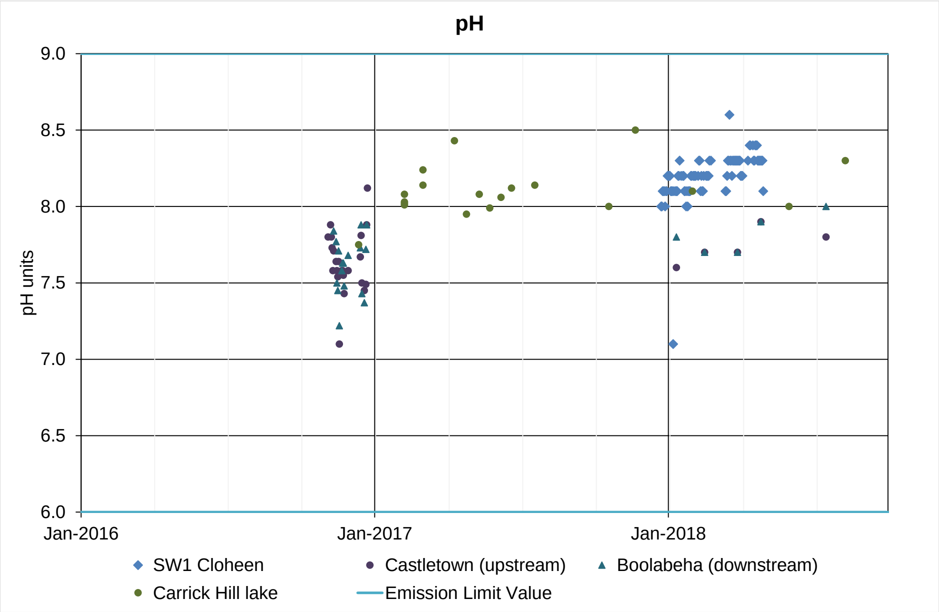
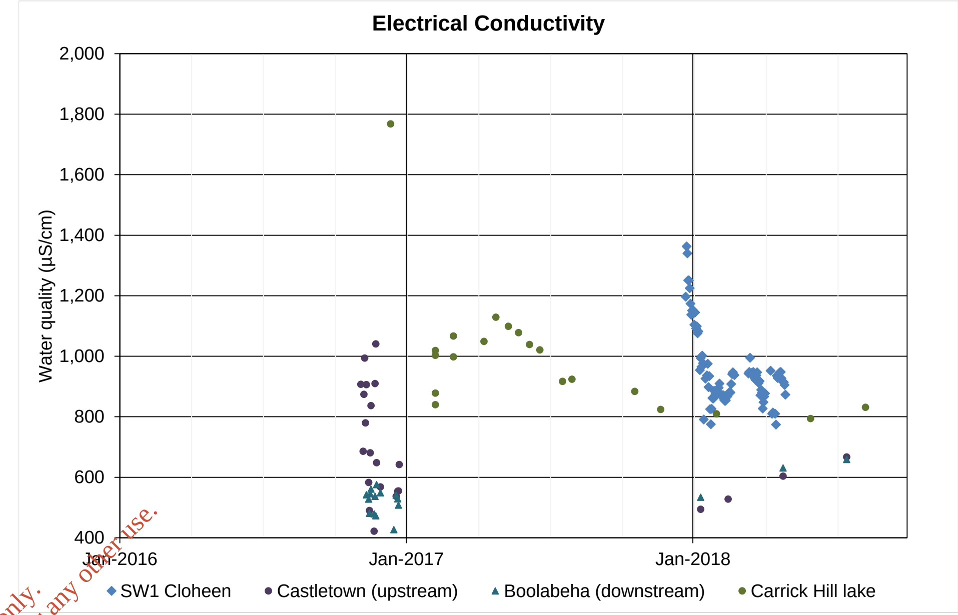
Water quality data for surface water monitoring





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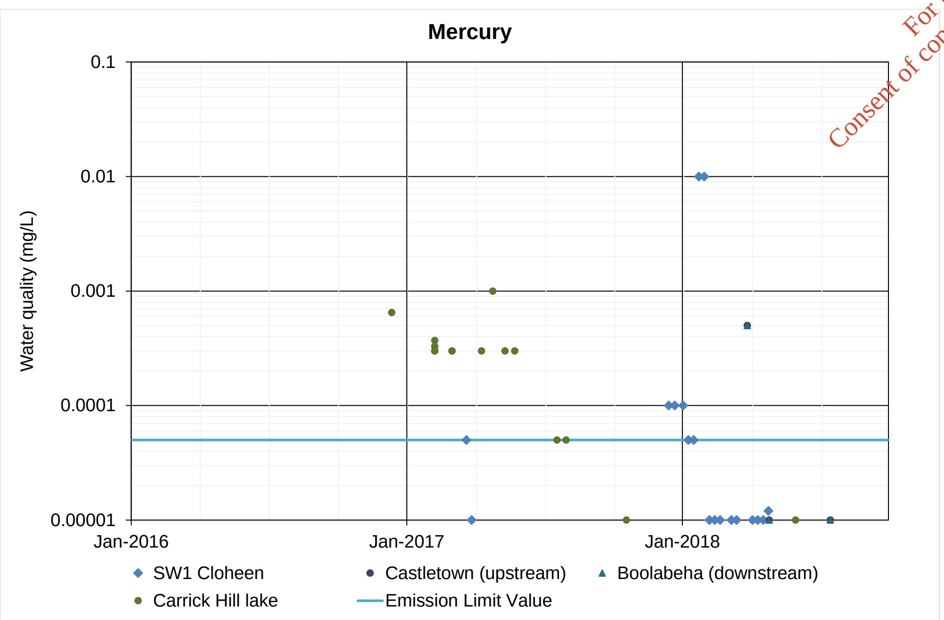

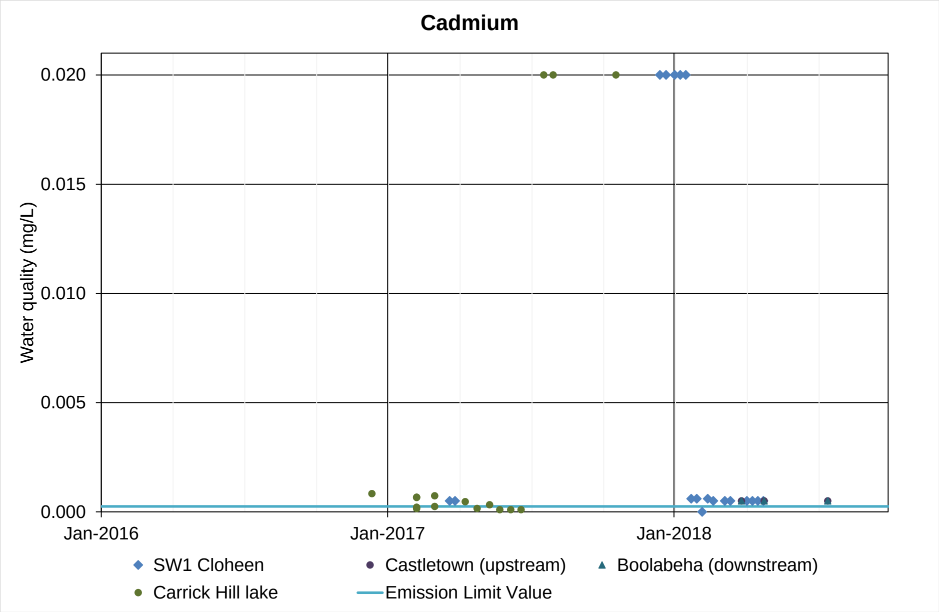

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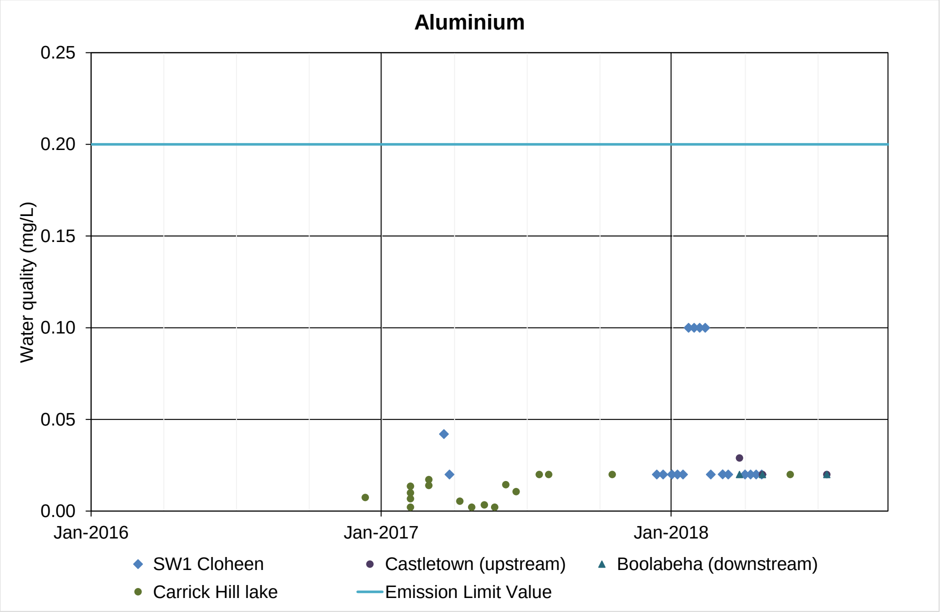

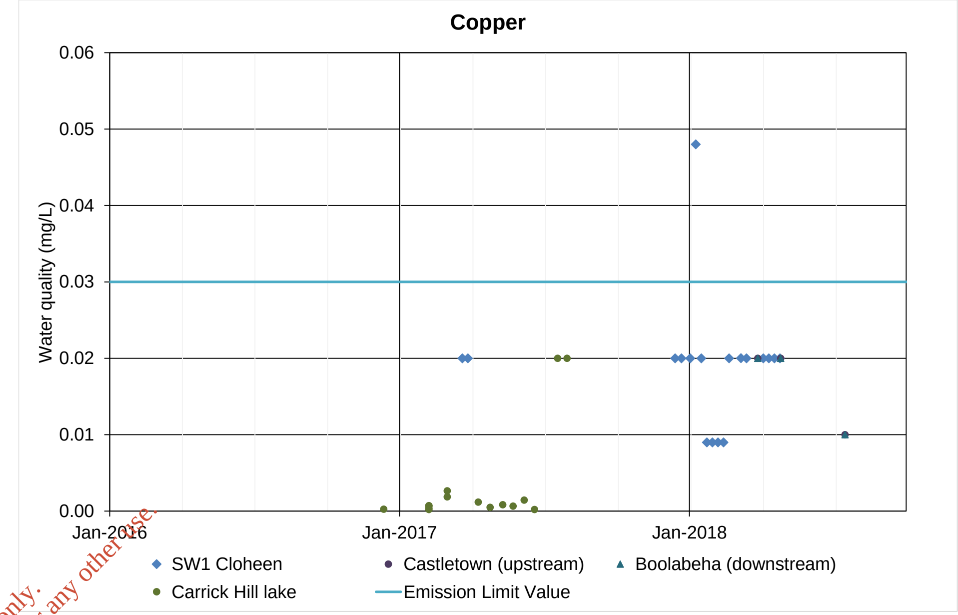

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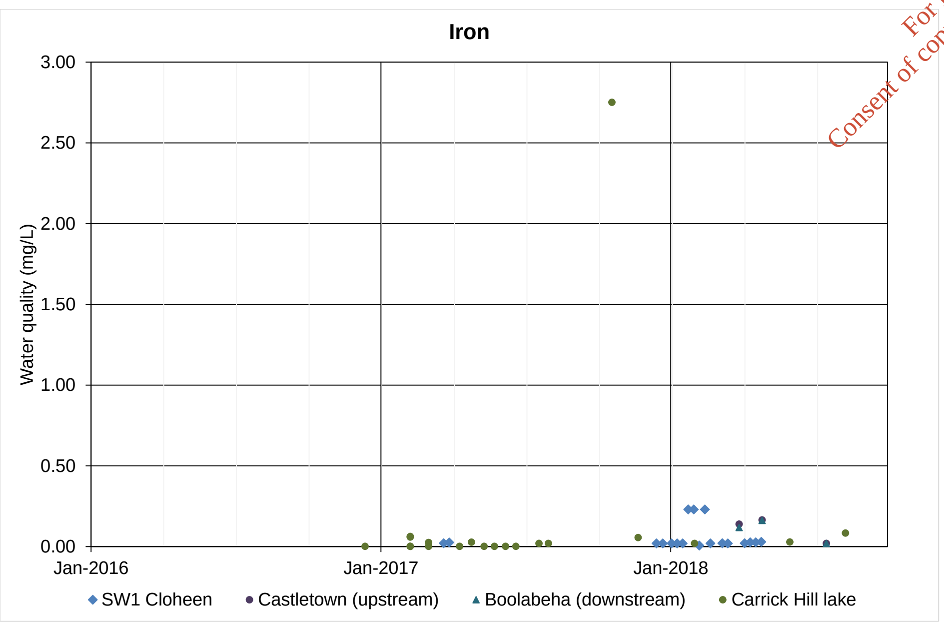

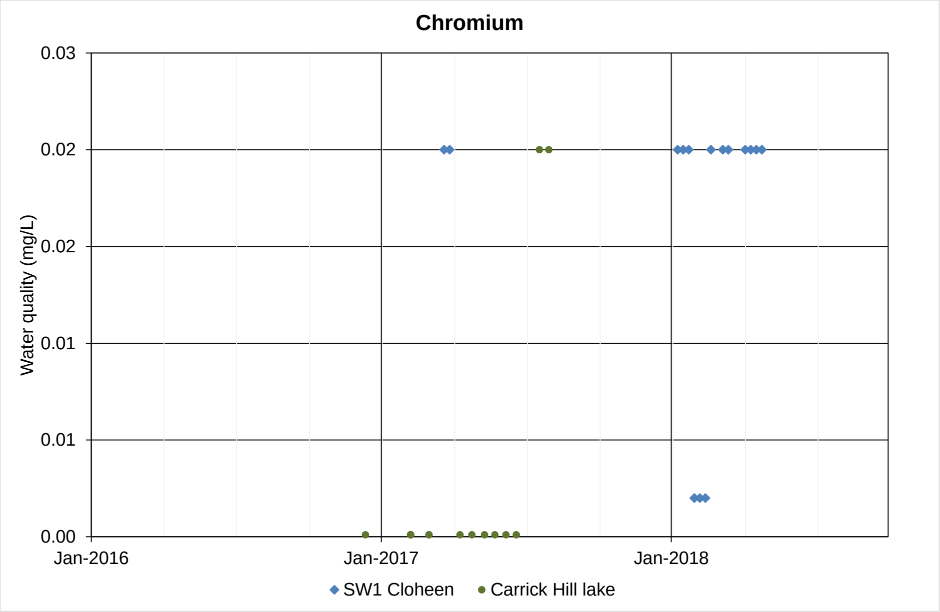

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APPENDIX E
Monitoring plan

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Monitoring Plan

GROUNDWATER

Area	Location	Type	Suite	Frequency
Compliance Wells	CW1 (TMF) CW2 (Workings)	Compliance	Dip	Monthly until December 2020
			Groundwater monitoring suite	Bi-annually until December 2020
Workings	Fogarty MW15 DW14 MW9 MW21	Site monitoring	Dip	Quarterly until December 2020
			Groundwater monitoring suite	Quarterly until December 2019 Bi-annually until December 2020
TMF rock fill	All locations	Site monitoring	Dip and field parameters	Monthly until 2020
TMF groundwater*	MW3 MW6 MW11 MW14 MW28 MW32 MW35 MW37 MW40A MW41A MW42A	Site monitoring	Dip	Quarterly until December 2020
			Groundwater monitoring suite	Bi-annually until December 2020
			IPC suite as per licence	IPC frequency as per licence
	Piezometers 1 - 12		Dip	Monthly until December 2020
Private water supply	James Maher Steve Hennessy Martin Moore Francis Cleere Paddy Fogarty Pat Healy's	Site monitoring	Dip and groundwater monitoring suite	Quarterly until December 2019 Bi-annually until December 2020

Groundwater monitoring suite:

- physicochemical – pH, electrical conductivity, temperature, dissolved oxygen and total dissolved solids (TDS)
- dissolved metals – Ag, Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, Pb, Sb, U and Zn
- nutrients – NH_3, NO_3, NO_2 and PO_4
- anions – Cl, SO_4, hardness and alkalinity.

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SURFACE WATER

Area	Location	Type	Suite	Frequency
TMF discharge	Phase 1 spillway Phase 2 spillway Phase 3 spillway	Site monitoring	Level and field parameters	Fortnightly** for 3 months
			Level and surface water monitoring suite	Monthly until chemistry has stabilised
Storm water attenuation basin	Transfer box Basin spillway	Site monitoring	Level and field parameters	Fortnightly** for 3 months
			Level and surface water monitoring suite	Monthly until chemistry has stabilised
Cloheen pond	Cloheen Pond (SW1)	Compliance	Level and surface water monitoring suite	Monthly* until chemistry has stabilised
			IPC suite as per licence	IPC frequency as per licence
Drish discharge	u/s Drish (2nd bridge Castletown) d/s Cloheen Drain before Drish d/s Drish (3rd Bridge Boolabeha)	Site monitoring	Surface water monitoring suite	Monthly* until TMF chemistry has stabilised
			IPC suite as per licence	IPC frequency as per licence
Carrick Hill lake	Ramp into pit lake	Site monitoring	Level and surface water monitoring suite	Quarterly until December 2019
			Level and surface water monitoring suite	Bi-annually in 2020

Surface water monitoring suite:

- physicochemical – pH, electrical conductivity, temperature, dissolved oxygen, TDS, total suspended solids (TSS) and turbidity
- dissolved metals – Ag, Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, Pb, Sb, U and Zn
- nutrients – NH_3, NO_3, NO_2 and P
- anions – Cl, F, SO_4, hardness and alkalinity.

Field parameters:

- physicochemical – pH, electrical conductivity, temperature, dissolved oxygen

* TMF well locations may vary depending upon IPCL requirements and input from Golder

** Surface water monitoring frequency will require review once discharge begins