

# **FFOS-Y-FRAN FINAL RESTORATION SCHEME**

## Hydrogeology Technical Report

Date:  
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# QUALITY CONTROL

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## LIST OF ABBREVIATIONS AND ACRONYMS

|       |                                              |
|-------|----------------------------------------------|
| BGS   | British Geological Survey                    |
| CAMS  | Catchment Abstractions Management Strategies |
| eFLaG | enhanced future FLOws and Groundwater        |
| DFDS  | Dowlais Free Drainage System                 |
| DTM   | Digital Terrain Model                        |
| EIA   | Environmental Impact Assessment              |
| ES    | Environmental Statement                      |
| GWDTE | Groundwater Dependent Terrestrial Ecosystem  |
| GWL   | Groundwater Level                            |
| HER   | Hydrologically Effective Rainfall            |
| HMAWB | Heavily Modified/ Artificial Water Bodies    |
| LiDAR | Light Detection And Ranging                  |
| LTA   | Long Term Average                            |
| mAOD  | Metres Above Ordnance Datum                  |

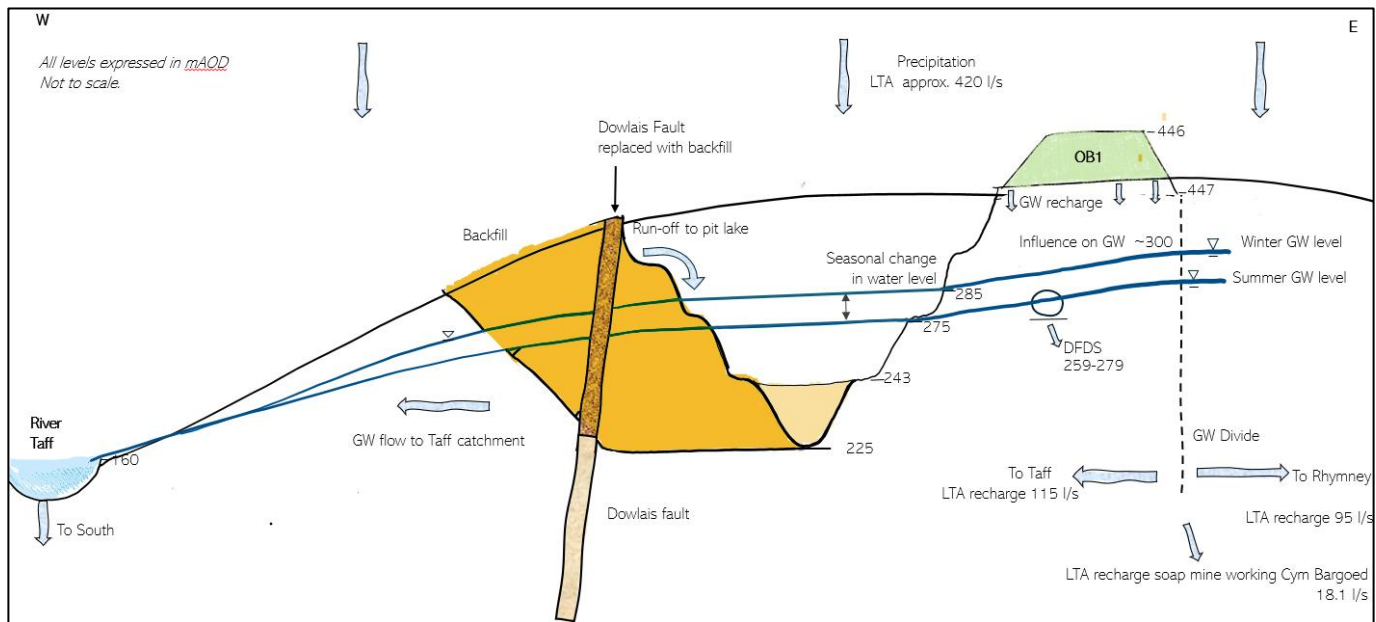
|        |                                               |
|--------|-----------------------------------------------|
| MTCBC  | Merthyr Tydfill County Borough Council        |
| NRW    | Natural Resources Wales                       |
| PE     | Potential Evapotranspiration                  |
| RBMP   | River Basin Management Plan                   |
| RCP8.5 | Representative Concentration Pathway 8.5      |
| SAC    | Special Area of Conservation                  |
| SCS-CN | Soil Conservation Service Curve Number method |
| SPA    | Special Protected Area                        |
| SPZ    | Source Protection Zone                        |
| SSSI   | Site of Special Scientific Interest           |
| SWAc   | Surface Water Accounting programme            |
| UKCP18 | United Kingdom Climate Projections 2018       |
| WFD    | Water Framework Directive                     |

# EXECUTIVE SUMMARY

An Environmental Impact Assessment (EIA) has been requested by the local planning authority Merthyr Tydfil County Borough Council (MTCBC) to assess the possible environmental effects that would result from the implementation of the final restoration strategy of the former surface mine and land reclamation scheme at Ffos-y-Fran, Merthyr Tydfil, South Wales. This document details technical aspects of the work undertaken to support the hydrogeological aspects of the EIA.

The scope of the hydrogeological assessment includes both consideration of change to groundwater level and availability for relevant groundwater receptors, and the long-term pit lake level fluctuations following implementation of the proposed restoration scheme. The evaluation was carried out within the framework of relevant legislation and policy including the WFD and CAMS for the South Valleys. A screening process was undertaken within the hydrogeological search area to identify receptors. Receptors identified through this process include SSSIs, WFD surface water and groundwater bodies, public water supply abstraction licences, private water supplies, CAMS catchments and a water supply SPZ.

The existing body of hydrogeological studies was reviewed to demonstrate how the conceptual understanding of the site hydrogeology has developed over time. The conceptual hydrogeological model has been updated with the benefit of recent field investigations. This has included spotflow surveys of nearby stream courses to characterise the magnitude of mine discharges, and tests undertaken within the pit void itself to characterise backfill infiltration rate and hydraulic conductivity. This work provides evidence that the conceptual model put forward in the 2003 Environmental Statement remains largely valid, and that existing drainage systems within the site area, such as the Dowlais Free Drainage System, remain instrumental in controlling groundwater levels and discharges from the site. Regular monitoring of the pit lake level since cessation of dewatering in July 2023 has also provided insights into the interaction between the pit lake and surrounding groundwater system. A conceptual cross-section of the pit lake hydrodynamics is shown in the following figure.



*ES Figure 1: Conceptual cross-section of the pit void and surrounding catchment*

A 3D numerical Modflow groundwater model was built to assess potential spatial impacts related to the implementation of the proposed restoration scheme, and to provide inputs to a pit lake water balance model designed to provide projections of future pit lake level fluctuations. This model was calibrated to records of groundwater level observations, measured and inferred discharge rates from the Dowlais Free Drainage System, and operational dewatering rates. Groundwater model projections suggest that groundwater level change at receptors within the hydrogeological search area are  $\leq 1\text{cm}$  and therefore the potential impact is considered to be negligible. The magnitude of projected changes to groundwater discharges to WFD surface water bodies represented at the most a change 1.3% change relative to the lowest flow of a receiving water body and therefore are acceptable based on criteria put forward by the JNCC Common Standard Monitoring for the allowable deviation in river flow range. The projected magnitude of change would not result in a change to both quantitative and overall WFD status.

A pit lake water balance model was developed to generate future projections of pit lake level for both the existing and proposed restoration landforms. The model tracks the water level and volume within the pit void in response to climatic inputs and user-defined relationships between pit lake stage and groundwater inflow/outflows and is calibrated too observations of pit lake level.

These simulations suggest that the simulated maximum pit lake level should remain more than 40m below the spill elevation (approximately 286 mAOD), providing assumptions inherent in the development of the water balance model remain valid. This assessment was also undertaken with consideration for the effects of future climate change on rainfall and temperature. Conservative climate change projections from the UKCP18 RCP 8.5 were used to perturb the rainfall and potential evaporation inputs to the water balance model. Projections from these simulations suggest that, even in the wettest future scenario, the pit lake level remains more than 40 m below the spill point of the void.

A summary of the main hydrogeological impacts and their significance, risk and suggested monitoring and/or mitigation is provided in the following table.

*ES Figure 1: Summary of impacts, significance and risk level, and any mitigation or monitoring that is required*

| Assessment                 | Impact                                                                                                                                                                                   | Significance / Risk | Mitigation / monitoring required                                             |
|----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|------------------------------------------------------------------------------|
| Regional groundwater users | No effect on groundwater users or groundwater supply within the search area. Limited to the immediate pit void area and of <1m change in groundwater level for both wet and dry periods. | Insignificant       | Continued monitoring of the pit lake level as a proxy for groundwater level. |
| WFD groundwater bodies     | No change in groundwater level or aquifer dynamic resulting in change to flow that could affect quantitative WFD indicators.                                                             | Insignificant       | None                                                                         |
| WFD surface water bodies   | No change in groundwater discharge to surface water bodies, either through the groundwater system or groundwater pathways, that are large enough to affect quantitative WFD indicators.  | Insignificant       | None                                                                         |

| Assessment                               | Impact                                                                                                                  | Significance / Risk | Mitigation / monitoring required                                                                                                                                     |
|------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Post-restoration pit lake level          | Simulated maximum pit lake level remains > 40 m below the spill point.                                                  | Highly unlikely     | Continue pit lake level monitoring through restoration and closure. Continual validation and update of the pit lake water balance model with latest monitoring data. |
| Climate change effects to pit lake level | Projected climatic changes lead to higher maximum pit lake levels that are still > 40 m below the lake spill elevation. | Highly unlikely     | Continue pit lake level monitoring through restoration and closure. Continual validation and update of the pit lake water balance model with latest monitoring data. |

# 1. INTRODUCTION

## 1.1 Purpose of this document

This report provides a summary of the hydrogeological investigations and modelling that have supported the assessment of hydrogeological impacts for the Ffos-y-Fran final restoration scheme Environmental Impact Assessment (EIA) (RML, 2025).

## 1.2 Summary of content

An overview of the hydrogeological EIA approach is provided in Section 2. This includes a summary of the assessment methodology, review of the relevant legislation and policy, an outline of the baseline conditions against which environmental impact are evaluated, and environmental receptor screening.

The conceptual hydrogeological model is covered in Section 3. The chapter includes a review of existing knowledge, including previous hydrogeological investigations and reviews from the site as well as neighbouring Trecatti landfill, before providing an overview of the main updates to the conceptual model following more recent hydrogeological investigations at the site and the conceptual review.

Section 4 describes the development, calibration and use of the numerical groundwater model. This tool was used to assess potential spatial impacts to environmental receptors identified during the screening process, as a result of the restoration scheme implementation.

Section 5 covers the pit lake water balance model development, calibration and use. This model was used to simulate future pit lake level and volume fluctuations for both the current pit topology and the proposed reclaimed landform. The impact of future climate change on these projections of future pit lake level ranges is also considered in this chapter.

The development of climate change projections used to provide rainfall and potential evaporation inputs to the pit lake water balance is described in Section **Error! Reference source not found..**

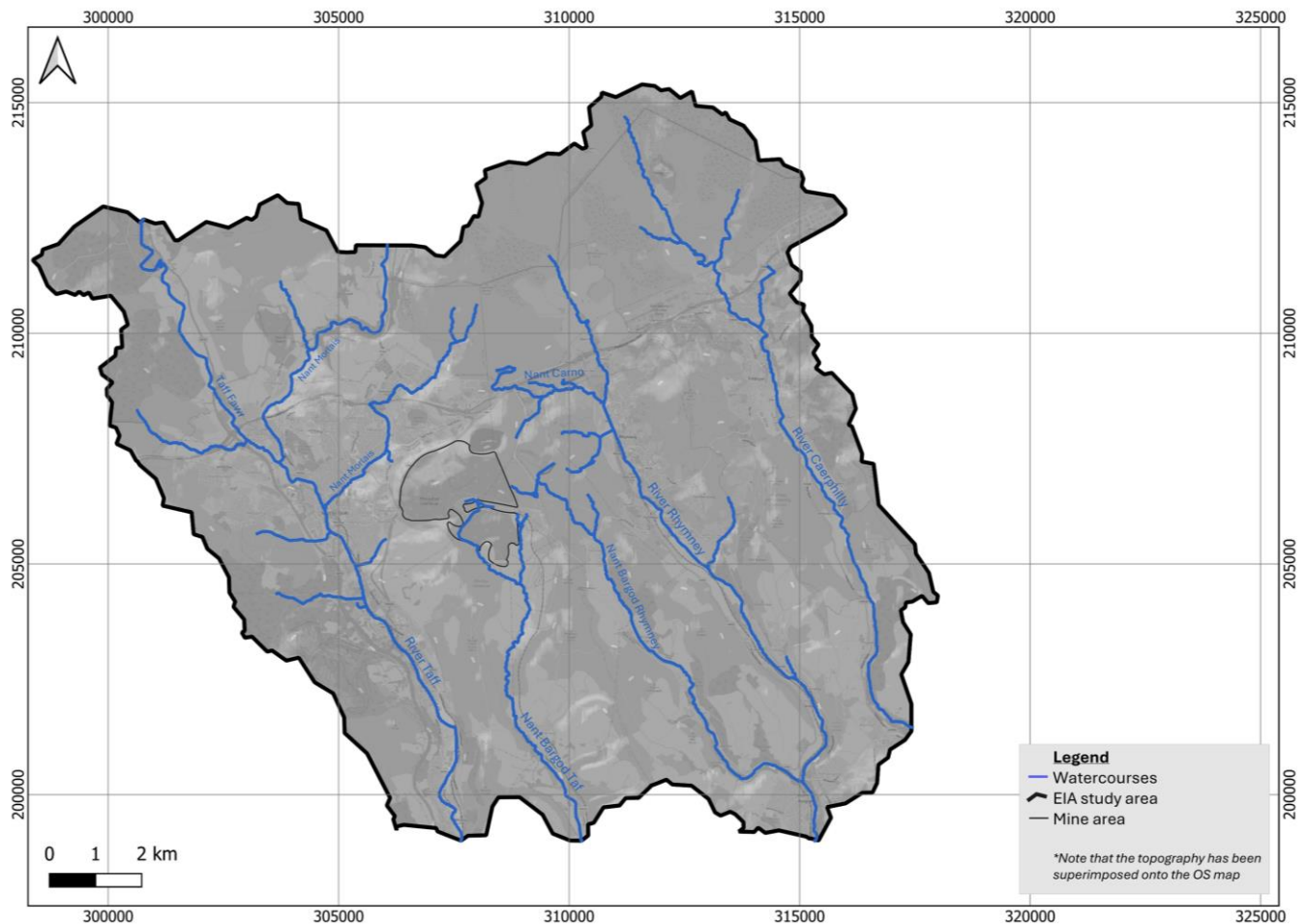
Section 7 gives a summary of the effects described in previous sections.

## 2. EIA APPROACH

### 2.1 Assessment methodology

The scope of the hydrogeological assessment includes both consideration of direct hydrogeological impacts that may result from completion of the proposed restoration scheme, and assessment of long-term future fluctuations in pit lake level, namely whether there is any risk of spill from the void.

A screening process was undertaken to identify the location of environmental receptors within the groundwater EIA search area. This area is shown in Figure 1 and is restricted to the surrounding groundwater catchment that may reasonably be expected to respond to changes in groundwater use or regime at the site, either through groundwater system continuity or receipt of groundwater-dependent waters discharging from the site. These groundwater catchments are likely to be in hydraulic continuity with the major surface water courses shown in Figure 1.1



Potential receptors within the groundwater search area include groundwater users and Water Framework Directive (WFD) water bodies. Post-restoration changes to receptors were evaluated using two parallel models. These are based on historical models calibrated to existing records of groundwater levels, mine discharges and pit lake level records. This process is described in Section 4.3. The parallel models comprise:

The climatic inputs to the model are based on a combination of publicly available HADUK rainfall (Hollis, et al., 2019) and EA PEt (Environment Agency, 2021) potential evapotranspiration (PE) data from January 1982 to June 2024, supplemented by rainfall data from the weather station at Cwmbargoed for the period from July 2023 to June 2024.

These historical datasets (HADUK rainfall and EA PEt) were also used to generate proxy future climates, giving modelled projections of future conditions. To represent climate change, projected changes in rainfall and temperature from the UKCP18 ensemble (Appendix 1) were used to perturb the historical data, thereby maintaining short-term variability, whilst including longer term, projected trends in rainfall and PEt. Representative wet, average and dry members of the UKCP18 ensemble were used to assess the potential range of future climates and evaluate possible ranges of future pit lake level fluctuation.

The numerical groundwater model is structured in the following manner for the impact assessment:

- A one-year period where there is no pit void to generate an initial distribution of groundwater heads.
- A 5.5-year dewatering period, where the excavation is kept dry, to simulate the initial impact of mining activities on the groundwater system.
- A recovery period 36-year duration, starting midway through simulation year 6. With respect to the climate dataset, this coincides with August 2023, when dewatering activities ceased and the pit lake level began to rebound. Potential impact to the groundwater system is evaluated from this point of the simulation onwards.

Simulated spatial impacts to groundwater receptors are evaluated for a dry and wet period, under the assumption that potential impacts are greatest at either of these two extremes. Dry and wet periods were selected based on the date when the lowest and highest pit lake levels are simulated by the pit lake water balance model, corresponding to months February 2056 and August 2026 respectively in the projected future climate dataset. These months reflect climatic conditions

experienced in August 1984 and February 2010 from the historical dataset. Climate change factors are applied to assess the impact of climate change.

The following, post-restoration changes to the groundwater system are assessed for known receptor locations, including WFD water bodies:

- Change in groundwater level and availability. Any observed impact is assessed to check whether this is within the margin of error of the commonly deployed monitoring techniques, such as dip meters, or beyond the resolution of the model to practically simulate. For the purpose of this assessment, this is taken as  $\leq 1$  cm. Impacts with a magnitude beyond this are assessed for adverse water availability effects and whether they may lead to a change in water body quantitative status on a case-by-case basis.
- Change in groundwater discharge to surface water receptors. The change in discharge of groundwater to the receiving surface water bodies is initially determined. If present, the magnitude is evaluated to assess whether this fall below the threshold of measurement error. This shall be taken as  $< 1$  l/s or 86.4 m<sup>3</sup>/d in this instance for WFD water bodies. Changes greater than this are assessed on a case-by-case basis relative to the Q95 flow at nearby flow gauges (or summer spot flow measurements if gauges are not present) to ascertain whether they may result in a change to quantitative status of the water body.

A water balance approach was used to simulate future pit lake level and volume fluctuations for both the current pit topology and the proposed, reclaimed landform. The potential impact of future climate change is also considered using this method. Development and use of the pit lake water balance model is described in Section 5.

## 2.2 Legislation and policy

There is no specific legislative framework in the UK for the assessment of hydrogeological impacts associated with mining activities, including closure. As such, the legislation of most relevance to the applicable to the hydrogeological aspects of the scheme relates to the following:

**Water Environment (Water Framework Directive) Regulations 2017.** This was adopted to transpose the Water Framework Directive (Council Directive 92/43/EEC) into UK law. These provide a framework for managing the water environment in England and Wales. Under the WFD Regulations, a river basin management plan must be prepared for each river basin district. In general, developments must demonstrate no deterioration in the ecological or chemical status of surface water bodies, as defined under the WFD objectives.

**Catchment Abstraction Management Strategies (CAMS) for the South Valleys (2017).** This document sets out how NRW manages water resources in the South Valleys river catchments, and provides an overview of the current water availability context for the search area.

## 2.3 Baseline conditions

The baseline conditions for the hydrogeological assessment are taken as the period from August 2023 to November 2024, during which time mineral extraction operations ceased and water levels recovered to equilibrium within the pit void. This interval coincides with the period during which pit lake levels have been measured on a regular basis and overlaps with both maximum (April) and minimum (September) water levels within the pit void. The core area of the site, defined as Phase 3, will be the subject of the most change during the proposed restoration scheme. This encompasses the main void, waste rock dump OB1 and the surrounding area north of Bogey Road. Other areas of the site would remain as they are at present, apart from surface treatments such as ground preparation, cultivation, grass seeding, and hydroseeding of trees and shrubs.

Contemporaneous field studies have been carried out to characterise baseline conditions. This includes: flow gauging of nearby surface water courses and mine discharges (in a repeat of the 1996 Celtic Energy spot flow survey used to quantify the site water balance for the 2002 Environmental Statement (ES)); regular monitoring of the pit lake water level; and rising heads tests to measure the hydraulic conductivity of backfill material. These investigations are documented in Section 3.2.

## 2.4 Receptor screening

### 2.4.1 Environmental receptors

A screening process was undertaken to identify the location of environmental receptors within the groundwater search area presented in Figure 1. The following receptors were checked during the screening process:

- European (Natura 2000) and international designation receptors:
  - Special Areas of Conservation (SAC)
  - Special Protected Area (SPA)
  - RAMSAR Wetlands
- Nationally designated receptors:
  - Sites of Special Scientific Interest (SSSI)
  - Groundwater Dependent Terrestrial Ecosystems (GWDTEs)

Nine SSSI receptors were identified during this process. These sites are summarised in Table 1, and shown with respect to the groundwater search area, surface water courses and mine site in Figure 2.

*Table 1 Summary of SSSI receptors within hydrogeological search area*

| SSSI Name                       | Description                                                                                                                                                                            | Distance from mine site and location                                                                         |
|---------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|
| Baltic and Tyle'r-bont Quarries | Site showing a section through the Carboniferous Limestone, here of Courceyan-Holkerian age. The section includes the Llanelly Formation, which contains an unusual clastic facies.    | 4.5 km to N.                                                                                                 |
| Cefn y Brithdir                 | Hill of Pennant grit. The slopes support the best example in Mid Glamorgan of a dwarf shrub heath community in which crowberry <i>Empetrum Nigrum</i> occurs as a co-dominant species. | 5.8 km to SE. Situated on the western side of the upper Rhymney Valley overlooking the town of New Tredegar. |

|                            |                                                                                                                                                                                    |                                                                          |
|----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Cwm Glo a Glyndyrys        | Extensive area of marshy grassland, species-rich neutral grassland and acid grassland.                                                                                             | 3.3 km to W.<br>To the west of the River Taff.                           |
| Cwm Taf Fechan Woodlands   | Mixed deciduous woodlands cover steep slopes and spoil from quarries with one of the few Glamorgan stations for <i>Gymnocarpium robertianum</i> .                                  | 4 km to NW.<br>Associated with the Taf Fechan River valley.              |
| Daren Fach                 | Open scrub on low limestone cliffs with screes and woodland on the gentler slopes. Presence of <i>Sorbus</i> spp. on the southern end of the Darren Fach crags.                    | 6.5 km to NW.<br>Downstream of Llwyn Reservoir.                          |
| Lower House Stream Section | Used to locate the boundary between the Marsdenian and Yeadonian stages of the Namurian. Most diverse <i>Gastrioceras cancellatum</i> Marine Band fauna known in southern Britain. | 4.2 km NE.<br>Rhymney River just to north of the A465.                   |
| Mynydd Llangynidr          | Mynydd Llangynidr is of special interest for its karstic geomorphology, particular the doline field.                                                                               | 7.9 km NE.<br>Situated approximately 1km north of the village of Trefil. |
| Nant Glais Caves           | Limestone gorge of the Nant Glais and two vadose cave systems. Important for their unusually large populations of white trout.                                                     | 4.8 km to NNW.<br>To the north east of Vaynor Quarry.                    |
| Penmoelallt                | A mixed woodland of ash, oak, wych elm and small-leaved lime. The rare Ley's whitebeam grows on a small escarpment within the wood.                                                | 6.2 km to NW.<br>On the west bank of the Rhondda Cynon Taf.              |

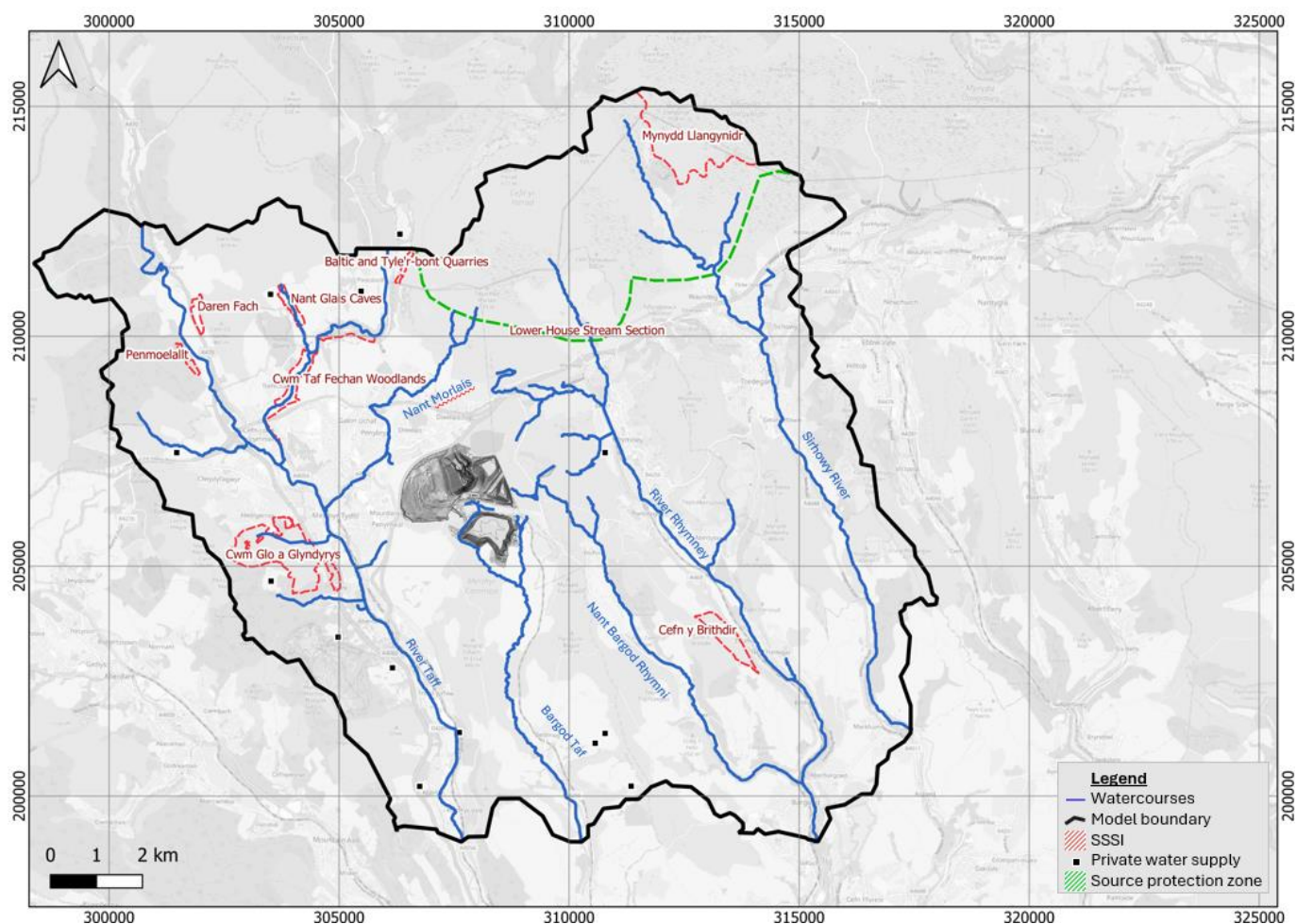


Figure 2: SSSIs, source protection zone and private groundwater abstraction within the hydrogeology search area

## 2.4.2 Groundwater users

Natural Resources Wales (NRW) and Merthyr Tydfil County Borough Council (MTCBC) were consulted to identify the location of groundwater and surface water abstraction licences for public supply, as well as private groundwater users.

A total of 10 separate water abstraction licences have been identified:

- 1 groundwater abstraction licence for public water supply associated with a borehole (21/57/11/0022).

- 1 abstraction licence for public water supply associated with a spring in the Sirhowy River catchment (20/56/65/0014).
- licences associated with public water supply from Llwyn Onn, Cantref and Taf Fechan reservoirs (21/57/21/0001, 21/57/21/0002 and 21/57/21/0004).
- 1 surface water abstraction licence relating to abstraction from the River Rhymney (21/57/11/0001).
- licences associated with surface water abstraction from the Taf Bargoed (21/57/22/0032 and WA/057/0021/001).
- 1 licence for surface water abstraction from the Taf Fechan (WA/057/0021/0011)
- 1 licence relating to abstraction of surface water from the Sirhowy River (20/56/65/0028).

For asset security reasons, licensed abstractions are not included on maps in this report. In addition, grid references are not provided. Licences attributed to operations (such as dewatering or dust suppression) at the MSW mine site are not considered.

A single source protection zone (SPZ) was identified within the hydrogeology search area and is located approximately 2.7 km to the northeast of the mine site at the closest point. This is shown on Figure 2 and coincides with the approximate catchments for public water supply abstractions.

There are 14 recorded private groundwater users within the search area. These are shown in Figure 2. The closest is situated 3.1 km from the centre of the excavation, with the remainder located more than 4 km away.

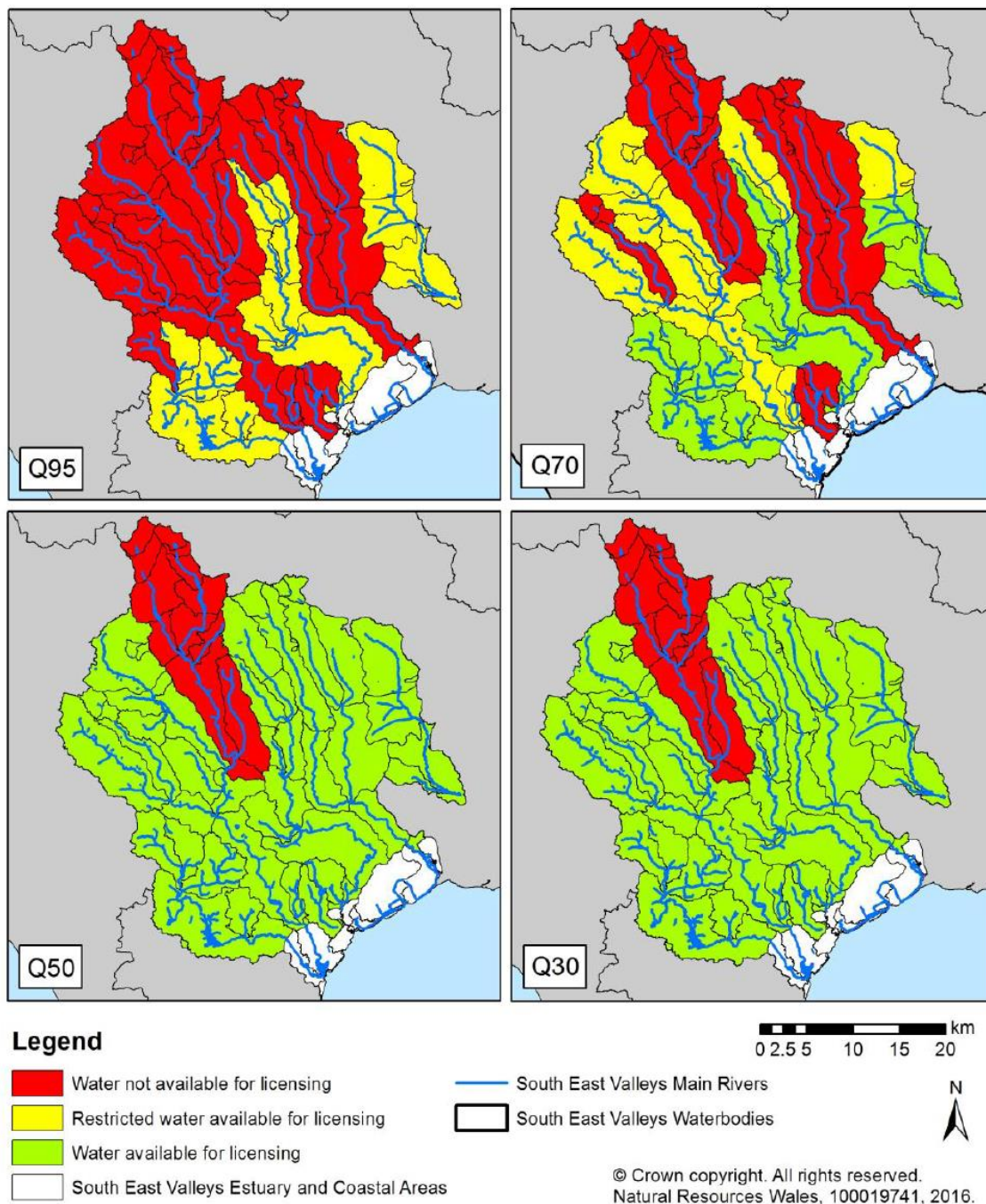
### *2.4.3 CAMS catchments*

The groundwater search area is coincident with the following CAMS catchments (NRW, 2017):

- Taf Fechan and Taf Fawr catchments (Taff u s Cynon operational catchment).
- River Taff catchment from Abercynon to Merthyr (Taff u s Cynon operational catchment).
- River Rhymney catchment upstream of Bargoed.
- River Ebbw and Sirhowy catchment.

Figure 3 shows the availability of water for consumptive licensing within the South Valleys CAMS area. It can be noted that:

- Water is not available for licensing within the Taf Fechan, Taf Fawr and River Taff catchment from Abercynon to Merthyr for Q30 to Q95 flow conditions.
- The availability of water within the Rhymney catchment upstream of Bargoed is limited to flow conditions of greater than Q50, otherwise restrictions apply.
- As surface water availability classifications are used as proxies for the underlying groundwater availability, it follows that groundwater bodies underlying these catchments where restrictions on water availability are in place are also subject to the same restrictions.



*Figure 3: Availability of water for consumptive licencing, from NRW 2017*

#### 2.4.4 WFD bodies and classification

The groundwater search area coincides with 9 WFD surface water bodies and 4 WFD groundwater bodies. The RBMP (River Basin Management Plan) WFD cycle 3 locations, nature and classifications are shown in Table 2. Groundwater and surface water WFD water bodies are shown in Figure 4 and Figure 5 respectively. In summary:

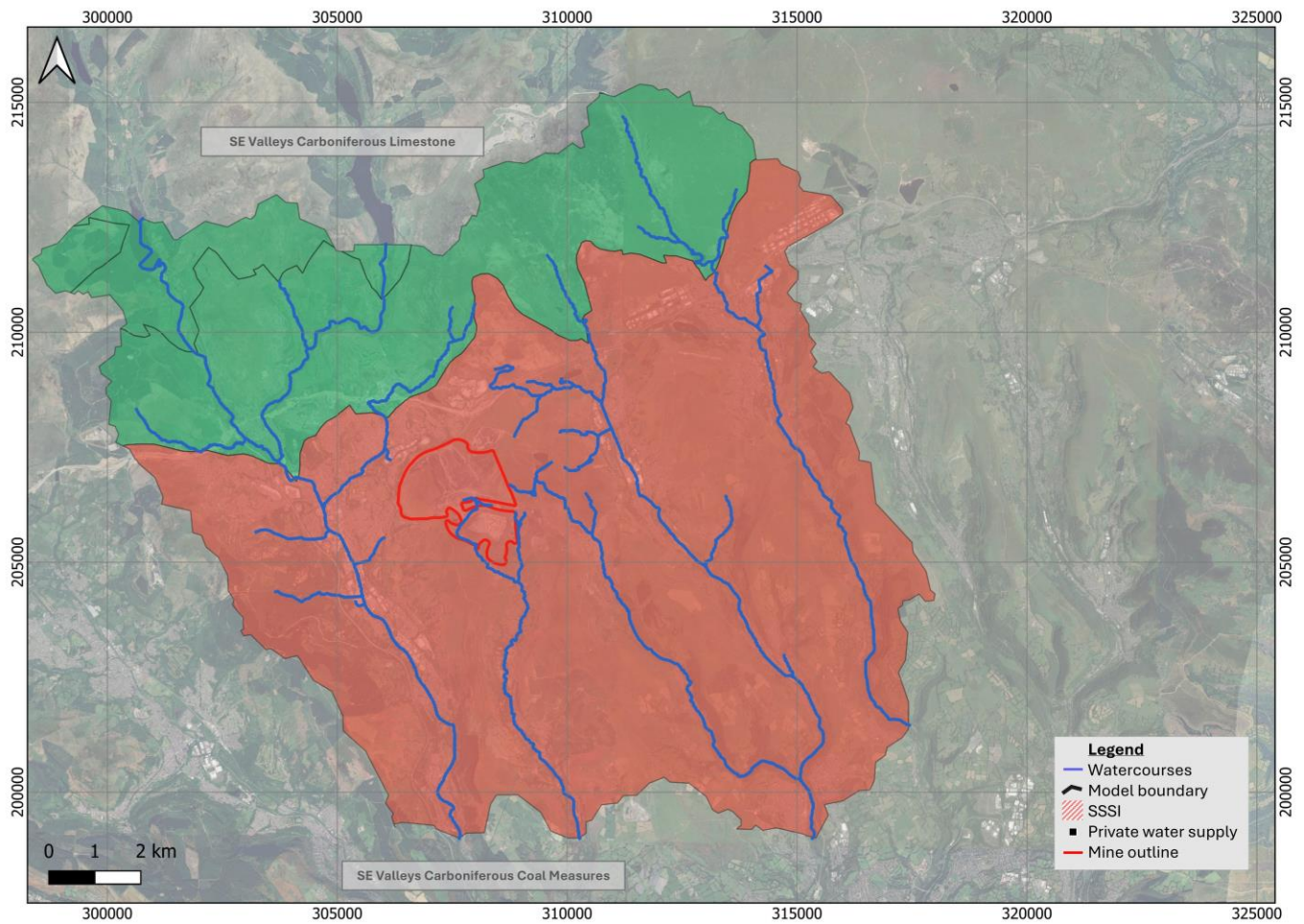
- The majority of surface water bodies have been assigned an overall classification of “moderate”.
- The main reason cited for not achieving “good” status is the modified and engineered nature of these water bodies and lack of mitigation to compensate for the impact on ecological and environmental factors. Ecological (primarily fish populations) and chemical factors (phosphate, nitrate) were also cited as reasons for not achieving “good” status.
- Southeast Valleys Carboniferous Coal Measures is the only groundwater body within the search area with a “poor” rating. This relates to the impact of groundwater chemistry on surface water chemistry and ecology. All other WFD groundwater bodies have a “good” status overall.
- The Southeast Valleys Carboniferous limestone is rated as “good” for all quantitative elements.

*Table 2: Summary of WFD water bodies within the hydrogeology search area*

| WFD water body                                                   | WFD classification | Overall rating | Reasons for not achieving good |
|------------------------------------------------------------------|--------------------|----------------|--------------------------------|
| Sirhowy River - source to Rock Villas                            | River              | Moderate       | Phosphate                      |
| Taff – confluence with Taf Fechan to confluence with River Cynon | River              | Moderate       | Mit_Assmnt*                    |
| River Rhymney - source to confluence with Nant Bargod Rhymni     | River              | Moderate       | Fish                           |
| Nant Morlais - source to confluence with River Taff              | River              | Moderate       | NH3; Mit_Assmnt                |
| Afon Taf Fawr - source to conf Taf Fechan                        | River              | Moderate       | Mit_Assmnt*                    |

| WFD water body                                                   | WFD classification | Overall rating | Reasons for not achieving good      |
|------------------------------------------------------------------|--------------------|----------------|-------------------------------------|
| Nant Bargod Rhymni - source to confluence with River Rhymney     | River              | Poor           | Fish                                |
| Taff Bargoed                                                     | River              | Moderate       | Mit_Assmnt*                         |
| Taf Fechan - source to conf Afon Taf Fawr                        | River              | Moderate       | Mit_Assmnt*                         |
| River Rhymney - Nant Bargod Rhymni to confluence with Nant Cylla | River              | Good           |                                     |
| SE Valleys Carboniferous Limestone                               | Groundwater        | Good           |                                     |
| Usk Devonian Old Red Sandstone                                   | Groundwater        | Good           |                                     |
| SE Valleys Carboniferous Coal Measures                           | Groundwater        | Poor           | Groundwater/surface water chemistry |
| SE Valleys Northern Devonian Old Red Sandstone                   | Groundwater        | Good           |                                     |

\* Mit\_Assmnt is the Mitigation Measures assessment which relates to water bodies that are classed as Artificial / Heavily Modified (HMAWB). This term determines the Ecological Potential of HMAWBs by evaluating whether the necessary measures are in place to reduce the impact of modifications on the water body's ecology.



*Figure 4: WFD Cycle 3 groundwater body classifications*

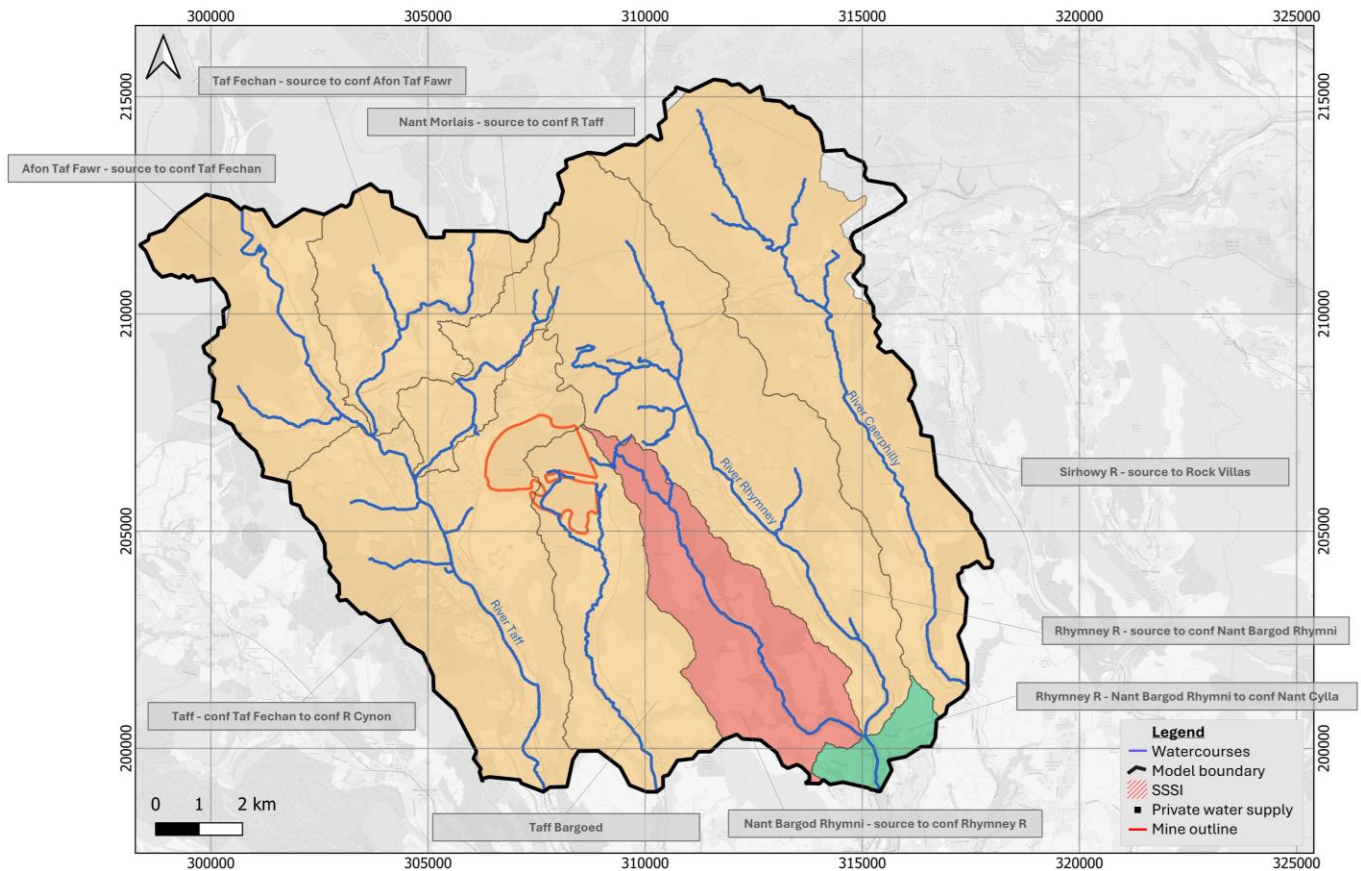


Figure 5: WFD Cycle 3 surface water body classifications

### 2.4.5 Summary of receptors

The groundwater EIA will be evaluated with respect to potential impacts on the following receptors:

- 9 nationally designated SSSIs
- 10 water abstraction licences
- 14 private water supplies
- 4 CAMS catchments within the search area
- 9 WFD surface water bodies within the search area
- 4 WFD groundwater bodies within the search area
- 1 SPZ

# 3. CONCEPTUAL MODEL

## 3.1 Summary of existing knowledge

The hydrogeological conceptual model of the site has been well established during previous studies. The main findings are summarised in the following review.

### *Hydrological and Hydrogeological Appraisal, East Merthyr Restoration Scheme (Halcrow, 1990)*

- Halcrow conducted a review and appraisal of both hydrological and hydrogeological conditions of the site prior to commencement of work on Phases 1 to 3 of the Merthyr Restoration Scheme.
- Noted that the strata that naturally occur at the site are argillaceous and do not easily transmit groundwater. Therefore, they are considered to be aquitards by Halcrow.
- Concluded that the hydrogeological system of the site is controlled by the extensive system of historical interconnected mine workings. The authors of the report believed these to drain down-dip towards the southeast.
- Identified four main drainage levels, designed to supply the iron ore industry at Dowlais and Penydarren with mine water. Levels that discharge to the west of the site include Black Ball Watercourse, Penyrheol watercourse and Penydarren Water levels. The Brewhouse level drains towards the Dowlais ironworks to the north of the site.
- The extent of the workings and the groundwater levels were unknown at the time.
- Considered it an essential recommendation that groundwater levels across the site should be established, particularly in the old workings and ironstones below the Lower Four Feet Seam.

### *Review of Hydrogeology (Celtic Energy Limited, 1996)*

- The site's strata consist of the Lower and Middle Coal Measures, comprising mudrocks, ironstone, coal seams, and occasional sandstone horizons. These strata dip at a gradient of 1 in 12 towards the southeast. Extensive mining activity, including numerous adits, shafts, bell pits, and spoil heaps, indicates that the coal measures and underlying ironstone have been extensively worked.
- There are five main underground drainage courses: The Black Ball Watercourse, Penyrheol Watercourse and Penydarren Water Level discharge to the west of the site, and the Bute and Nant Llesg watercourses discharge to the River Rhymney near Pontlottyn.

- The Trecatti and Royal Arms Group sites to the north of the Phase 3 site were mined to the Four Feet seam in the 1960s. The former is now a landfill.
- While the site's strata primarily consist of low-permeability mudrock, coal seams, and ironstone, old workings are anticipated to create preferential flow paths for rainfall infiltration and groundwater movement.
- Faults act as aquitards and have a compartmentalising effect. East of the Dowlais fault, groundwater levels range from 260 to 285 m Above Ordnance Datum (mAOD) with an average level of 275 mAOD. There is evidence from water quality sampling that mine water flows northwest from this area to the Dowlais Culvert via the Dowlais Free Drainage System (DFDS) or mine working and adits at 260 mAOD and 275 mAOD. These are believed to act as a control on groundwater levels.
- Water levels to the west of the Dowlais fault vary between 212 and 220 mAOD. It is thought that they are controlled by a spill point at 212 mAOD across the Pennydaren Fault.
- A site water balance was derived using estimates of rainfall, an assumption of no runoff, measured surface water flows and measured mine discharges to surrounding surface water courses. The findings are summarised in Table 3.
- It is anticipated that dewatering during operations, baseflow in the Nant Morlais would increase as water is discharged from the site. Upon cessation of mining, it was deemed likely that baseflow in the Nant Morlais would temporarily reduce before recovering to pre-mining levels, as groundwater levels recover and the old drainage networks become re-established.
- It is stated that dewatering should impact flow to the Nant Cwm Blacks, Bargeod Taff and Nant Gyrawd watercourses.
- Post-closure, the backfill consisting of permeable, granular material, combined with existing drainage pathways beneath the pavement level in the Ironstone and Farewell Sandstone, will facilitate the return to pre-mining groundwater flow conditions. A low permeability (hydraulic conductivity of  $1 \times 10^{-9}$  m/s) barrier would be emplaced along the strike of the mined-out Dowlais Fault to an elevation of 260 mAOD, to replicate the compartmentalising effect of the fault on the groundwater regime.

*Table 3 Summary of site water mass balance (adapted from Celtic Energy 1996)*

| INFLOWS                                               |              |
|-------------------------------------------------------|--------------|
| Catchment [Area]                                      | Inflows l/s  |
| Dowlais workings [4.46 km <sup>2</sup> ]              | 134          |
| Soap mineworking at Cwmbargoed [0.7 km <sup>2</sup> ] | 21           |
| Bute Workings [3.5 km <sup>2</sup> ]                  | 105          |
| <b>TOTAL Inflows l/s</b>                              | <b>260</b>   |
| OUTFLOWS                                              |              |
| Receiving water body / catchment                      | Outflows l/s |
| Nant Cwm Blacks from west of Dowlais Fault            | 2            |
| To Nant Morlais from east of Dowlais Fault            | 52           |
| To Nant Morlais from west of Dowlais Fault            | 80           |
| Bargoed Taff from Soap workings                       | 1            |
| River Rhymney via Bute Watercourse overflow           | 115          |
| River Rhymney via Bute Working overflow               | 10           |
| <b>TOTAL Outflows l/s</b>                             | <b>260</b>   |

*Review of Hydrogeology (Miller Argent, 2002)*

- The purpose of the report was to review the current understanding of the hydrogeological regime ahead of the commencement of Phase 3 of the Merthyr Restoration Scheme, and to assess the potential long-term post-closure and redevelopment groundwater conditions

at the site. The report provides in-depth discussion about the groundwater system in the vicinity of the area of interest with the benefit of piezometric data, however this is largely based on material published in the 1996 Celtic Energy Limited report and does not build upon the conceptual model in a significant manner.

#### *Environmental Statement (ES) (Miller Argent, 2003)*

- The material presented in the hydrogeology chapter of the 2003 ES is largely based on the 1996 Celtic Energy report and the Millar Argent 2002 Review of Hydrogeology. It does not provide any additional insight into the conceptual setting of the site.

#### *Trecatti landfill: Data review and conceptual model report (ESI, 2011)*

- This report presents the results of a conceptual review of the Biffa landfill site and surroundings following exceedance of certain water quality trigger levels at groundwater piezometers situated downgradient of the site.
- A conceptual review is presented and largely repeats what is presented in the 1996 Celtic Energy review of the Hydrogeology, and Millar Argent 2002 Review of Hydrogeology, although the report does note the significance of the DFDS and historical mine workings in controlling groundwater levels in the Trecatti Landfill area.
- Of relevance to the conceptual hydrogeology are the location and construction details of piezometers situated around the perimeter of the site. Groundwater levels are available through publicly accessible sources.

## 3.2 Updates to the conceptual model

The hydrogeological conceptual model has been extensively documented in at least five published studies. Therefore, this report will not provide a detailed summary of it. Instead, this section will focus on presenting findings from recent site investigations and a review of historical hydrogeological data. Additionally, it will highlight the key updates to the conceptual model to reflect the site's current condition.

### *3.2.1 Stream flow surveys*

An extensive spot flow survey was carried out by Celtic Energy in June 1996 to measure stream flows and to establish discharges from the groundwater regime to surface. This was done during the summer after a long period of low rainfall, when contributions of runoff to the total flow would be negligible and therefore stream flow would primarily reflect groundwater and subsurface mine

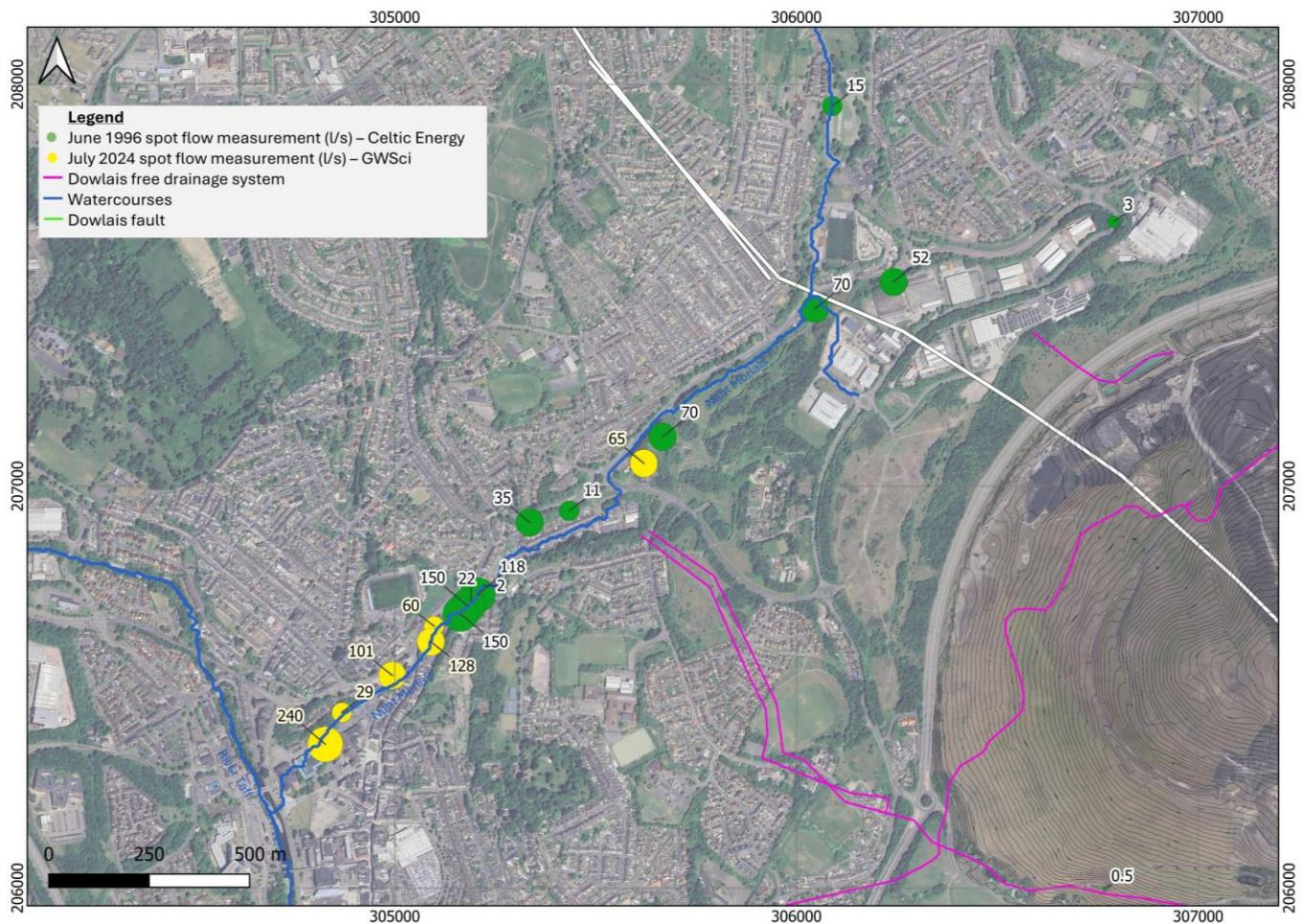


completed during a particularly wet period, and as such a comparison was made between the June 1996 and July 2024 surveys.

### *Nant Morlais Valley*

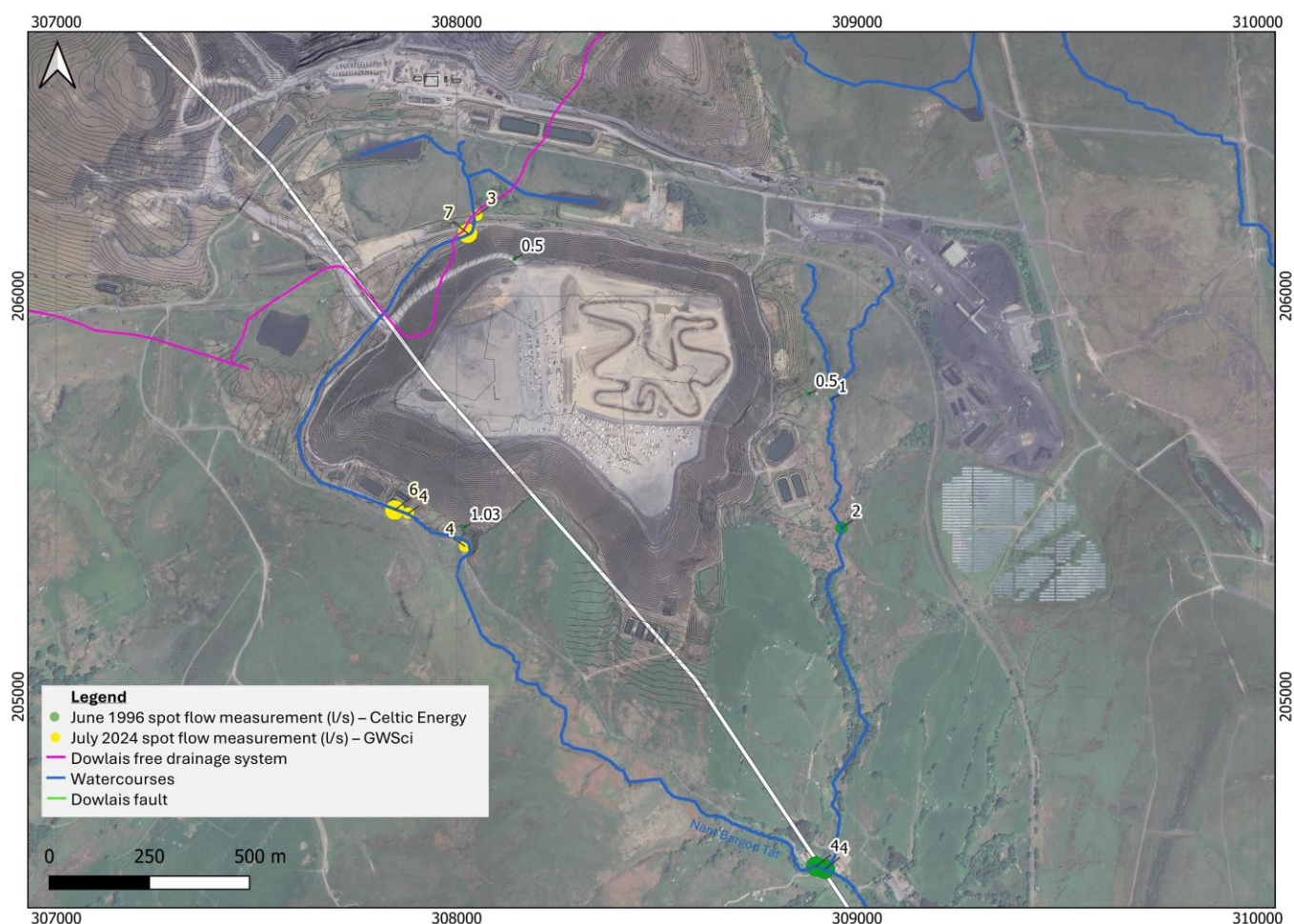
Measured discharges and stream flows within the Nant Morlais Valley area are shown in Figure 7. The July 2024 spot flow measurement locations are shown in yellow and the 1996 measurements in green. The magnitudes of measured flows broadly agree with those recorded in 1996, although a minor reduction is perceptible from Whitney Park onwards. Given the relatively high margin of error associated with spot flow measurement techniques and dependence on antecedent weather conditions, this suggests that there has been little change in the volume of water reporting from the mine workings, and therefore that the capacity of the sub-surface drainage regime to convey water to the Nant Morlais culvert doesn't seem to have changed markedly as a consequence of mining activity at the site.

The spatial pattern of mine water discharges to the Nant Morlais culvert also appears to reflect what was observed in 1996. Of the estimated 132 l/s of mine water discharge to the Nant Morlais, 52 l/s was estimated to originate from the west of the fault and discharge to the Dowlais long culvert before the confluence with the main Nant Morlais channel. The remaining 80 l/s was thought to originate from the east of the Dowlais Fault and join the Nant Morlais culvert at several locations upstream of the confluence with the River Taff. The measured flow along the culvert through Whitney Park of 65 l/s is close to the 70 l/s reported in 1996, which is likely to comprise mine water discharges from the east of the Dowlais Fault and water from the Nant Morlais stream. Further downstream, there is an increase in stream flow to 128 l/s and 150 l/s in July 2024 and June 1996 respectively. This represents an accretion of 80 l/s in 1996 and 63 l/s in 2024, perhaps indicating a small reduction in mine discharges from the western part of the site.



*Figure 7 June 1996 (Green) and July 2024 (Yellow) spot flow measurements in l/s, Nant Morlais Valley*

Measured discharges and stream flows within the Bargoed Taff catchment are shown in Figure 8. The July 2024 spot flow measurement locations are shown in yellow, whereas measurements made in 1996 are shown in green. The magnitude of discharge of mine water to the Bargoed Taff valley appears to reflect what was measured in 1996, suggesting that despite the development of the pit and associated waste rock dumps (notably OB3), sub-surface drainage to this catchment is mostly unchanged. It should be noted in this instance that discharges to watercourses that report to the Bargoed Taff occur above the main water table, and are likely to be associated with shallower, perched groundwater rather than the regional groundwater system.



*Figure 8 June 1996 (Green) and July 2024 (Yellow) spot flow measurements in l/s, Bargoed Taff catchment*

### *Rhymney Valley*

Measured discharges and stream flows within the Rhymney catchment are shown in Figure 9. The July 2024 spot flow measurement locations are shown in yellow, whereas 1996 measurements are shown in green. Celtic Energy (1996) estimated that mine discharges to the River Rhymney via the Bute workings were equivalent to 125 l/s. This represents 45% of the Q95 river flow (274 l/s) recorded at the Bargoed river gauge, located approximately 5 km downstream of the mine discharge point.. Measured stream flows along the Rhymney are within +/-10% of flows measured in similar location in June 1996, which is suggestive that the magnitude of mine

er discharges to the Rhymney valley from the Bute workings and associated drainage system remained largely unaffected by activities at the site.

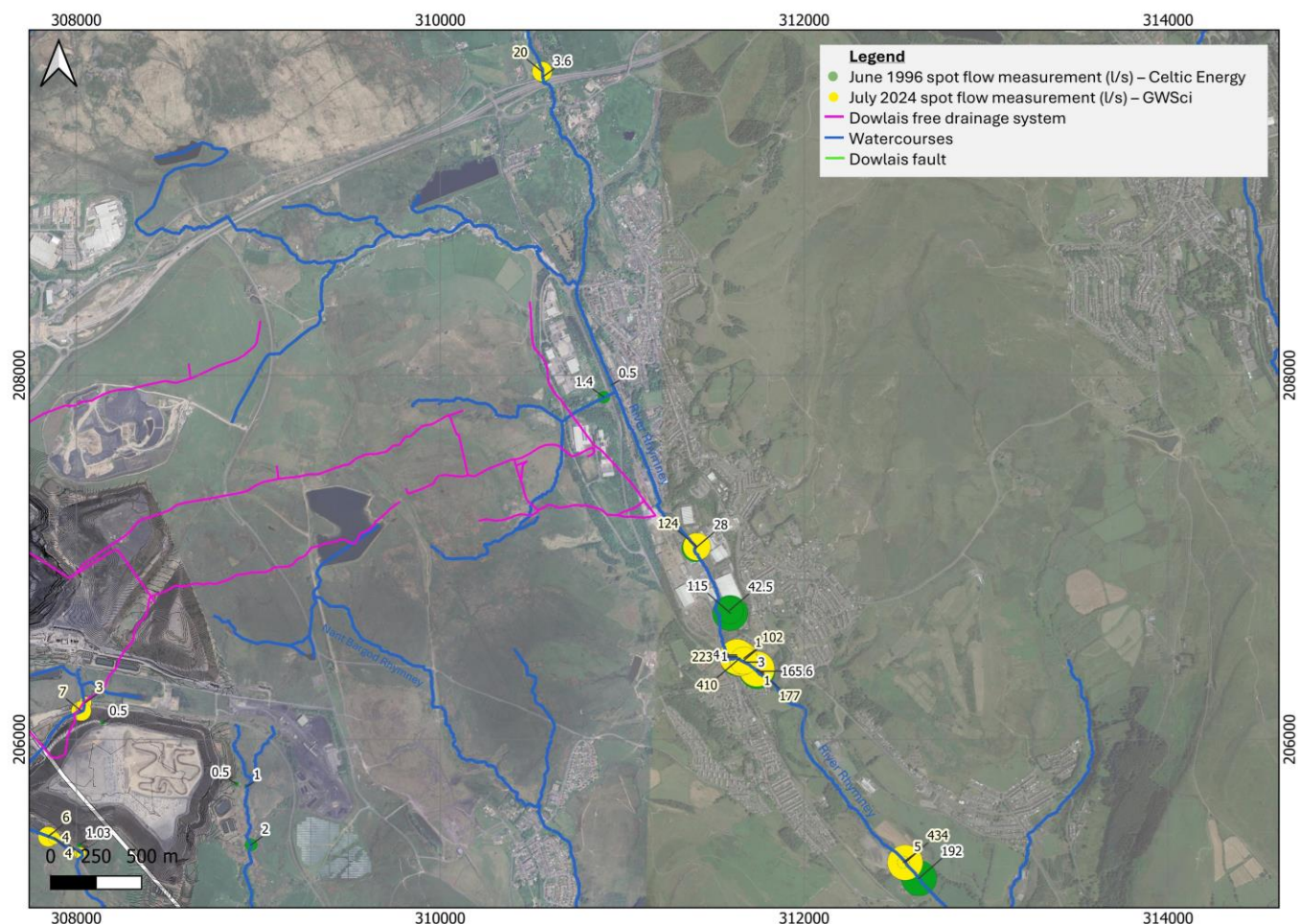


Figure 9 June 1996 (Green) and July 2024 (Yellow) spot flow measurements in l/s, Rhymney Valley

## Conclusions

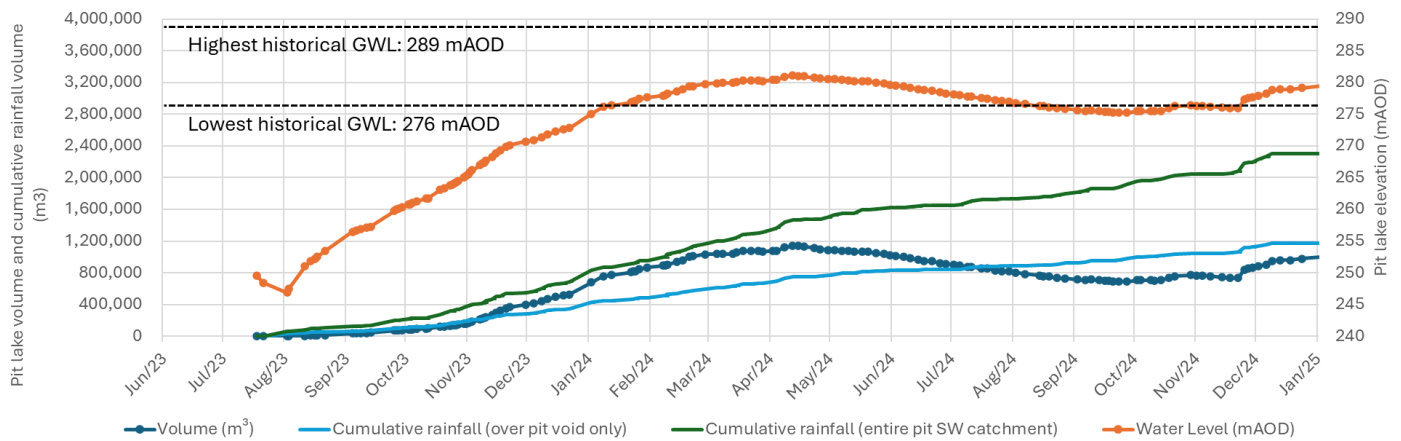
The spot flow survey did not reveal any noteworthy changes to mine discharges from the site relative to what was recorded in June 1996, other than the suggestion that mine discharges from the Phase 3 area to the west of the Dowlais fault to the Nant Morlais culvert may have reduced slightly. This represents a small reduction however and given the relatively large margin of error associated with spot flow measurements this finding should not be treated as definitive. Since rainfall over the site is unlikely to have changed substantially since 1996 and in the absence of

evidence to the contrary, the site mass balance developed by Celtic Energy in 1996 is likely to still approximately reflect the water balance of the site.

### *3.2.2 Pit lake monitoring*

The water level within the pit void has been monitored continuously since the 18<sup>th</sup> of July 2023. This period coincides with the cessation of dewatering in August 2023 and subsequent recovery of pit lake levels to an equilibrium regime. A full record of measured pit lake level and volume from July 2023 to December 2024 is provided in Figure 10. Cumulative rainfall totals over both the full pit catchment and the void footprint are plotted for reference, as are the highest and lowest groundwater levels recorded in piezometers within the pit footprint area prior to excavation of the void.

The pit lake level rose from a low of 246.9 mAOD (384 m<sup>3</sup>) in early August 2023 to 281.1 mAOD (1,139,484 m<sup>3</sup>) on the 12<sup>th</sup> of April 2024. The average rate of inflow to the pit during this period was 4,485 m<sup>3</sup>/d (52 l/s), which is a combination of groundwater inflow, direct rainfall and runoff. The pit lake level then receded to a minimum of 275.2 mAOD (688,670 m<sup>3</sup>) on the 27<sup>th</sup> of September, which represents a 40% decrease in the pit lake volume relative to its peak. The average daily loss of water from the pit during this period remained steady at 2,683 m<sup>3</sup>/d (31 l/s). This was lost predominantly to groundwater with minor losses to evaporation. The measured outflow during the pit lake recession period of 31 l/s is similar in magnitude to the estimated 52 l/s mine discharge to the Nant Morlais culvert from the mine area to the west of the Dowlais fault, lending further confidence to the water balance. Additional groundwater is likely to report directly to the drainage network from the groundwater system, making up the residual balance.

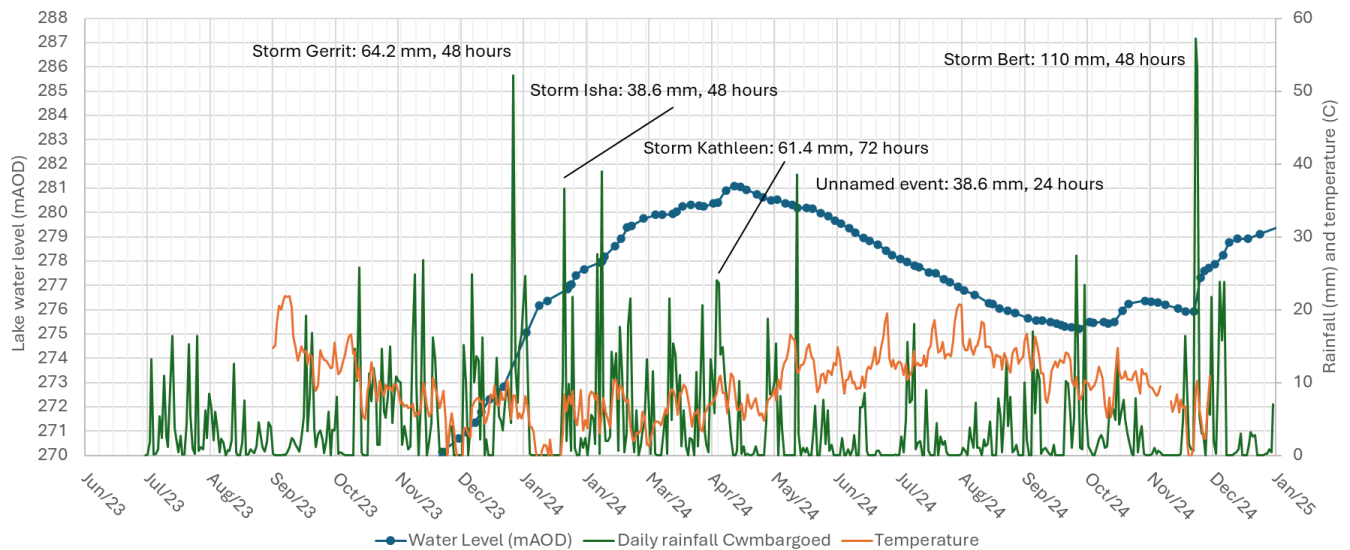


*Figure 10 Pit lake level and volume timeseries, July 2023 to December 2024*

The gradual long-term rise and fall in the pit lake level through the monitoring period is suggestive that most inflows and outflows to the lake occur through the surrounding groundwater system. This implies that the surrounding groundwater level is the main control on lake level.

The pit lake level does respond dynamically on a short-term basis to rainfall events as water reports to the void through direct rainfall, runoff and groundwater inflow. This can be clearly seen in Figure 11, notably during Storm Bert when 110 mm of rainfall was recorded over two days, resulting in the lake level increasing by approximately 1.4 metres. This is equivalent to an additional 124,271 m<sup>3</sup> of water within the void.

High intensity rainfall events during warmer months, for example the 38.6 mm that occurred on the 13<sup>th</sup> of May 2023, seem to have a lesser effect on pit lake levels. This may be due to several factors, including the attenuating effect of increased storage in drier soils, increased evapotranspiration within the soil horizon, and increased runoff away from the site outside of the pit void catchment due to the harder, drier ground. These mechanisms all act to reduce recharge to groundwater and therefore limit the potential groundwater rise that could result in an increase in pit water level.



*Figure 11 Timeseries of pit lake level, daily rainfall and average daily temperature*

There are no current operational piezometers within the excavation area of the site, and as such the pit lake level is the only means by which the approximate groundwater level can be inferred, assuming it is well connected hydraulically to the groundwater system (Section 3.2.2). The tests described in Section 3.2.3, which suggest that the backfill is permeable and generally free-draining, support this hypothesis. However, the Trecatty landfill site situated just 200 m northwest of the site is surrounded by a network of 12 piezometers in which groundwater level is measured monthly. Data from these monitoring locations is only available to September 2023, one month after cessation of pit dewatering and as such there was no record of groundwater level recovery available to this present study. It would be helpful to obtain more recent groundwater level records when it is possible to do so. These could be compared against pit lake level records to further improve our understanding of the hydraulic connectivity between the pit lake and surrounding groundwater system.

### *3.2.3 Other site investigations*

Investigations were conducted within the pit void to characterise the hydraulic properties of the backfill as part of an effort to better understand the role of the material in the post-closure groundwater system.

### *Infiltration rate (Trench infiltration tests)*

Trench infiltration tests were undertaken at four locations along a haul road at the base of the pit to measure the infiltration rate within the unsaturated zone. This was done to quantify the infiltration capacity of the pit floor in relation to long term average direct rainfall and runoff reporting to the void.

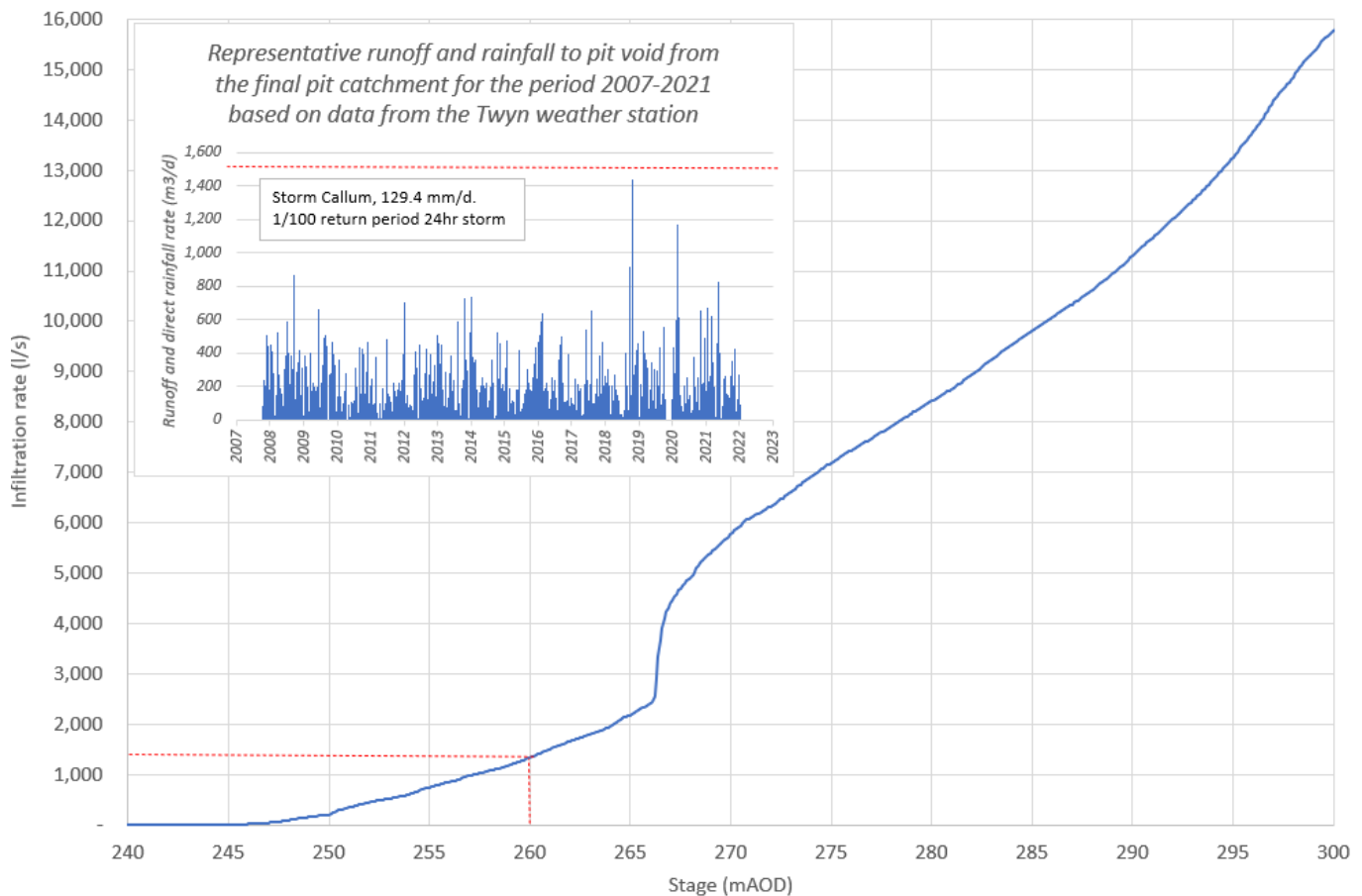
Test results are compiled in Table 4. The measured infiltration rate ranges from 9 m/d to 221 m/d.

*Table 4 Summary of infiltration test findings*

| Trench | Test | Infiltration rate (m/d) |
|--------|------|-------------------------|
| 2      | 1    | 76                      |
|        | 2    | 60                      |
| 3      | 1    | 9                       |
| 4      | 1    | 221                     |
|        | 2    | 154                     |
|        | 3    | 176                     |

The stage dependent infiltration capacity of the pit void was calculated under the conservative assumption that the lowest measured infiltration rate of 9 m/d is representative of the bulk infiltration capacity of the backfill material. This was then compared to daily runoff and rainfall totals generated for the existing pit surface water catchment for climate records from the Twyn weather station for the period 2008 to 2022. Runoff was conservatively assumed to be 100% and only report to the pit void.

The analysis shows that the infiltration capacity of the pit void is theoretically capable of accepting all daily rainfall and runoff totals for the assessment period. This includes Storm Callum in October 2018, a 1 in a 100-year 24-hr event, during which 129.4 mm of rainfall was recorded. Corresponding rainfall/runoff volumes and infiltration rate vs stage are shown below using a dotted red line, highlighting that a pit area equivalent to a stage of 261 mAOD is sufficient to drain even highly intense rainfall events.



*Figure 12 Daily infiltration versus pit stage, and representative runoff and rainfall to the pit void generated from the final pit catchment for the 2007 to 2021 Twyn weather station rainfall record (Inset)*

### *Rising head tests (Hydraulic conductivity)*

These tests were undertaken to measure the saturated hydraulic conductivity of the backfill, a parameter that is required for analytical and numerical modelling of groundwater flow. During the testing it was found that the pump, with a rating of up to 5 l/s, was not sufficient to generate the drawdown necessary to complete the rising head tests. Therefore, an analytical approach was used, based on the Dupuit-Theim formulation (Kruseman and de Ridder, 1994) for steady-state flow to a well in an unconfined aquifer, to loosely constrain a lower bound for the hydraulic conductivity of the backfill material. Noting that 0.1 m of steady-state drawdown in the well was achieved and that the radius of influence is likely to range between 0.1 and 0.5 m, a hydraulic

conductivity of at least 3 to 10 m/d was found to be required to produce the observed drawdown at the lowest pumping rate used during the test (1 l/s). Assumptions apply to the Dupuit-Theim equation that aren't strictly valid in this instance, such as an aquifer of infinite areal extent and that the well is fully penetrating, and therefore the result of this assessment must be considered as an order of magnitude estimate at best. Nonetheless this analysis does provide a loose constraint for the lower bound of backfill hydraulic conductivity and suggests that groundwater is able to flow through the backfill material.

### *3.2.4 Conceptual model*

The conceptual model does not differ significantly from that put forward in the 2003 ES. Recent stream flow surveys suggest that the site water balance has not changed markedly during operations, and that the sub-surface drainage mechanisms, including the DFDS and underlying historical workings, particularly in the ironstone horizons below the pavement level, are likely to still be in place and controlling groundwater levels within the site area. The main changes to the conceptual model are associated with the presence of the void and backfill, as summarised below.

#### *Backfill*

It is stated in Celtic Energy (1996), Millar Argent (2002) and Millar Argent (2003) that a low-permeability barrier would be installed where the Dowlais fault was removed, up to an elevation of 260 mAOD. This corresponds to the presumed spill elevation for groundwater flowing from the groundwater body situated to the east of the fault, to that situated to the west (Celtic Energy Limited, 1996). Upon closure and following recovery of groundwater levels, this feature would maintain a similar control on groundwater levels as the original fault, particularly to the east, through maintaining a spill elevation over the fault line from east to west of 260 mAOD. However, as mining and backfilling progressed a barrier was not implemented. As a result of this, the behaviour of the groundwater system post-closure, namely the hydraulic “step” across the fault from east to west, is now unlikely to reflect what was assumed in the 2003 ES.

In the absence of a low-permeability barrier, the local groundwater levels and rate at which water can flow through the backfill is dictated principally by the hydraulic conductivity of the backfill

material. The backfill consists of coarse, granular material, comprising waste material from the mining process and includes fragments of siltstone, sandstone and mudstone. Due to the coarse nature of the material, it was initially anticipated that since the hydraulic conductivity would likely be higher in the backfill than in the excavated ground, and that the low-permeability Dowlais fault had been removed, groundwater levels in the pit area would recover to a lower elevation than recorded in piezometers prior to commencement of the mining operations. However, monitoring of the pit lake levels through 2023 and 2024 has demonstrated that levels have recovered to within the pre-mining groundwater range within the pit area. This appears to suggest that the presence of the backfill and removal of the Dowlais fault has not significantly affected groundwater levels, and that perhaps the DFDS and historical workings situated beneath the base of the pit exert more of a controlling influence in determining the position of the water table.

### *Void*

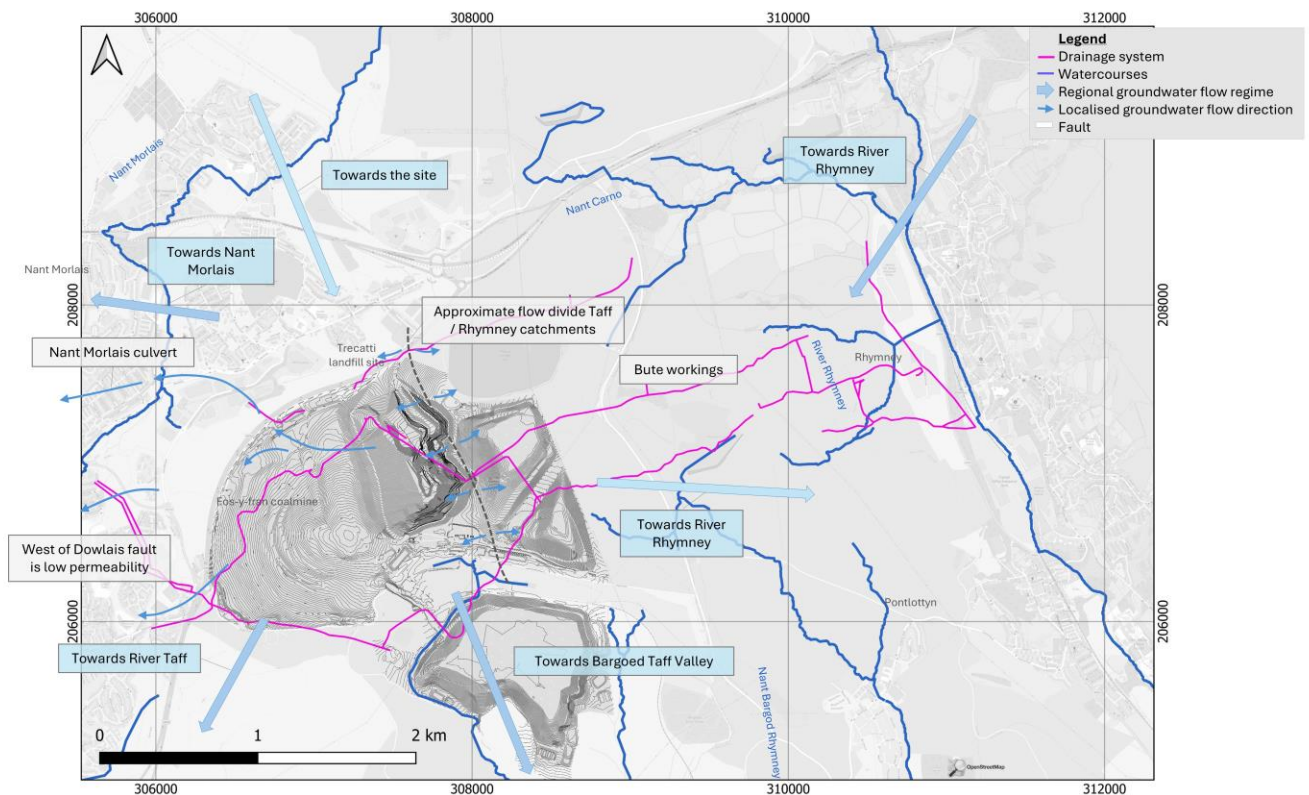
Dewatering of the void ceased in August 2023 and a pit lake has formed. The water level has reached a seasonally-dependent equilibrium, ranging from 275 mAOD to 281 mAOD, that is highest in the early spring, and lowest in the early autumn. The principal, hydrogeological effects of the void are increased local water storage capacity relative to the original coal measures, and provision of a shortcut for rainfall and runoff to reach the water table. The combined effect of these changes is difficult to ascertain, particularly since they are likely to have opposing influences: greater storage within the groundwater system is likely to buffer the groundwater response to rainfall events and/or slow groundwater recession, whilst the provision of a rapid means for rainfall and runoff to reach the water table will result in faster groundwater reaction times to significant rainfall events.

### *Conceptual model summary*

The mean annual rainfall is 1,650 mm, based on the 14-year long record at Twyn weather station. Of this, about 945 mm (Miller Argent, 2002) (57% of mean annual rainfall), is thought to contribute to groundwater recharge. Runoff and evapotranspiration accounts for the remaining water. Historical disturbance of the near surface, including bell pits, vertical shafts and backfill comprising

predominantly mine waste material, is likely to have increased permeability locally and may facilitate infiltration of recharge.

The average pre-mining piezometric level in the excavation area of 277 mAOD, ranging from 260 to 285 mAOD, does not appear to have substantially changed following the completion of operations at the site and rebound of the pit void water level, although direct observations are limited to the pit lake and nearby piezometers at the Trecatty landfill site to the northwest. The natural groundwater gradient is from the northwest to the southeast. The solid strata consist of interbedded mudstone, coal seams and ironstone, with occasional sandstone horizons that do not represent significant aquifer units but do allow for the flow of groundwater along preferential pathways, which may also exist at contacts between formations, especially downdip and along strike. The presence of cross-cutting drainage adits and tunnels such as the DFDS, as well as the presence of extensive historical workings and shafts, means that localised, cross-measure drainage of groundwater at the site occurs to the north and west towards the Nant Morlais and Taff catchments, as well as to the Rhymney and Bargoed valleys. This drainage system maintains a significant control on groundwater levels at the site, which is reflected by the absence of significant change in groundwater levels associated with completion of the operations relative to what existed at the site historically. The groundwater flow directions, receptors for groundwater discharge, and approximate flow divides at the site are shown in Figure 13.



*Figure 13 Plan view of main groundwater flow directions and flow divides*

The existing void receives water from groundwater ingress, surface water runoff from the pit walls and wider catchment, and direct rainfall. The water level within the void fluctuates seasonally in tandem with the surrounding groundwater system. Superimposed on this relationship are periodic and abrupt rises associated with inflow of runoff and direct rainfall. The backfill, consisting of coarse granular material, is permeable and does not impede the flow of water between the lake and surrounding groundwater system. The lake is likely to both receive groundwater and lose to the groundwater system, depending on the location within the void and the season, with gains and losses being generally associated with winter (October – April) and summer months (May – September) respectively. The presence of the void is likely to have increased the volume of storage available locally to groundwater, which may buffer seasonal groundwater level responses, however this may be mitigated to some extent by the direct route it provides for rainfall and runoff to reach the groundwater system, rather than having to infiltrate through over 100 m of unsaturated ground. A conceptual diagram of the groundwater system and pit lake hydrodynamics is presented in Figure 14.

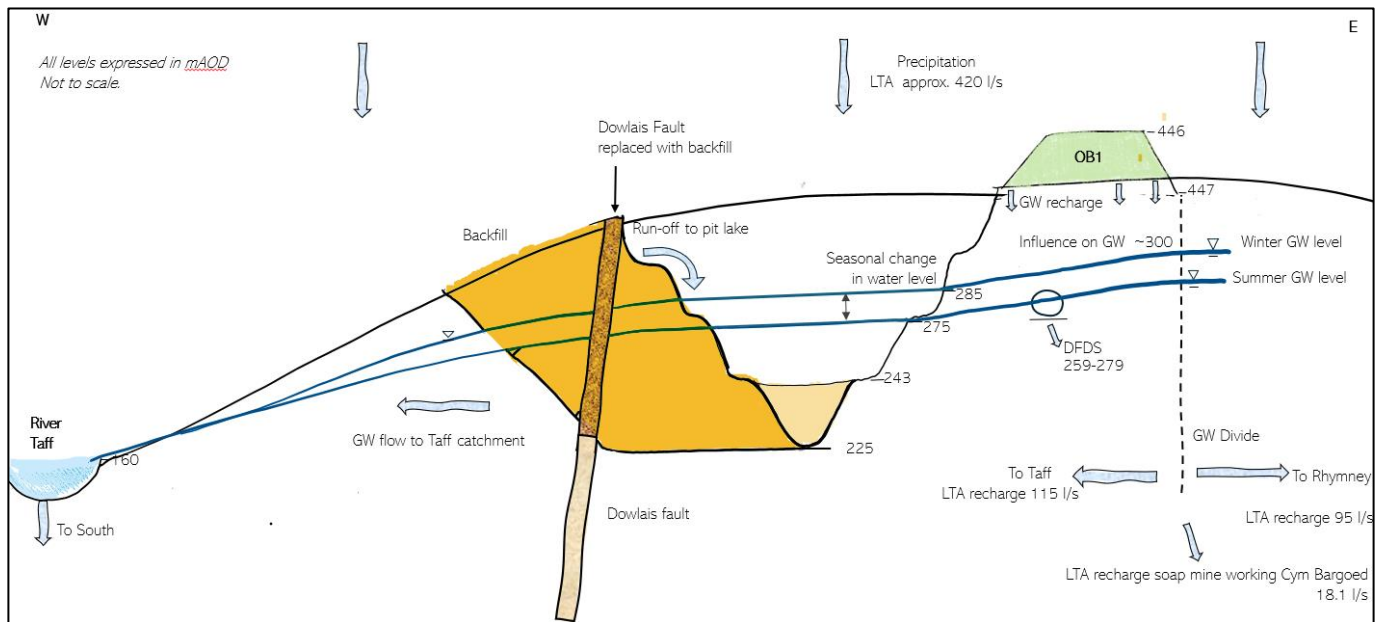


Figure 14 Conceptual diagram of pit lake hydrodynamics and relationship with the groundwater system. Flow rates are taken from the water balance presented in Table 3.

# 4. GROUNDWATER MODEL

## 4.1 Introduction and purpose

A 3D numerical groundwater model was developed to assess post-restoration spatial impacts to receptors within the groundwater search area, including groundwater users and WFD water bodies. This comprises an evaluation of possible changes to groundwater level and availability at groundwater receptors, and groundwater discharges to surface water receptors. Furthermore, the model was used to assess the relationship between the lake level and groundwater flux in and out of the pit void. These relationships were used to parameterise the pit lake water balance model (Section 5).

The following section describes how the model was built, referencing the conceptual model in the process. The model calibration is subsequently presented and discussed in Section 4.3. Finally, projected scenarios for hydrogeological impact assessment are covered in Section 4.4, together with key findings from the impact assessment.

## 4.2 Model build

The model build relates to the development of the numerical model itself, independent of its calibration or predictive use. Aspects of the development that will be covered include the delineation of the model domain, development of the unstructured mesh, model layering, parameterisation of groundwater bodies, boundary conditions and temporal discretisation. A separate recharge/runoff model developed using the opensource software SWAc, used to generate timeseries of groundwater recharge for the groundwater model, will also be documented.

### 4.2.1 Model domain

The model domain is designed to ensure that potential receptors are situated within it, that the boundaries of the model are located sufficiently far from the area of interest to ensure that they do not influence or interfere with the model projections, and that, as far as is reasonably practicable, they follow natural groundwater divides (likely to be associated with topographic

highs) and groundwater sinks (major rivers, streams and other water bodies in contact with the groundwater system).

The model domain is shown in Figure 15 and is centred on the site area. The model domain overall coincides with the hydrogeology EIA study area. The domain includes the Taff and Rhymney valleys, which are situated to the west and east of the site respectively, as well as the Sirhowy valley, to ensure that the southern-most part of the Mynydd Llangynidr SSSI and three public water supplies boreholes associated with licence ID 20/56/65/0028 are within the domain. Out of necessity, the northern and southern domain boundaries are associated with surface water catchment boundaries that are unlikely to be true groundwater divides.

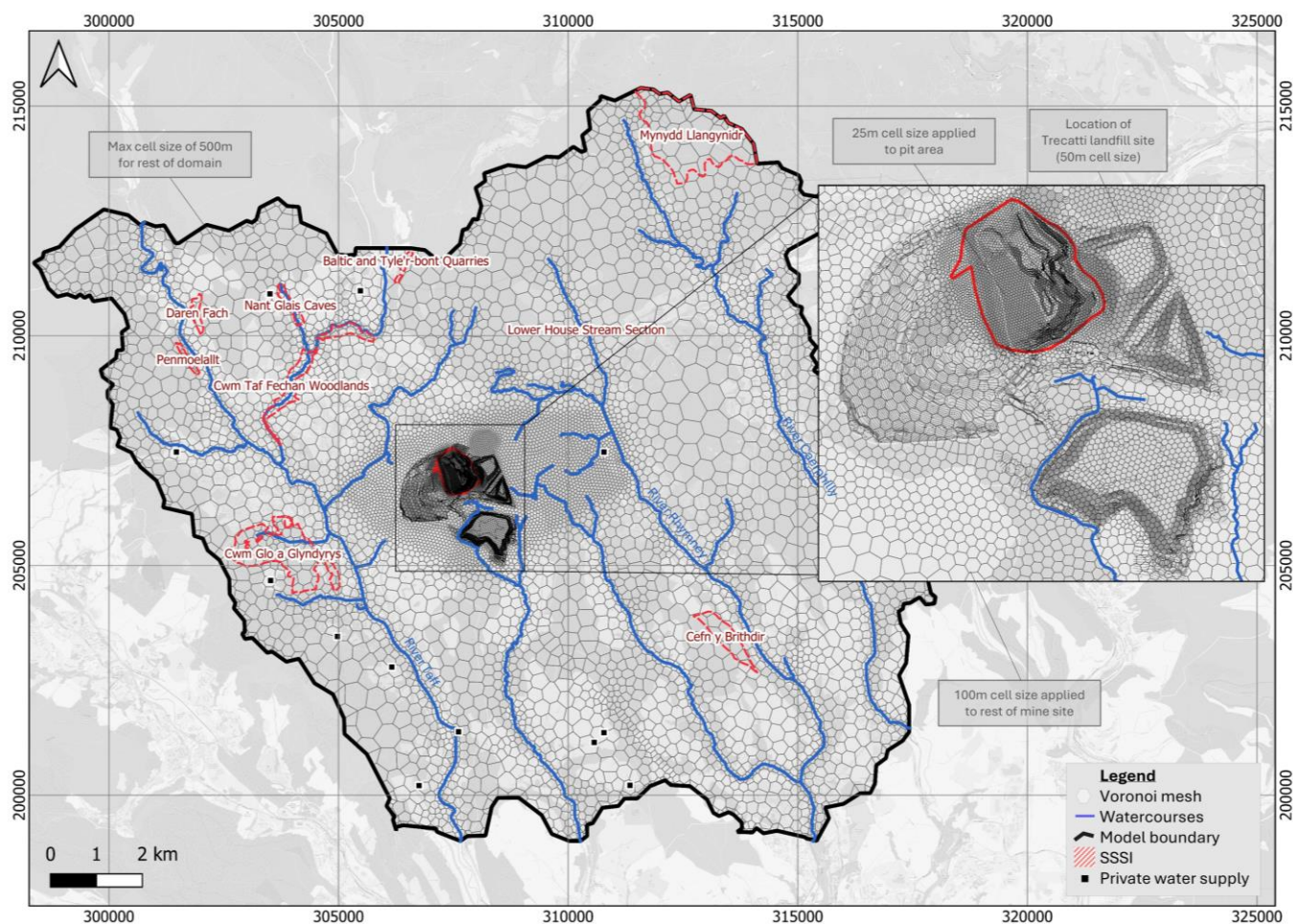


Figure 15 Model domain and meshing scheme

### *4.2.2 Mesh*

A Voronoi (variable resolution polygon) meshing scheme is used to discretise the model domain. There are a total of 11,435 nodes across the full model domain. The distribution of mesh elements across the model domain is shown in Figure 15. A mesh refinement constraint of 25 m (this corresponds to the maximum allowable width of a polygon) is set in the vicinity of the pit area. This degree of mesh refinement is needed to faithfully represent the geometry of the pit and is important to the study, since inaccuracies in the representation of the pit can lead to large errors in the modelled storage of the void. This can result in mis-representative projections of pit lake recovery and/or groundwater/lake water interaction. A mesh resolution of 50 m is applied over OB1, OB2 and OB3, and a resolution of 100 m is used across the remaining area of the mine site. Mesh element size for surface water features and faults is set at a maximum of 100 m. Where there is no other constraint, the maximum mesh element size allowed is 500 m.

### *4.2.3 Runoff/recharge model*

The Surface Water and Accounting model (SWAc) model runoff/recharge developed by Groundwater Science (Groundwater Science, 2018) is a deterministic model that allows the user to simulate processes that delay, attenuate and partition rainfall between groundwater recharge, surface flow and actual evapotranspiration.

The SWAc runoff/recharge model is applied using a lumped approach to estimate recharge to the Ffos-y-Fran groundwater model. The main inputs to the model include the HADUK rainfall (Hollis, et al., 2019) and EA PEt (Environment Agency, 2021) datasets for the period 1980 to 2024. These data are available for 1 km<sup>2</sup> grid squares throughout England and Wales. The rainfall and PEt timeseries for the grid square associated with the centre of the site are in this study. Parallel models are used for the pit area and the waste rock dumps, due to the distinctive nature of the terrain in those areas and consequent effect on hydrological process.

The SWAc runoff/recharge model is calibrated against the conceptual site mass balance recharge rates. A comparison is provided in Table 5. The LTA recharge rates generated using the SWAc model compare favourably to those reported by Celtic Energy in the 1996 Review of Hydrogeology

and are consistent with dry period baseflow measurements (Section 3.2.1). The estimated LTA recharge rates calculated by the SWAc runoff/recharge model are slightly lower than those in the 1996 review, but are calculated more rigorously, though the inclusion of influential processes that were not considered in the 1996 estimates, such as runoff and interflow, soil moisture balance and potential evapotranspiration, lending greater confidence to the output.

*Table 5 Comparison of recharge rates for catchment areas used in the 1996 site water balance.*

| Catchment [Area]                                      | Long term average recharge from the Celtic Energy (1996) water balance model (l/s) | SWAc runoff/recharge long term average recharge rates (l/s) |
|-------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------|
| Dowlais workings [4.46 km <sup>2</sup> ]              | 134                                                                                | 115                                                         |
| Soap mineworking at Cwmbargoed [0.7 km <sup>2</sup> ] | 21                                                                                 | 18                                                          |
| Bute Workings [3.5 km <sup>2</sup> ]                  | 105                                                                                | 95                                                          |
| <b>TOTAL Inflows l/s</b>                              | <b>260</b>                                                                         | <b>228</b>                                                  |

#### 4.2.4 Topography

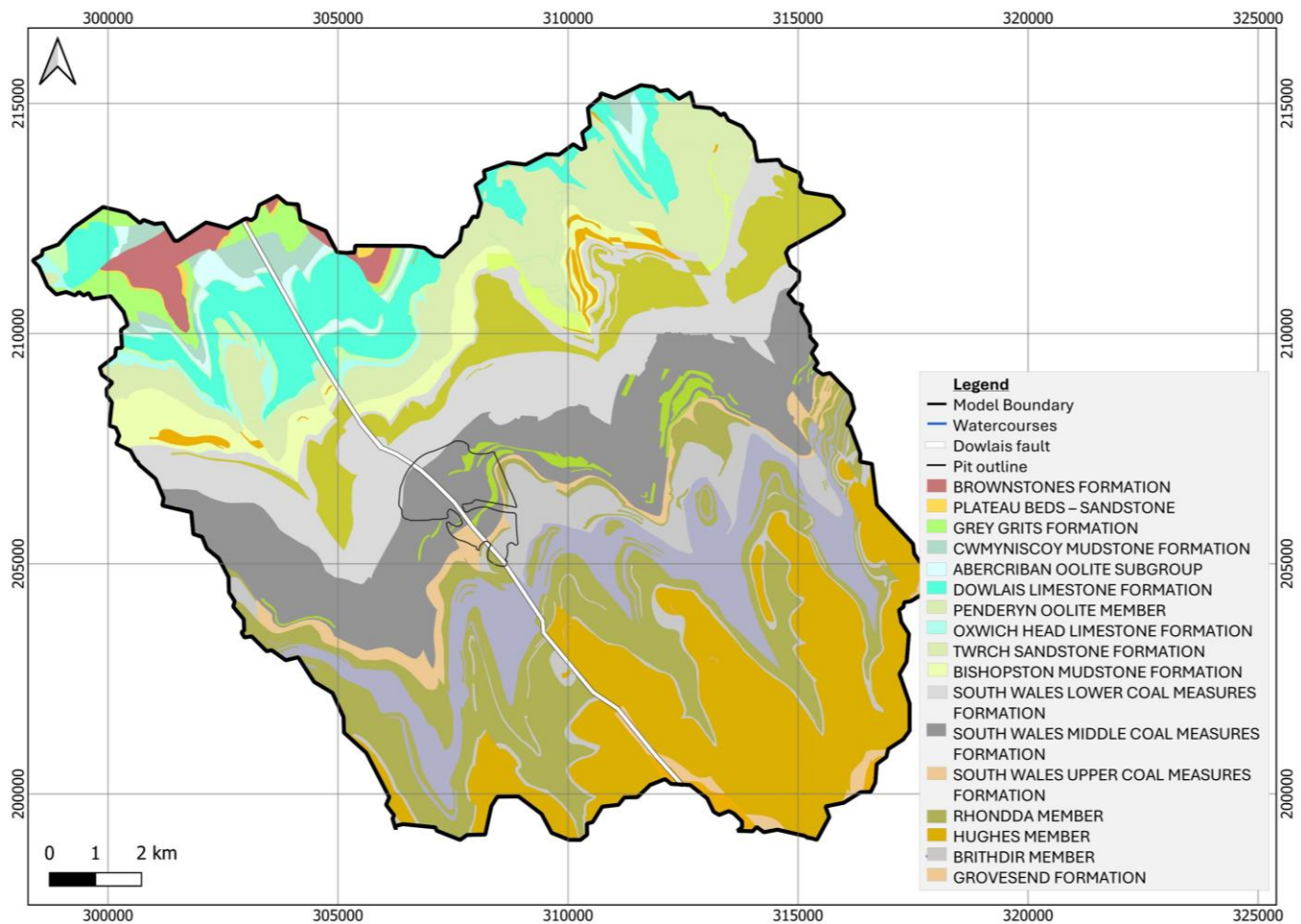
Topography data for the numerical groundwater model were derived from the publicly accessible Light Detection and Ranging (LiDAR) composite Digital Terrain Model (DTM) (10 m resolution, resampled from 2 m DTM) dataset (Environment Agency, 2023). In addition, local datasets were used for the mine site area, reflecting the landform pre-and post-mine development.

#### 4.2.5 Geological modelling and layering

##### *Geological modelling*

The stratigraphy of the model area is characterised by the presence of the Carboniferous South Wales Middle and Lower Coal Measures. These formations consist of interbedded mudstones, ironstones, coal seams and occasional sandstone bands. Within the model domain, the South Wales Lower and Middle Coal Measures are overlain by the Rhonda, Hughes and Brithdir

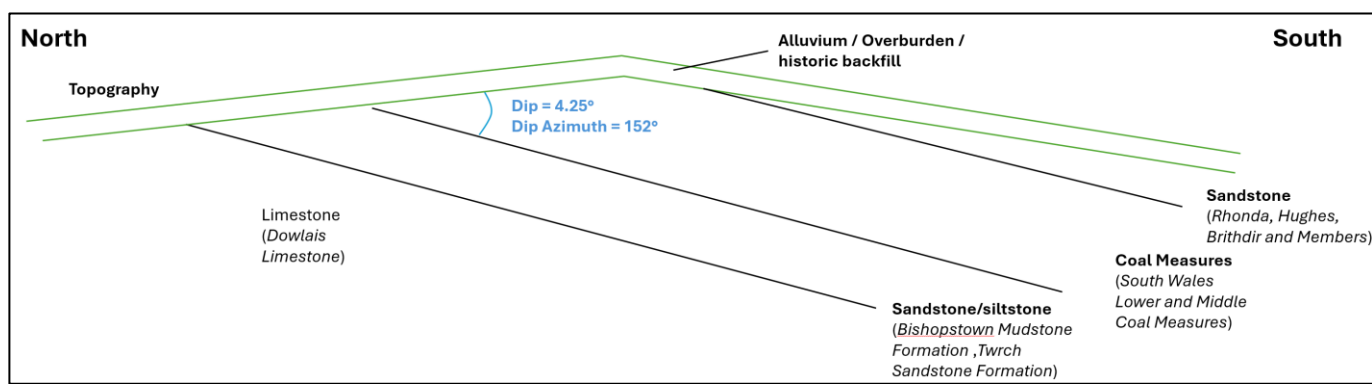
Sandstone Members and underlain by the Bishopstow Mudstone, Twrch Sandstone Formation and Dowlais Limestone Formation. This succession dips to the south-southeast at an angle of around 4.25°, although this varies locally from 4° to 11°. The Dowlais and Penndyaren Faults transect the mine site from north-northeast to south-southwest. With respect to the Dowlais Fault, this results in a downthrow of approximately 20-30 m on the western hanging wall. A map of the geology is shown in Figure 16.



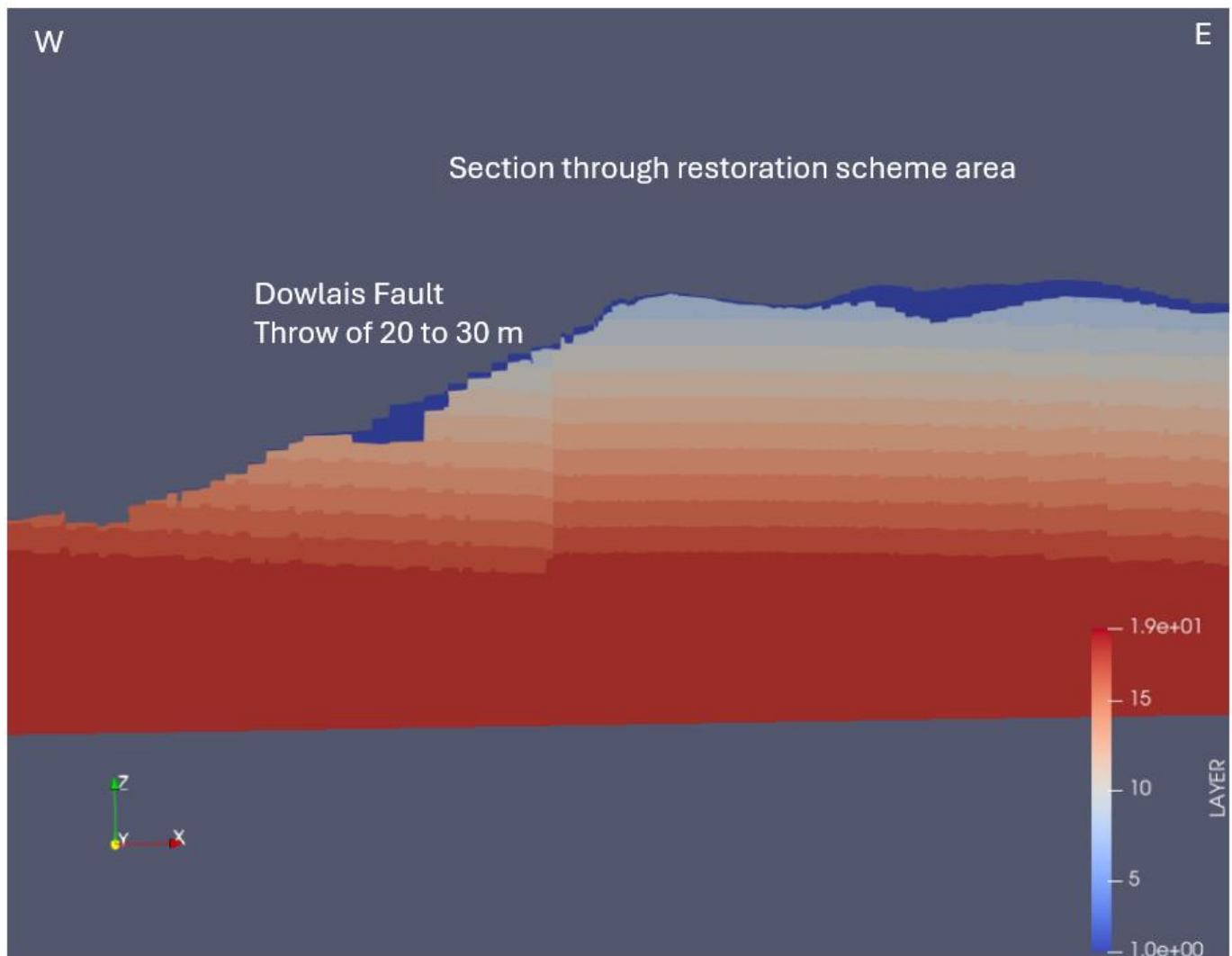
*Figure 16 Surface geology map, BGS 1:50k*

A simplified geological model was derived to support the development of the numerical model, which is shown conceptually in Figure 17. Basal surfaces for each of the main lithologies were generated by delineating the outcrop at surface, and assuming a dip of 4.25° and dip azimuth of 152°. Separate surfaces were created for the base of the Lower and Middle Coal Measures to

either side of the Dowlais Fault to replicate the observed 20 m downthrow to the west of the fault line. A cross-section of the model domain, showing the model structure through the Dowlais Fault is provided in Figure 18. The Pennydarren Fault was not represented explicitly, as it is not thought to provide a strong control on groundwater flow and is situated further from the main area of interest in the vicinity of the pit void. Depths to the base of the Coal Measures were checked against a selection of 25 deep borehole logs available through the British Geological Survey (BGS Onshore GeoIndex database).



*Figure 17 Conceptual cross-section of simplified geological model*



*Figure 18 West to east cross-section through the restoration scheme area, showing the model layering and offset in the vicinity of the Dowlais Fault*

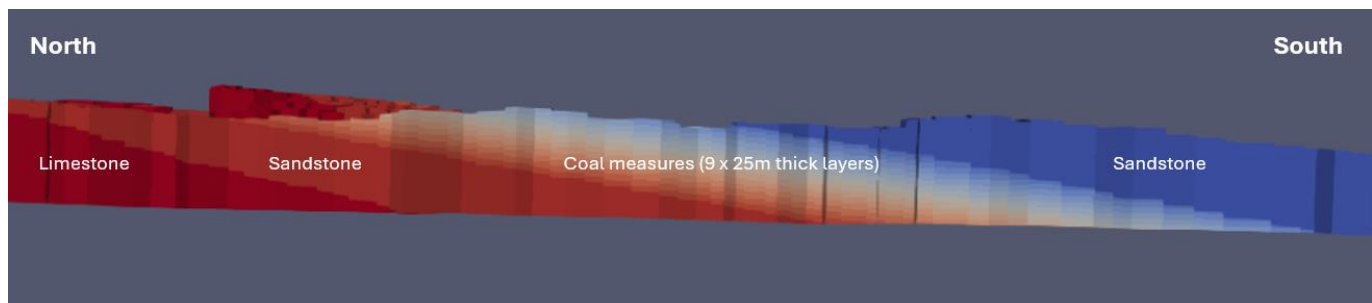
Overburden and alluvium were generated over the extent of the model domain using point measurements from 97 boreholes accessed through the BGS Onshore GeoIndex database, a further 855 measurements of overburden depth within the mine site boundary, and additional dummy points to constrain the thickness of backfill around the New Tredegar Pit, which coincides with the present Trecatti landfill site.

### *Model layering*

The geological model was translated into groundwater model layers. There are a total of 14 layers in the model, which are listed in Table 6. All lithologies are represented as a single layer within the model, except for the South Wales Lower and Middle Coal Measures. This unit is instead split into 15 25 m thick layers. This was done to reflect the interbedded nature of the formation, which provides a strong anisotropic control on groundwater movement within the Coal Measures. The representation of multiple layers within Coal Measures is also important for accurately representing the geometry of the pit void and groundwater gradients in the vicinity. Discrete horizons within the South Wales Lower and Middle Coal Measures were not represented, since this would have resulted in the creation of an excessive number of layers in the model and would have compromised the model runtime. A cross-section through the model domain showing the layering is provided in Figure 19 .

*Table 6 Summary of groundwater model layers*

| Layer | Function            |
|-------|---------------------|
| 1     | Overburden          |
| 2     | Sandstone           |
| 3     | Coal Measures       |
| 4     | Coal Measures       |
| 5     | Coal Measures       |
| 6     | Coal Measures       |
| 7     | Coal Measures       |
| 8     | Coal Measures       |
| 9     | Coal Measures       |
| 10    | Coal Measures       |
| 11    | Coal Measures       |
| 12    | Coal Measures       |
| 13    | Coal Measures       |
| 14    | Coal Measures       |
| 15    | Coal Measures       |
| 16    | Coal Measures       |
| 17    | Coal Measures       |
| 13    | Sandstone/Siltstone |
| 14    | Limestone           |



*Figure 19 North to south cross-section showing model layers*

#### **4.2.6 Properties**

Table 7 lists the initial hydraulic properties applied to the main groundwater units represented in the model prior to model calibration. These values are based on a combination of literature values and ranges constrained by means of in-situ rising head tests. There is not a large body of literature relating to the hydraulic properties of the Lower and Middle Coal Measures and Carboniferous sandstones in this part of Wales, perhaps owing to their limited use as aquifers for water supply. Whilst mudstone bands within the succession are unlikely to support significant flow of groundwater, the transmissivity of sandstone horizons is estimated to range between 0.1 and 20 m<sup>2</sup>/d (Ineson, 1967), and the presence of fractures, whether natural or anthropogenic, can significantly increase the permeability. The initial horizontal and vertical hydraulic conductivity were set at 0.5 m/d and 0.005 m/d respectively to reflect the highly worked nature of the Coal Measures in the site area, and anisotropy related to preferential flow parallel to the bedding plane. The hydraulic conductivity of sandstone horizons is generally below 1 m/d (Robins & Davies, 2024), whilst Carboniferous sandstones in the UK are associated with hydraulic conductivity values of between  $1 \times 10^{-4}$  and 1 m/d, depending on the degree of cementation, fracturing and weathering (Jones, 2000). A value of 1 m/d was applied initially in the model to sandstone units to give a conservatively high estimate of groundwater flow. hydraulic conductivity values associated with the Dowlais Limestone are also limited, although testing in analogous formations nearby, including the Pembroke Limestone Formation and Carboniferous limestone in the Chepstow area gives ranges of 0.1 to 5 m/d (Robins & Davies, 2024) and 0.1 to 10 m/d (Shabani & Vincent, 2008). A starting value of 2 m/d was used for the limestone within the model domain.

The Dowlais Fault is conceptually understood to comprise a discrete, low-permeability feature and is parameterised as thus. A discrete, high-permeability alluvium zone associated with surface water features was added during calibration to facilitate drainage to streams. This is included in the table below for completeness but was not present in the initial model build. Similarly, the backfill and void properties were added during the calibration process for simulating dewatering and recovery of the pit void. The location of these zones is shown in Figure 28.

*Table 7 Summary of initial hydraulic properties*

| Unit                                    | Layer(s)           | Horizontal hydraulic conductivity (m/d) | Vertical hydraulic conductivity (m/d) | Specific yield (-) | Specific storage (1/m) |
|-----------------------------------------|--------------------|-----------------------------------------|---------------------------------------|--------------------|------------------------|
| Overburden / Alluvium                   | 1                  | 10                                      | 10                                    | 0.1                | $1 \times 10^{-5}$     |
| Sandstone (Brithdir and Hughes Members) | 2                  | 1                                       | 0.1                                   | 0.02               | $5 \times 10^{-6}$     |
| Coal Measures                           | 3 to 17            | 0.5                                     | 0.005                                 | 0.02               | $5 \times 10^{-6}$     |
| Sandstone (Twrch)                       | 18                 | 1                                       | 0.1                                   | 0.02               | $5 \times 10^{-6}$     |
| Dowlais Limestone                       | 19                 | 2                                       | 0.2                                   | 0.02               | $5 \times 10^{-6}$     |
| Dowlais Fault                           | All except 1       | 0.01                                    | 0.1                                   | 0.02               | $5 \times 10^{-7}$     |
| High permeability alluvium              | 1                  | 40                                      | 40                                    | 0.1                | $1 \times 10^{-5}$     |
| Backfill                                | All where relevant | 2                                       | 2                                     | 0.1                | $5 \times 10^{-6}$     |
| Void                                    | Pit nodes          | 100                                     | 100                                   | 0.9                | $5 \times 10^{-7}$     |

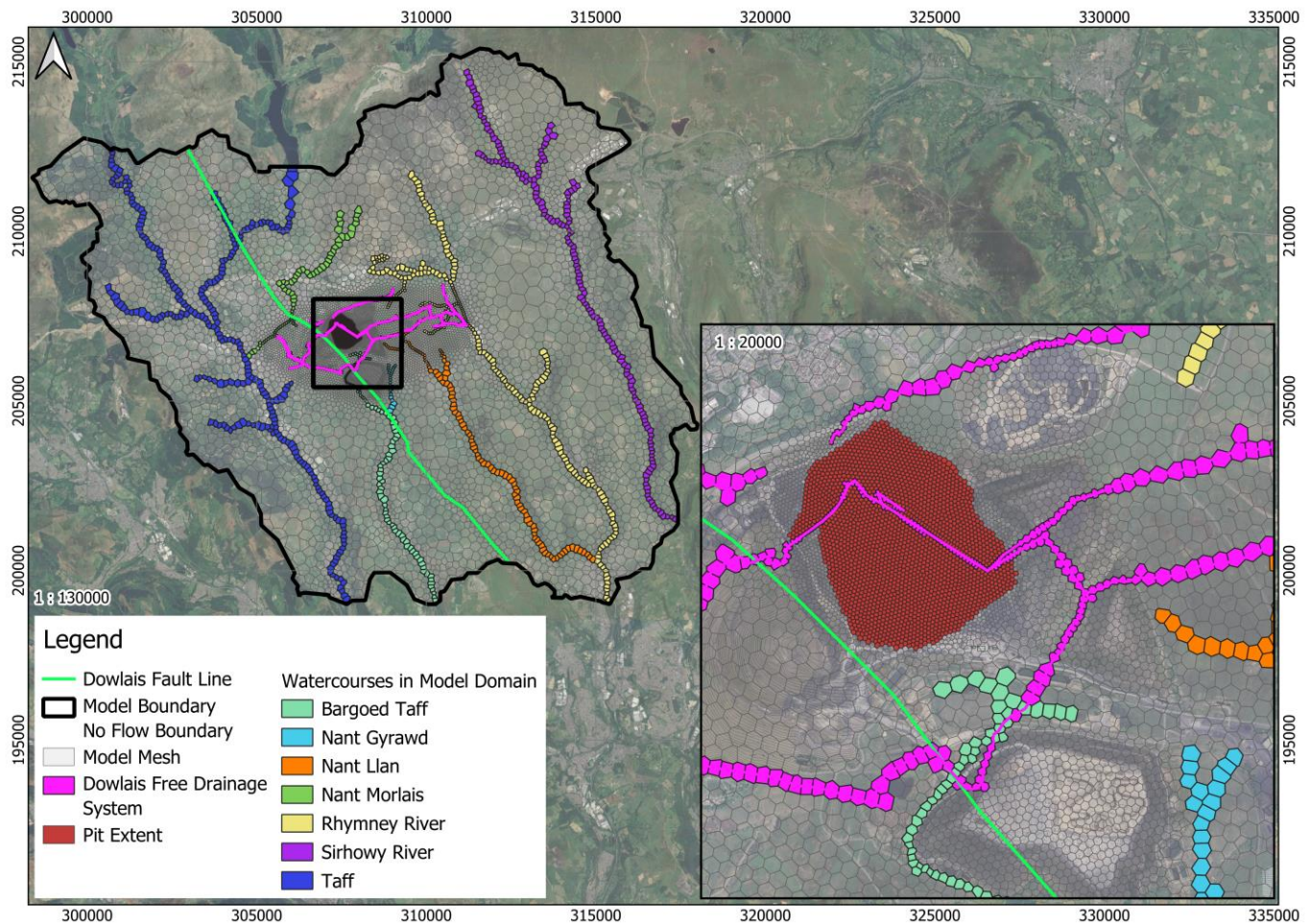
#### *4.2.7 Boundary conditions*

Boundary conditions relate to areas of the model where groundwater flow or head conditions are imposed. In the Ffos-y-Fran groundwater model this includes rivers and streams, no-flow boundaries, and drains to represent the DFDS and the pit void during dewatering. Recharge to

groundwater is a boundary condition discussed previously in Section 4.2.3. An overview of all boundary conditions is provided in Figure 20.

### *Streams*

River type boundary conditions are used to represent streams and rivers within the model domain. Large watercourses thought to be in hydraulic continuity with groundwater (including the River Taff, River Rhymney and River Sirhowy) are parameterised to allow inflows and outflows to and from the groundwater system, whereas smaller tributaries that are perched above the water table (much of the Nant Morlais, Bargoed Taff) may only accept groundwater inflows. This is done to prevent exaggerated leakage to ground in areas where the stream bed surface is perched well above groundwater level, which can result in an artificially elevated water table. Furthermore, rivers in the model do not track the volume held within them. This is a simplification warranted by the purpose of the model, which is to assess the possible magnitude of groundwater related impacts to nearby receptors that may result through implementation of the proposed restoration scheme. Since only the change in groundwater flux entering streams and rivers is of concern, rather than the total flow, there was no need to implement a stream system capable of tracking flow. The main watercourses simulated within the model domain using river type boundary conditions are shown in Figure 20.



*Figure 20 Overview of groundwater model boundary conditions*

### *No-Flow boundary*

The model domain boundary is assigned a no-flow boundary condition. Although it is expected that groundwater flow and exchange does occur between the model domain and outside, this simplification means that there is no need to assign groundwater heads along the boundary in areas where there are no data related to the depth to water, and the boundary is positioned at a sufficient distance (at least 4.2 km) from the mine site to prevent any impact to simulation results owing to the absence of groundwater flow across the boundary.

### *Pit void drains*

In scenarios where the dewatering of the pit is simulated, drain type boundary conditions are used to reduce the groundwater level to the elevation of the pit floor. Drains in each mesh element coinciding with the pit area are assigned a “stage” equivalent to the minimum pit void elevation within that mesh element area. Drains are assigned over the extent of the pit void, which is shown in Figure 20.

### *DFDS drains*

The DFDS is represented as a series of drain type boundary conditions. Similarly to the pit, these were assigned a “stage” equivalent to the mean elevation of the DFDS conduits within each overlapping mesh element. Conduit elevation was based on a 3D model of the DFDS, which was developed using invert levels and gradients identified in previous work. Although this represents a step forward with respect to our understanding of the likely layout of the DFDS, there is still considerable uncertainty about both the spatial extent of the drainage system and the degree of connectivity with the groundwater system. The conductance of these drains, which governs the rate at which groundwater can enter the boundary condition under a given head condition, is calibrated in the model against constrained discharge rates from the mine drainage system, as noted in the conceptual site mass balance.

### *4.2.8 Temporal discretisation*

The model consists of 510 monthly stress periods. During each stress period, model boundary conditions (recharge, evaporative potential, drain elevation) remain constant. Seasonal climatic changes are represented through changes in recharge between stress periods. Commencement and cessation of pit dewatering is represented by activating and deactivating the drain boundary conditions representing the pit. Each stress period corresponds to a month, starting in January 1982 and ending in June 2024. Climatic data from these months are used to populate the SWAc runoff/recharge model, which in turn generates the recharge timeseries used in the groundwater model.

Specific details relating to the setup of the models used for calibration are covered in Section 4.3.1.

## 4.3 Model calibration

The principle aim of groundwater model calibration is to ensure that the model can reproduce observed data, such as groundwater levels or stream flows, using hydraulic properties and boundary conditions that adhere to realistic ranges, based on the conceptual groundwater model. The calibration process builds confidence in the ability of the model to assess the likely response of the groundwater system to a change in use or state, such as the likely groundwater rebound following cessation of mine dewatering.

Calibration was carried out with consideration for the main purposes of the model, which are twofold:

- To assess potential spatial impacts to environmental receptors, including:
  - Change in groundwater level and availability
  - The change in groundwater discharge to surface water receptors
- To assist in the parameterisation of the pit water balance model, through provision of lake stage/groundwater inflow and lake stage/groundwater outflow relationships.

### 4.3.1 Approach

Calibration criteria were tailored to meet the needs of the impact assessment as follows:

- The simulated range and magnitude of groundwater heads within the site area, and in particular near the pit void, should be consistent with recorded, historical groundwater levels. Given the uncertainties related to the extensive historical mining at the site and impact of this on groundwater levels at the local scale, it was recognised that it would not be possible to achieve a close fit to all observations without unjustified granularity in the distribution of hydraulic parameters. As such, certain observations and areas were

prioritised to the detriment of others, depending on their relevance and importance to the overall aim of the groundwater head calibration. This is discussed further in Section 4.3.2.

- The seasonal response of groundwater levels, both temporally and quantitatively, should be comparable to what is observed on site. As with groundwater heads, the heterogeneity of the sub-surface means achieving close seasonal fits to seasonal groundwater fluctuation at all locations is unlikely to be possible and therefore some areas were prioritised.
- The magnitude and spatial distribution of discharge from the DFDS should approximate what has been measured and calculate in-situ. This is reported in the site water balance.
- Simulated pit dewatering should be of a similar magnitude to what was required during site operations to manage groundwater levels within the excavation.

Piezometer records to 2007 reflect pre-mining conditions. Once mining began in 2007, it was not until the excavation mined through the Dowlais fault after 2013, and continued eastwards, that the operation started to incur significant inflows from groundwater. Subsequent records may be affected to some extent as a result of drawdown from the excavation, although the high priority piezometers located in the pit area (5808A, 5812) do not appear to show a clearly discernible response until after 2017. The period 2007 to 2017 encompasses the majority of the data available for site piezometers, and as such, calibration to groundwater levels did not require the explicit simulation of the pit. However, there was also a need to calibrate to mine inflows, and as such a simulation including the pit was necessary. For these reasons, model calibration was undertaken using the following approach:

- A historical model with no excavation was used to calibrate to groundwater head measurements from 2001 to 2013, although later records were used if the piezometer in question did not show a clear response to the approaching excavation. This model was also used to calibrate outflows from the DFDS.
- A historical model including the backfill and pit void for calibration to pit dewatering rates was set up, including the pit shell and the backfill as of November 2023. This model starts in 2017 rather than 1982, as in the historical model, to allow for a longer period post-closure for the pit lake levels to equilibrate. This was achieved by appending the historical climate

record from 1982 to 2017 to the period 2017 to 2024 to create a future climate proxy (which was also perturbed by projected changes in rainfall and PEt during the climate change scenarios). A dynamic representation of the excavation is not included in this simulation; instead, it is modelled as a static, dewatered feature for the period from January 2018 to July 2023. This simplification is adopted because the pit's depth and dimensions have remained relatively constant during this time, despite its gradual migration eastwards (as new excavations occurred in the east, alongside backfilling of the void in the west). Due to these relatively consistent dimensions, the potential for groundwater ingress is considered to be relatively constant over time. Therefore, incorporating mining progression was not necessary for calibrating the simulation against known pit dewatering rates.

### *4.3.2 Groundwater monitoring*

#### *Summary of record*

There is an extensive record of groundwater monitoring from within the site area. There are 31 individual monitoring points where at least one groundwater level measurement has been taken. This dataset is available for the period May 2001 to July 2023, although most records are truncated because site piezometers were mined out during operations at the site. In addition to this, there are 13 piezometers situated around the perimeter of the Trecatti landfill site, for which groundwater level measurements are available for the period July 2022 to September 2023. It should be noted that these data were received after model calibration and therefore were not used during this process. A summary of all available groundwater monitoring points and summary information associated with them is provided in

Table 8. These locations and average measured groundwater levels are also shown in Figure 21 and Figure 22 respectively.

There are no groundwater monitoring locations outside of the restoration scheme area or the Trecatti landfill site to constrain groundwater levels, other than the stage of rivers that are likely to be in hydraulic continuity with groundwater, such as the River Taff and River Rhymney.

*Table 8 Summary of existing groundwater monitoring data*

| Name     | Location  | First reading | Latest reading | Average (mAOD) | MinGWL* (mAOD) | MaxGWL (mAOD) | Range (m) |
|----------|-----------|---------------|----------------|----------------|----------------|---------------|-----------|
| 5814a    | Mine site | May/01        | May/14         | 396.89         | 393.38         | 397.20        | 3.82      |
| 5530     | Mine site | May/01        | May/08         | 281.29         | 271.01         | 295.96        | 24.95     |
| 5567     | Mine site | Oct/01        | Jan/07         | 231.24         | 228.83         | 234.53        | 5.70      |
| 5807     | Mine site | May/01        | Jan/07         | 257.52         | 243.33         | 263.33        | 20.00     |
| 5808     | Mine site | May/01        | Mar/09         | 280.46         | 271.43         | 287.15        | 15.72     |
| 5809     | Mine site | May/01        | Sep/08         | 298.09         | 288.74         | 308.48        | 19.74     |
| 5810     | Mine site | May/01        | Mar/09         | 281.39         | 272.86         | 286.96        | 14.10     |
| 5812     | Mine site | May/01        | Oct/22         | 274.18         | 268.76         | 283.64        | 14.88     |
| 5813     | Mine site | May/01        | Dec/08         | 282.29         | 274.18         | 289.50        | 15.32     |
| 5816     | Mine site | May/01        | Aug/04         | 290.44         | 278.91         | 301.83        | 22.92     |
| 5817     | Mine site | May/01        | Mar/09         | 282.17         | 267.74         | 289.06        | 21.32     |
| 5818     | Mine site | May/01        | Aug/17         | 255.00         | 249.49         | 280.54        | 31.05     |
| 5820     | Mine site | May/01        | Aug/17         | 254.06         | 225.69         | 263.28        | 37.59     |
| 5821     | Mine site | May/01        | Jul/07         | 277.32         | 262.80         | 282.77        | 19.97     |
| 5822     | Mine site | May/01        | Jul/07         | 272.42         | 264.34         | 280.57        | 16.23     |
| 5823     | Mine site | May/01        | Aug/17         | 226.59         | 215.52         | 231.52        | 16.00     |
| 5824     | Mine site | May/01        | Jul/23         | 206.24         | 202.73         | 213.48        | 10.75     |
| 5826     | Mine site | May/01        | Jul/23         | 201.89         | 195.13         | 203.26        | 8.13      |
| 6051     | Mine site | May/01        | Mar/03         | 281.91         | 277.18         | 287.46        | 10.28     |
| 6055     | Mine site | May/01        | Aug/05         | 279.67         | 262.89         | 288.59        | 25.70     |
| 9064     | Mine site | May/01        | Jan/07         | 239.88         | 226.56         | 244.68        | 18.12     |
| SC1      | Mine site | Feb/06        | Sep/11         | 282.17         | 274.32         | 291.46        | 17.14     |
| SC2      | Mine site | Feb/06        | May/08         | 323.13         | 321.88         | 323.89        | 2.01      |
| 5808A    | Mine site | Jun/11        | Oct/22         | 277.85         | 264.93         | 288.84        | 23.91     |
| NL100    | Mine site | Feb/12        | Feb/17         | 274.90         | 274.05         | 276.60        | 2.55      |
| NL169    | Mine site | Feb/12        | Oct/15         | 254.83         | 249.11         | 264.17        | 15.06     |
| NL170    | Mine site | Feb/12        | Feb/17         | 270.21         | 250.85         | 285.43        | 34.58     |
| NL175    | Mine site | Feb/12        | Oct/15         | 305.00         | 296.39         | 310.99        | 14.60     |
| NL186    | Mine site | Feb/12        | Oct/15         | 284.73         | 278.72         | 291.23        | 12.51     |
| NL192    | Mine site | Feb/12        | Feb/17         | 264.44         | 249.12         | 279.93        | 30.81     |
| NL Shaft | Mine site | Feb/12        | Feb/17         | 252.14         | 241.16         | 254.45        | 13.29     |
| GW1      | Trecatti  | Nov/21        | Sep/23         | 290.07         | 255.33         | 285.24        | 29.91     |
| GW2      | Trecatti  | Nov/21        | Sep/23         | 281.96         | 255.35         | 284.90        | 29.55     |
| GW3      | Trecatti  | Oct/22        | Sep/23         | 316.91         | 266.19         | 284.97        | 18.78     |
| GW4      | Trecatti  | Nov/21        | Sep/23         | 291.94         | 270.01         | 285.59        | 15.58     |

| Name | Location | First reading | Latest reading | Average (mAOD) | MinGWL* (mAOD) | MaxGWL (mAOD) | Range (m) |
|------|----------|---------------|----------------|----------------|----------------|---------------|-----------|
| GW5  | Trecatti | Nov/21        | Sep/23         | 272.37         | 255.34         | 273.77        | 18.43     |
| GW6  | Trecatti | Nov/21        | Sep/23         | 282.46         | 266.11         | 290.86        | 24.75     |
| GW7  | Trecatti | Nov/21        | Sep/23         | 295.88         | 272.45         | 409.95        | 137.50    |
| GW8  | Trecatti | Nov/21        | Sep/23         | 299.27         | 272.52         | 409.95        | 137.43    |
| GW9  | Trecatti | Jan/22        | Sep/23         | 273.26         | 262.43         | 409.95        | 147.52    |
| GW10 | Trecatti | Nov/21        | Sep/23         | 274.51         | 271.56         | 287.09        | 15.53     |
| GW11 | Trecatti | Nov/21        | Sep/23         | 279.97         | 272.32         | 320.86        | 48.54     |
| GW12 | Trecatti | Nov/21        | Sep/23         | 275.35         | 262.13         | 285.33        | 23.20     |
| GW13 | Trecatti | Nov/21        | Sep/23         | 276.54         | 255.34         | 280.28        | 24.94     |

\*GWL stands for GroundWater Level

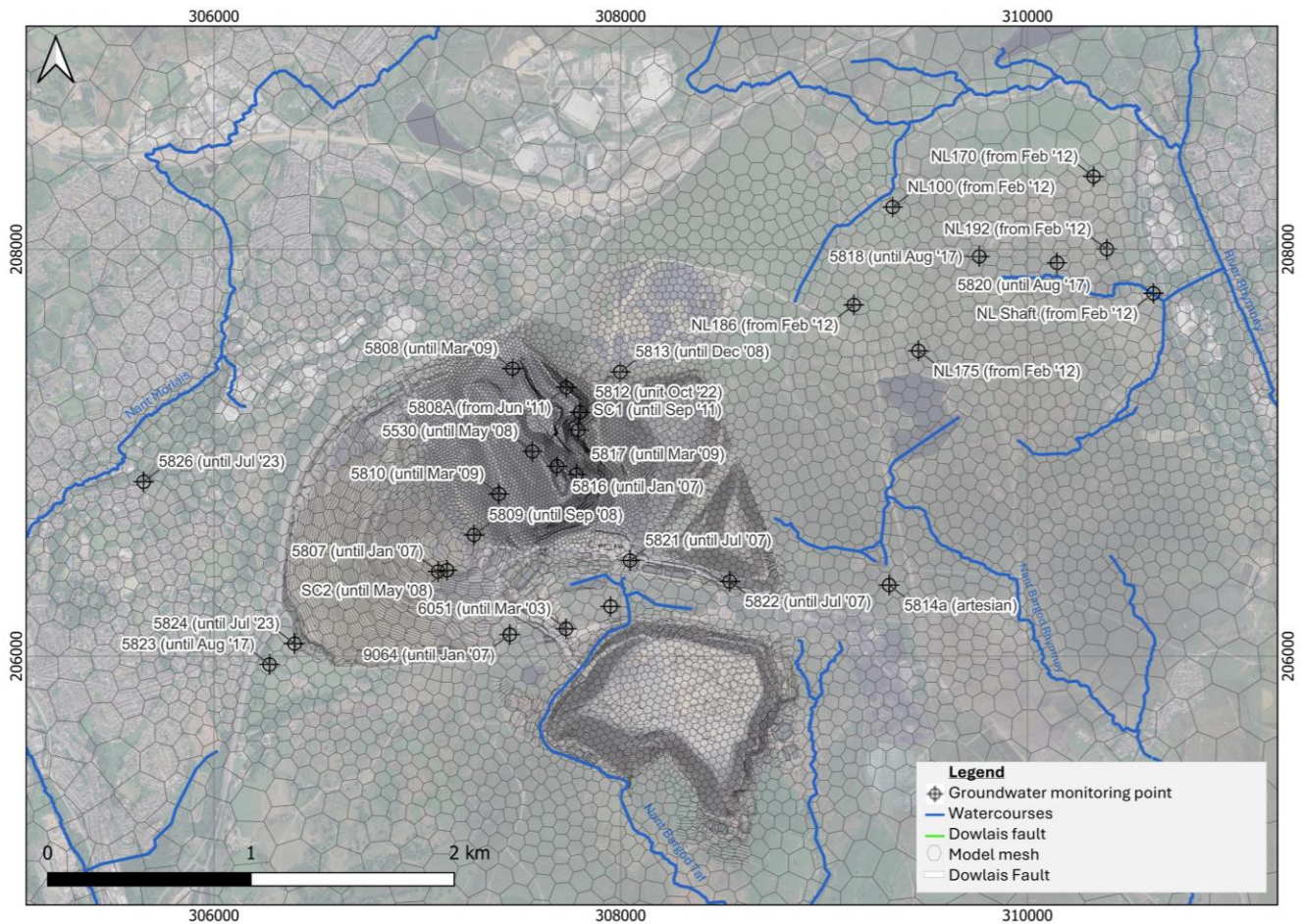
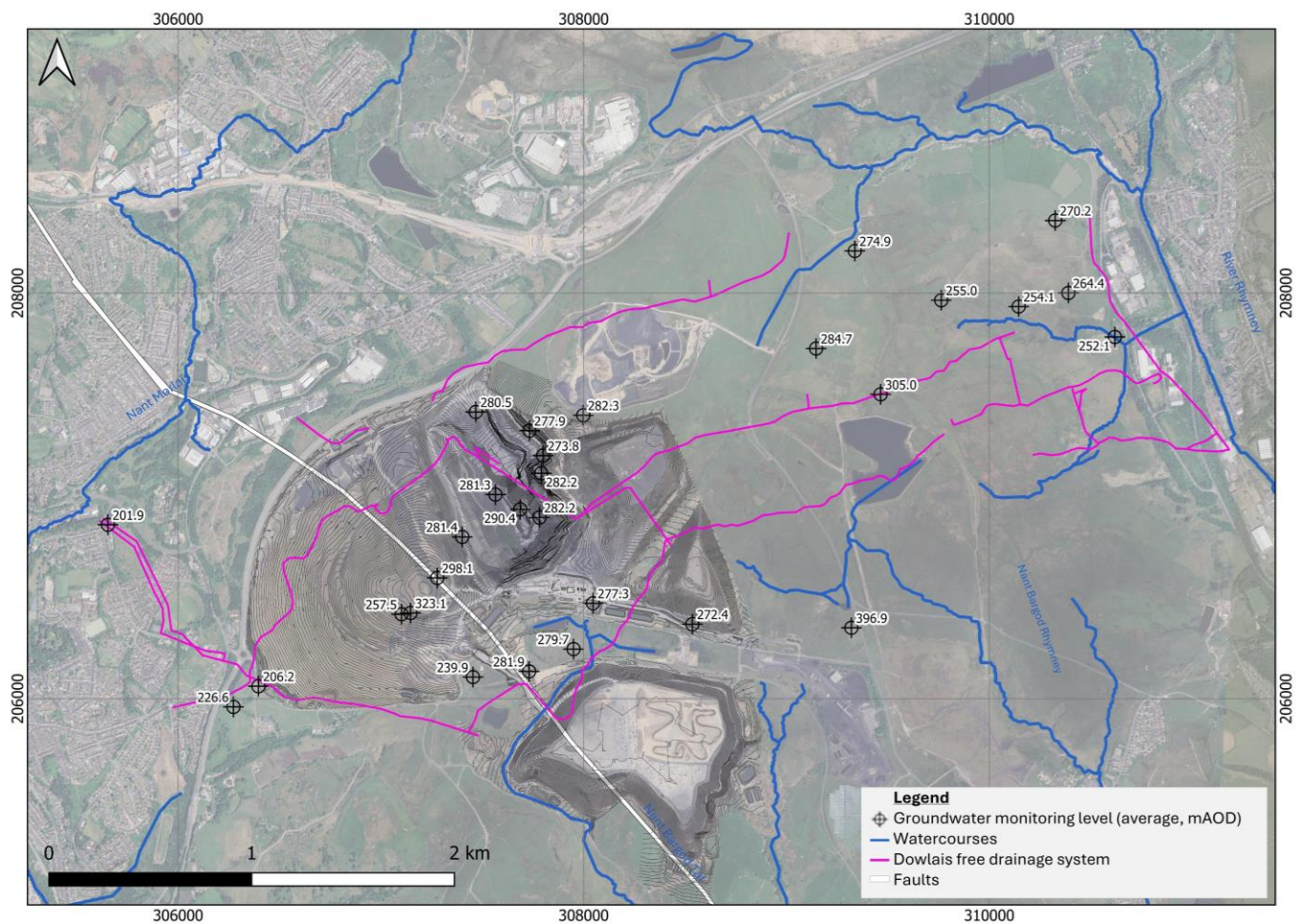


Figure 21 Location of groundwater monitoring points



*Figure 22 Average measured groundwater levels (mAOD)*

### *Summary of monitoring location priority*

#### *Higher priority*

Groundwater monitoring records from within the pit void were assigned a high priority. This includes 5530, 5816, 5817, 5813, 5808, 5808A, 5812 and SC1.

#### *Lower priority*

Lower priority observations are monitoring locations situated further from the mine void and are generally most useful for constraining the groundwater gradient away from the site. These include

those to the south of the pit (9064, 6051, 6055 and 5821), which coincides with the central part of the site near the workshops and Bogey Road. To the east of the site there are eight monitoring locations situated within the Rhymney catchment, in the vicinity of the Bute watercourse. These are NL186, NL175, NL100, 5818, 5820, NL192, NL170 and NL Shaft. Piezometers 5823, 5824, near the A4060 and 5826, just to the north of Bradley Gardens are also deemed to be lower priority, but remain helpful for constraining the groundwater gradient to the west.

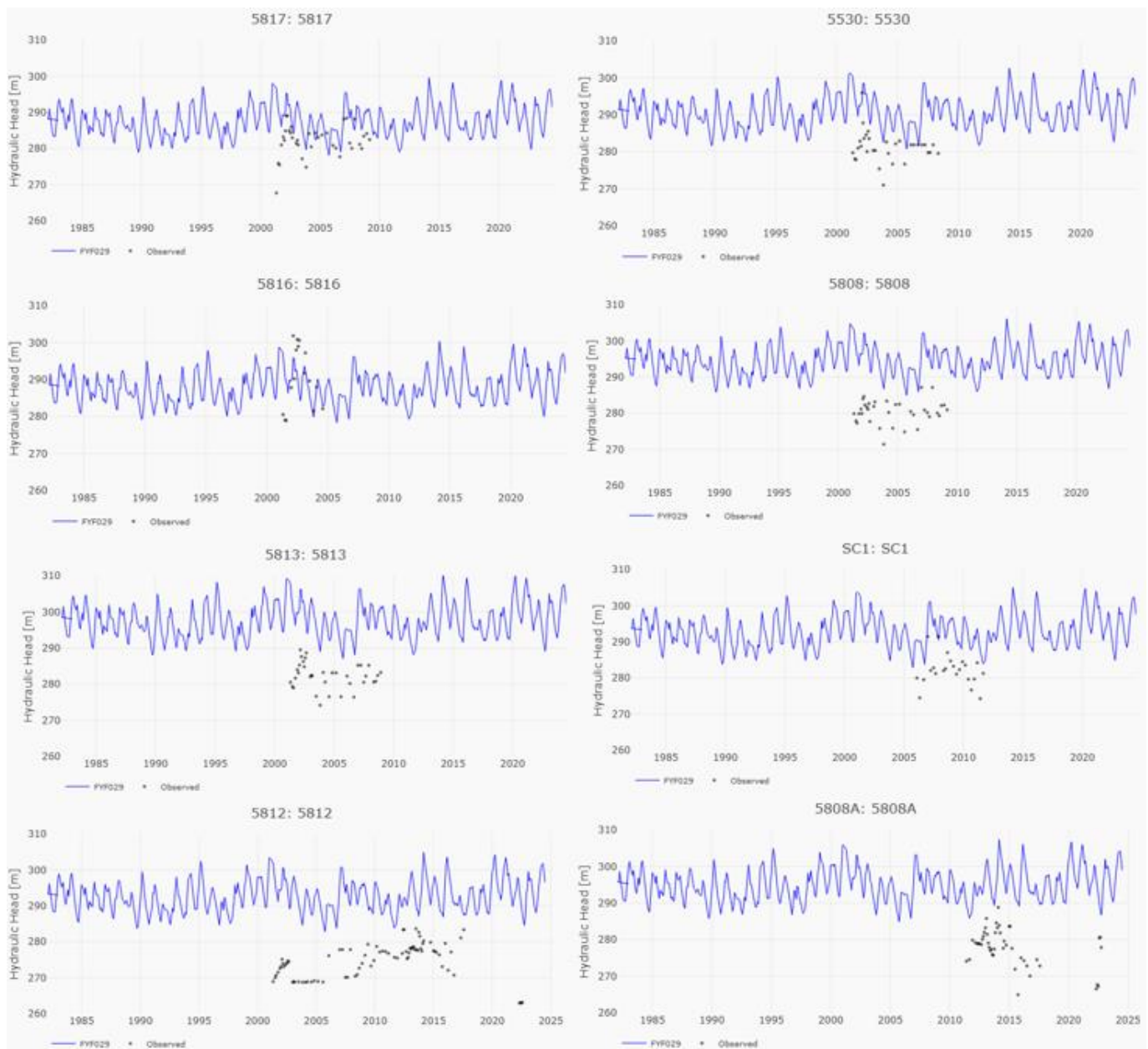
### Ignored

Piezometers 5809 and SC2 to the southwest of the pit appear to show anomalously high groundwater levels ranging from 290 to 320 mAOD and may reflect locally perched water. As such, these were not used during calibration. Similarly, measured groundwater head at artesian piezometer 5814a, located to the south of Rhaslas pond, is 100 m above the regional groundwater level in the area and was therefore not used during calibration.

### *4.3.3 Calibration to groundwater levels*

Groundwater level calibration to high priority piezometers is shown in Figure 23. The groundwater model is best calibrated to heads within the central part of the void at locations 5817, 5530 and 5816. Simulated heads are high relative to the observed levels to the north. An improved calibration was achieved through increasing the conductance of the DFDS (a parameter that affects how well the drain boundary condition can remove water from the ground), however this led to an excessive drainage rate for the DFDS relative to conceptual understanding and underestimation of groundwater heads to the south and west of the site. As such, the preferred option was to accept the higher heads to the north of the pit whilst maintaining a better fit elsewhere and to honour the conceptual mass balance of the DFDS.

The timing and amplitude of seasonal fluctuations in groundwater level, as well as general long-term trends, appear to be reasonably well represented, although this isn't always clear due to the discontinuous nature of the groundwater level records and the offset in simulated versus observed groundwater levels in higher priority piezometers along the northern margin of the pit (5813, 5808, 5808A, 5812 and SC1).



*Figure 23 Groundwater model calibration to high priority piezometers*

A selection of calibration hydrographs to representative lower priority piezometers is provided in Figure 25. All monitoring calibration hydrographs are included in Appendix 2. The groundwater model calibrates well to groundwater levels and seasonality to both the south and west of the site (6051, 5821, 5823, 5807). Absolute groundwater level range is also relatively well represented at NL175, situated to the east of the pit. Simulated groundwater levels further to the east in the

Rhymney catchment are generally overestimated (NL170, 5820). This may reflect several factors, including the absence of unknown drainage infrastructure in the model present in-situ, errors relating to the stage of the DFDS in the area, or locally significant hydraulic property or structural differences within the Coal Measures in this area relative to the pit area to the west. Similar reasons may explain why simulated groundwater levels at piezometer 5826 in Merthyr Tydfil are also higher than observed.

Calibration residuals at each of the piezometer locations are displayed in Figure 24 below. The average residual was -13.53 throughout the simulation. Spatial heads for dry and wet periods in the calibrated run are included in Appendix 3.

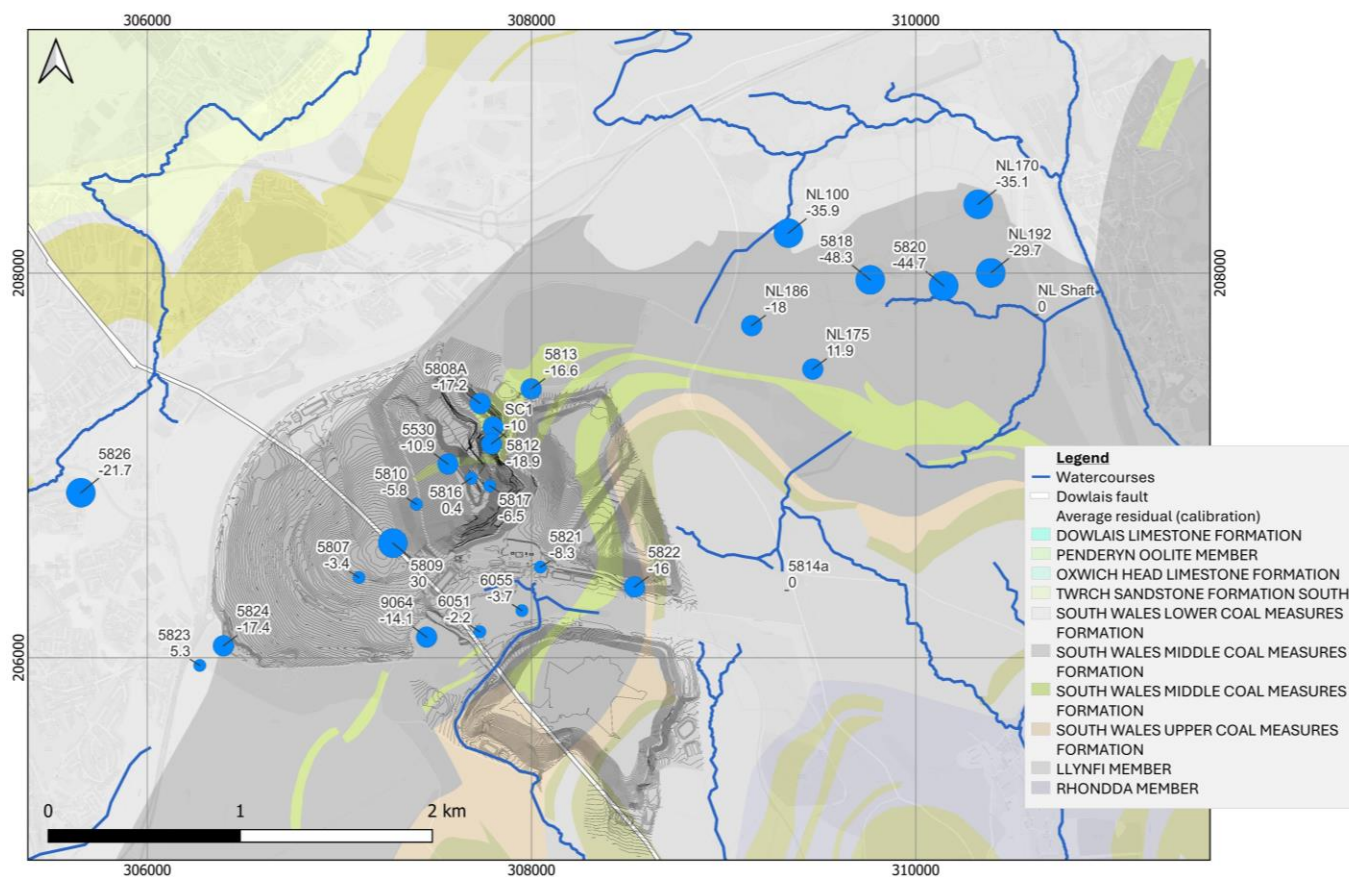


Figure 24 showing calibration residuals



*Figure 25 Groundwater model calibration to selected lower priority piezometers*

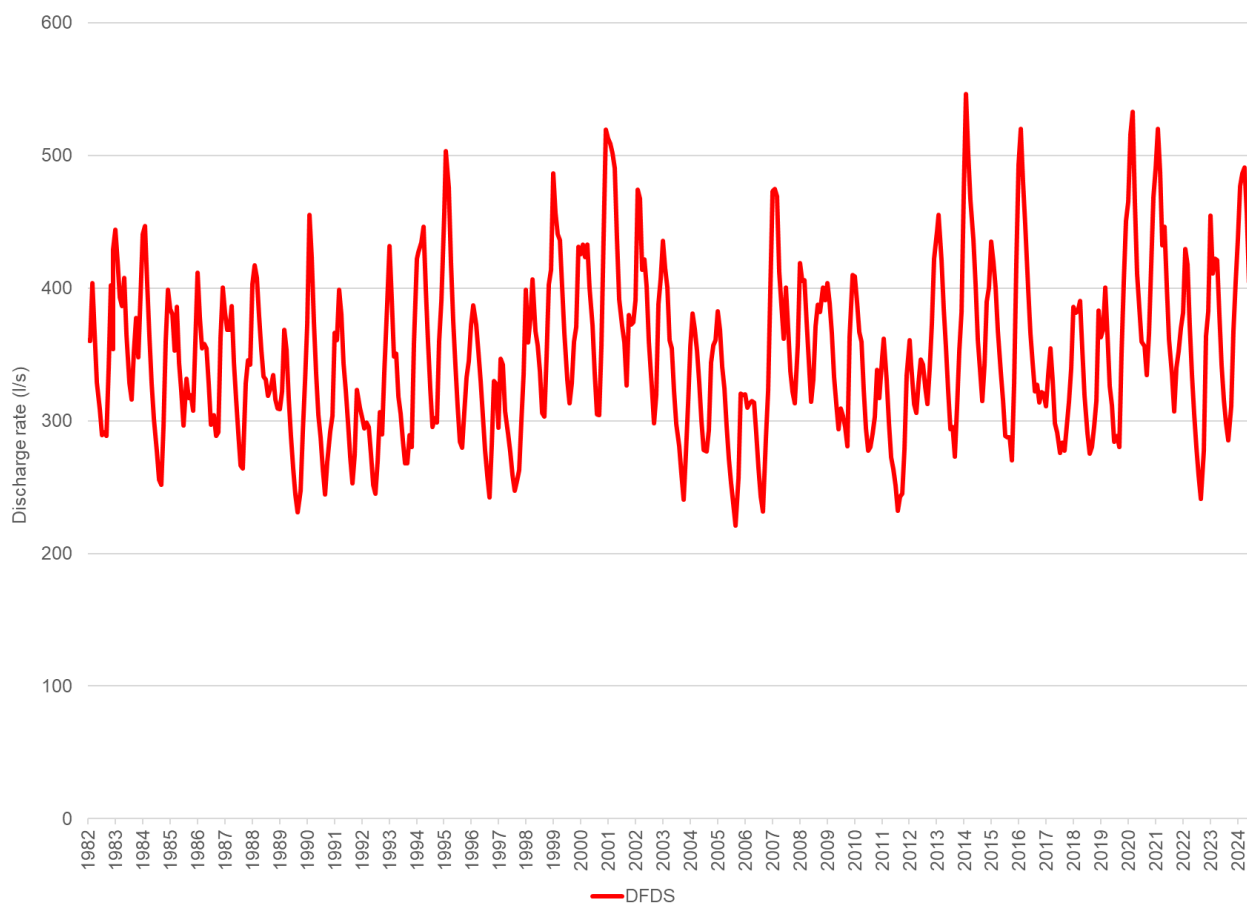
#### *4.3.4 Calibration to DFDS discharge*

Conceptually, the DFDS comprises the primary means by which groundwater is controlled at the site. The approach to calibration of the DFDS discharge was to maintain control groundwater

levels across the site such that groundwater heads and seasonal fluctuations are reflective of observed trends (Section 4.3.3), whilst simulating a discharge rate that is similar to that identified in the site water balance (260 l/s).

The simulated average monthly DFDS discharge rate over the site area is plotted in Figure 26 in relation to recharge. It is apparent that the modelled drainage rates vary seasonally from 221 l/s to 546 l/s with a long-term average of 351 l/s. This exceeds the rate identified in the water balance model of 260 l/s by 91 l/s, although it is worth noting that the Q95 is 258 l/s, which does compare favourably to the water balance model derived using data collected during a dry period when discharge rate are likely to have been lower.

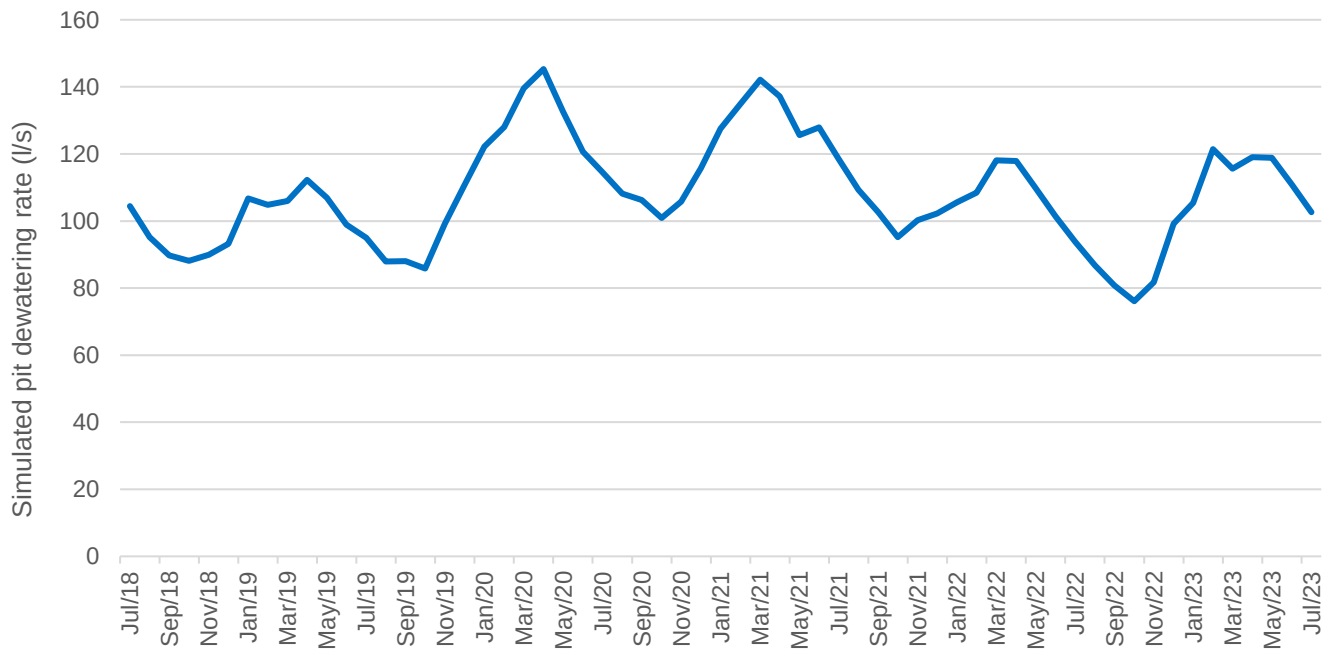
When set to mimic a lower average discharge rate of 260 l/s the DFDS failed to lower the heads in the pit area sufficiently to achieve an acceptable calibration. This could suggest that the groundwater catchment area of the DFDS, both in the model but also in reality, may be more extensive than initially assumed when the water balance model was initially derived.



*Figure 26 Simulated DFDS discharge, historical model with no excavation*

### **4.3.5 Calibration to mine dewatering rates**

Dewatering of the pit void has generally been achieved by means of a single 400 m<sup>3</sup>/hr (111 l/s) pump. During wet periods, this has been complemented by up to two additional pumps to maintain dry working conditions, with much of the additional dewatering demand consisting of direct rainfall and runoff. As such, the LTA pumping rate is generally slightly higher: for example, from available records in 2020 it equates to 475 m<sup>3</sup>/hr, or 132 l/s. The simulated pit dewatering rate, assuming a static pit between July 2018 and July 2024, is shown in Figure 27. The LTA dewatering rate is 108 l/s, and it generally fluctuates seasonally between 80 and 140 l/s. This compares favourably with the historical pit dewatering demand.



*Figure 27 Simulated pit dewatering rate, historical model with excavation, July 2018 to July 2023*

#### **4.3.6 Calibrated hydraulic parameters**

Calibrated hydraulic properties are presented in Table 9. Only the vertical hydraulic conductivity of the coal measures was changed relative to the initial setup, from 0.005 m/d to 0.1 m/d. Simulated heads and drains inflows were found to be most sensitive to the conductance of the DFDS and to the high permeability alluvial zone that was positioned alongside the valley bottoms in the model, to facilitate the movement of groundwater towards river boundary conditions. The coverage of this area is shown in Figure 28 in relation to watercourses represented in the model. The backfill area and pit are also shown.

*Table 9 Summary of calibrated model hydraulic parameters*

| Unit                                    | Layer(s)           | Horizontal Hydraulic conductivity (m/d) | Vertical Hydraulic conductivity (m/d) | Specific Yield (-) | Specific Storage (1/m) |
|-----------------------------------------|--------------------|-----------------------------------------|---------------------------------------|--------------------|------------------------|
| Overburden / Alluvium                   | 1                  | 10                                      | 10                                    | 0.1                | $1 \times 10^{-5}$     |
| Sandstone (Brithdir and Hughes Members) | 2                  | 1                                       | 0.1                                   | 0.02               | $5 \times 10^{-6}$     |
| Coal Measures                           | 3 to 17            | 0.5                                     | 0.1                                   | 0.02               | $5 \times 10^{-6}$     |
| Sandstone (Twrch)                       | 18                 | 1                                       | 0.1                                   | 0.02               | $5 \times 10^{-6}$     |
| Limestone                               | 19                 | 2                                       | 0.2                                   | 0.02               | $5 \times 10^{-6}$     |
| High permeability alluvium              | 1                  | 40                                      | 40                                    | 0.1                | $1 \times 10^{-5}$     |
| Backfill                                | All where relevant | 2                                       | 2                                     | 0.1                | $5 \times 10^{-6}$     |
| Void                                    | Pit nodes          | 100                                     | 100                                   | 0.9                | $5 \times 10^{-7}$     |

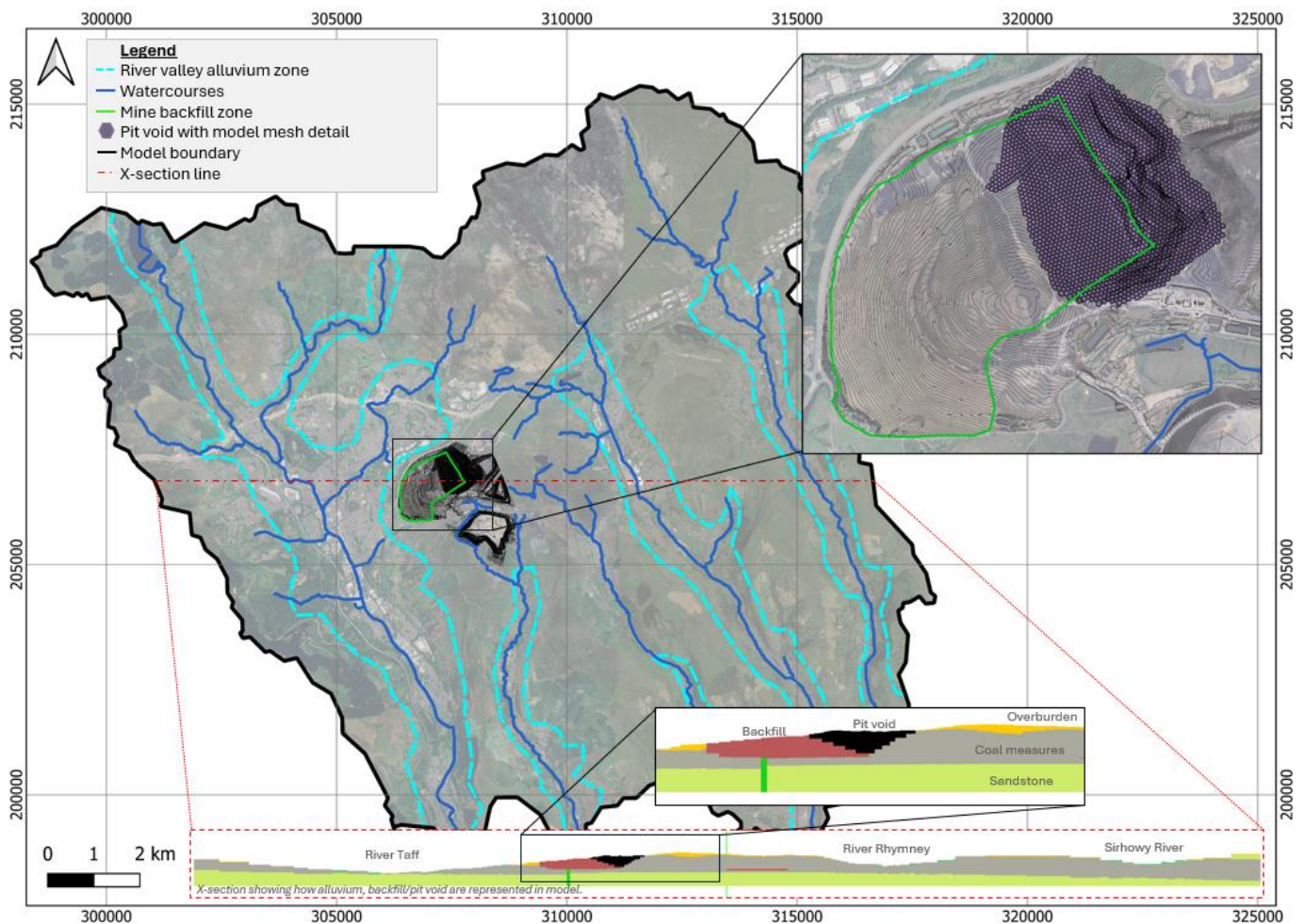


Figure 28 Location of river valley alluvium zone. The mine backfill zone and pit void are also shown in cross-section.

## 4.4 Model projections

The groundwater model was used to assess the potential, future hydrogeological impacts of the restoration scheme. As discussed in Section 2.1, this was undertaken by using the groundwater model to quantify:

- Change in groundwater level and availability for groundwater users and WFD water groundwater bodies.
- The change in groundwater discharge to surface water receptors through both the groundwater system and the DFDS.

Two parallel predictive models were set up, based on the calibrated groundwater model with the representation of the backfill and pit void. In the first model, the current pit void landform was represented. The proposed post-restoration landform was applied to the second model. Differences in projected groundwater levels and fluxes during representative dry and wet periods were then used to quantify change, and therefore impact, for receptors identified during the receptor screening process (Section 2.4). The dry and wet conditions correspond to the months of August 2026 and February 2056 respectively in the projected climate dataset. These months reflect climatic conditions experienced in August 1984 and February 2010 from the historical dataset. Climate change factors are applied to assess the impact of climate change.. These months were chosen because they coincide with the lowest and highest lake levels simulated by the pit lake water balance model. This is described in detail in Section 5.

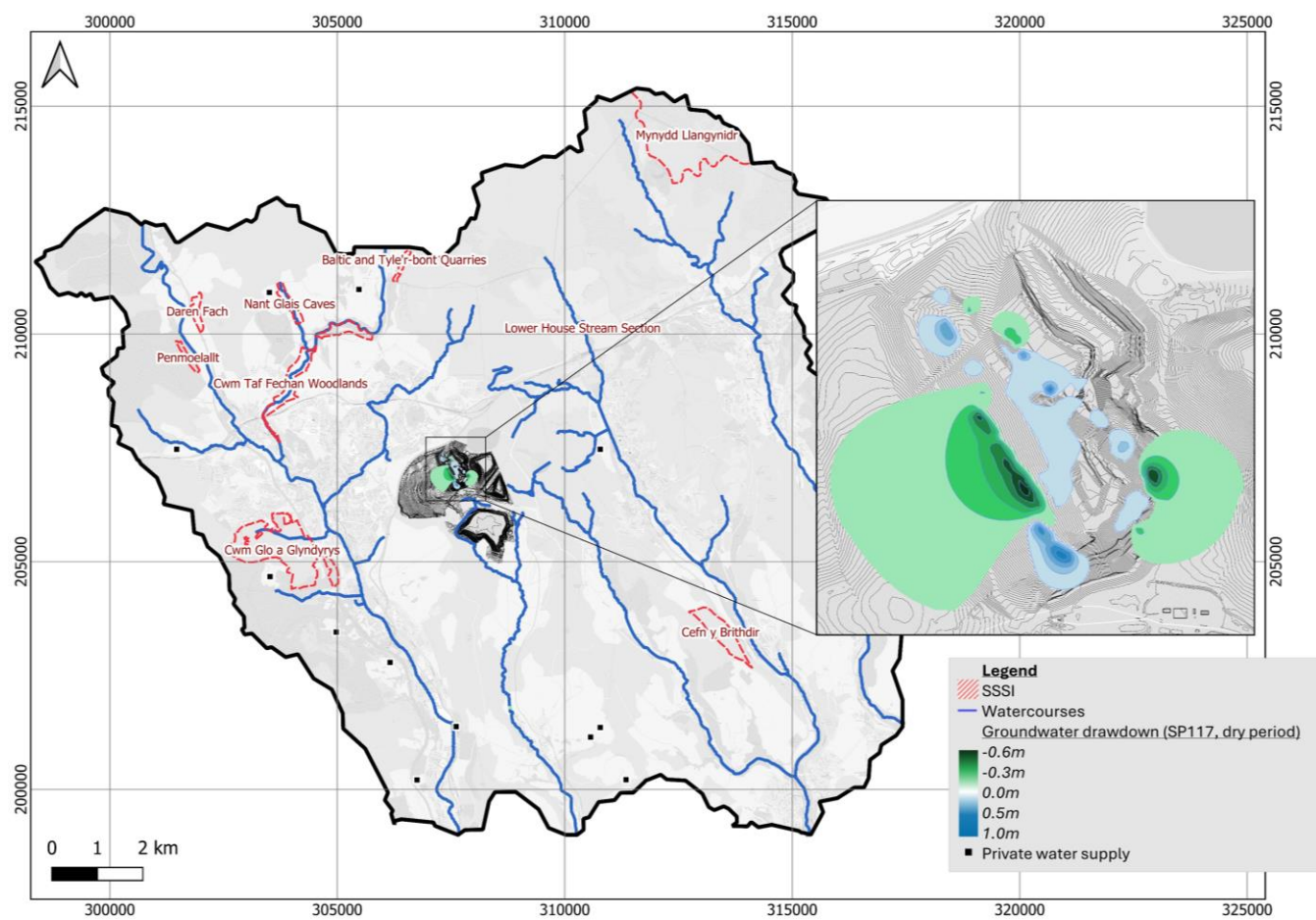
The future-facing groundwater model is structured similarly to the historical calibration model, incorporating the backfill and pit void as described in Section 4.3.1. The model includes the following components:

- **Initial Groundwater Head Distribution:** A one-year simulation period without a pit void, representing the climatic conditions from January 2017 to January 2018, to establish an initial distribution of groundwater heads.
- **Dewatering Simulation:** A 5.5-year simulation where the excavation remains dry, to assess the initial impact of mining activities on the groundwater system. This corresponds to the climatic period from January 2018 to July 2023.
- **Recovery Simulation:** A 36-year recovery period starting in August 2023 (midway through simulation year 6), when dewatering activities cease and the pit lake level begins to rebound. From August 2024 onward, the historical climate dataset for 1982 to 2017 is appended (along with projected changes in rainfall and PEt during the climate change scenarios) to create a future climate projection to 2059.

The content of Section 4.4 is also covered in the Environmental Statement (RML, 2025).

#### *4.4.1 Spatial impact to groundwater receptors*

The difference in groundwater level was calculated for both dry and wet periods and found to be restricted to the pit void. There is no recorded change or deviation in groundwater level at any point receptors or SPZ of more than 1 cm and hence impacts are considered negligible. The changes in groundwater level are highly localised to the footprint of the pit void and minor in scale (<1 m). As a result, it is highly unlikely that WFD status for groundwater and surface water bodies in the search area would be affected through the implementation of the proposed restoration scheme. The availability of groundwater for consumptive licensing within CAMS catchments, to public water supplies and private groundwater users, would similarly be unaffected. Spatial impacts on groundwater levels for both dry and wet periods are shown in Figure 29 and Figure 30 respectively.



*Figure 29 Dry period spatial difference in groundwater head*

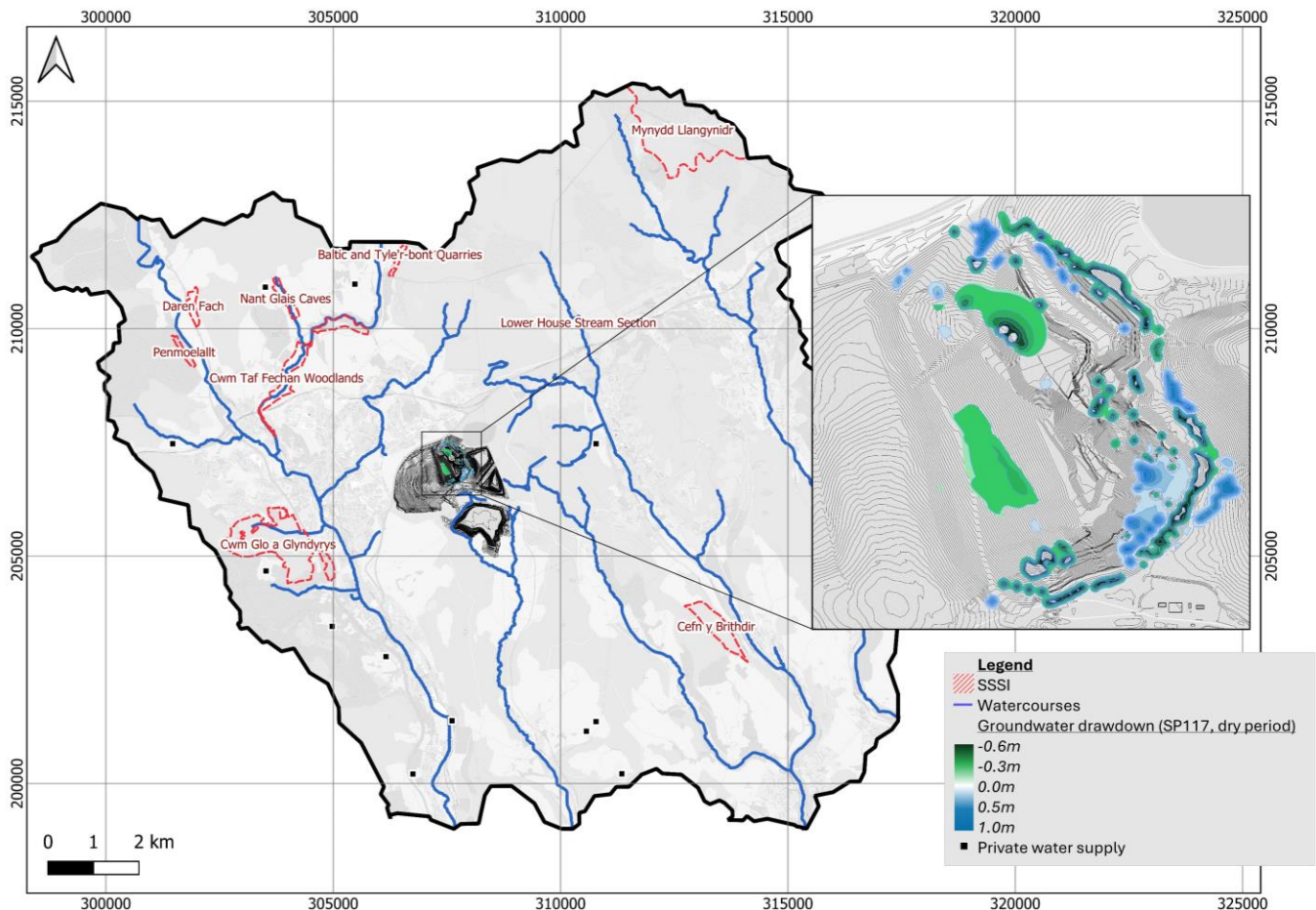


Figure 30 Wet period spatial difference in groundwater head

## 4.4.2 Impact to surface water receptors

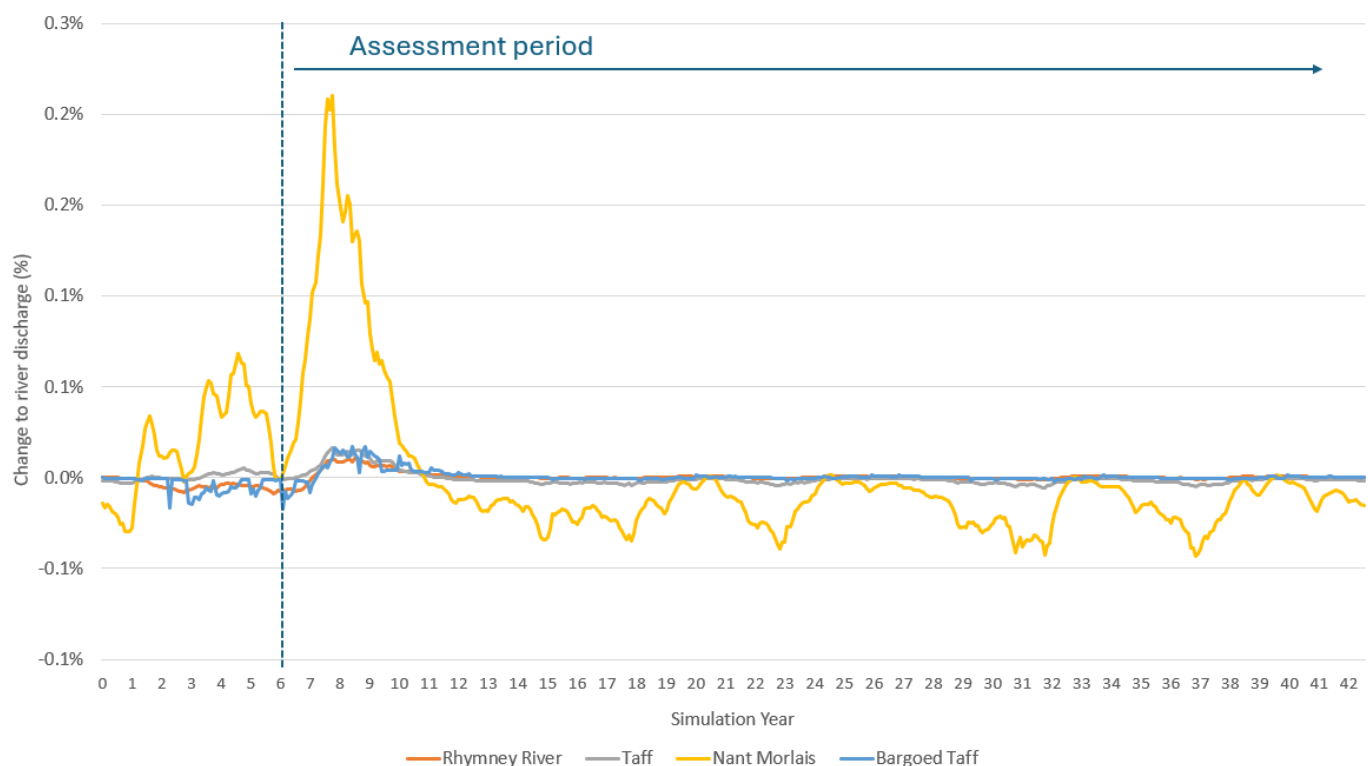
### Direct groundwater discharge to surface water bodies

Figure 31 shows the change in simulated discharge of groundwater to surface water bodies via the groundwater pathway, relative to baseline conditions. The largest change is observed to the Nant Morlais, where simulated discharge is projected to increase by 0.2% (equivalent to 0.6 m<sup>3</sup>/d) relative to the current baseline shortly after cessation of dewatering (simulation year 8) and decrease by up to 0.05% (0.1 m<sup>3</sup>/d) in the period thereafter.

To place this into context, dry period discharge rates through the Nant Morlais culvert to the River Taff measured in June 1996 and July 2024 ranged from 12,960 m<sup>3</sup>/d to 20,649 m<sup>3</sup>/d. The

simulated post-restoration change in groundwater discharge to the Nant Morlais therefore represents less than 0.01% of the lowest observed stream flow. Furthermore, this represents an even lower fraction of the Q95 (63,072 m<sup>3</sup>/d) of the River Taff at the Merthyr Tydfill gauging station, which is located just upstream of the confluence with the Nant Morlais.

The magnitude of the simulated change in direct groundwater discharge to nearby surface water bodies is minimal in relation to measured flow and furthermore is well within the margins of error of typical stream flow gauging instrumentation. As such, impacts would be highly unlikely to influence any WFD criteria and therefore affect WFD status for the receiving water bodies.



*Figure 31 Simulated change in groundwater discharge to nearby surface water bodies post-restoration  
Discharge to surface water bodies via the DFDS*

The DFDS comprises a network of cross-cutting drainage adits and tunnels that were collectively used to drain the mine site, enabling safe access to the historical mine workings and providing water to the Dowlais Iron works. It is assumed that much of this infrastructure remains in place, is

operational to this day and has been unaffected by contemporaneous mining operations. It is understood that the DFDS drains to nearby watercourses, including the Nant Morlais, River Taff and River Rhymney, although the exact distribution of outflows by volume cannot be measured directly.

The 3D numerical model incorporates a 3D representation of the DFDS, which was developed based upon our current understanding of the drainage system layout and invert levels. Since the DFDS is believed to drain to nearby watercourses, the impact of the restoration scheme implementation on discharge from the drainage network was evaluated to assess how the scheme may affect receiving water bodies.

The simulated change in outflow from the DFDS is shown in Figure 32 relative to pre-restoration conditions. The simulation indicates a minimal effect to the discharge rates from the DFDS, with a maximum change of +0.5%, equivalent to approximately 2 l/s (172.8 m<sup>3</sup>/d). This represents 1.3 % of the lowest measured flow (12,960 m<sup>3</sup>/d, June 1996) through the Nant Morlais culvert. This would fall within the acceptable range of flow deviation (<5% deviation at <Q95, <10% deviation at >Q95) presented in the JNCC Common Standard Monitoring for Rivers (JNCC, 2016), and furthermore represents an increase in flow.

The scale of the difference in simulated outflows suggests that the impact to receiving water courses is acceptable and should not affect WFD status.



*Figure 32 Simulated change in discharge from the DFDS post-restoration*

# 5. PIT LAKE WATER BALANCE

## 5.1 Introduction

A discrete pit void water balance model was developed to provide an assessment of post-restoration long-term pit lake level and volume fluctuations.

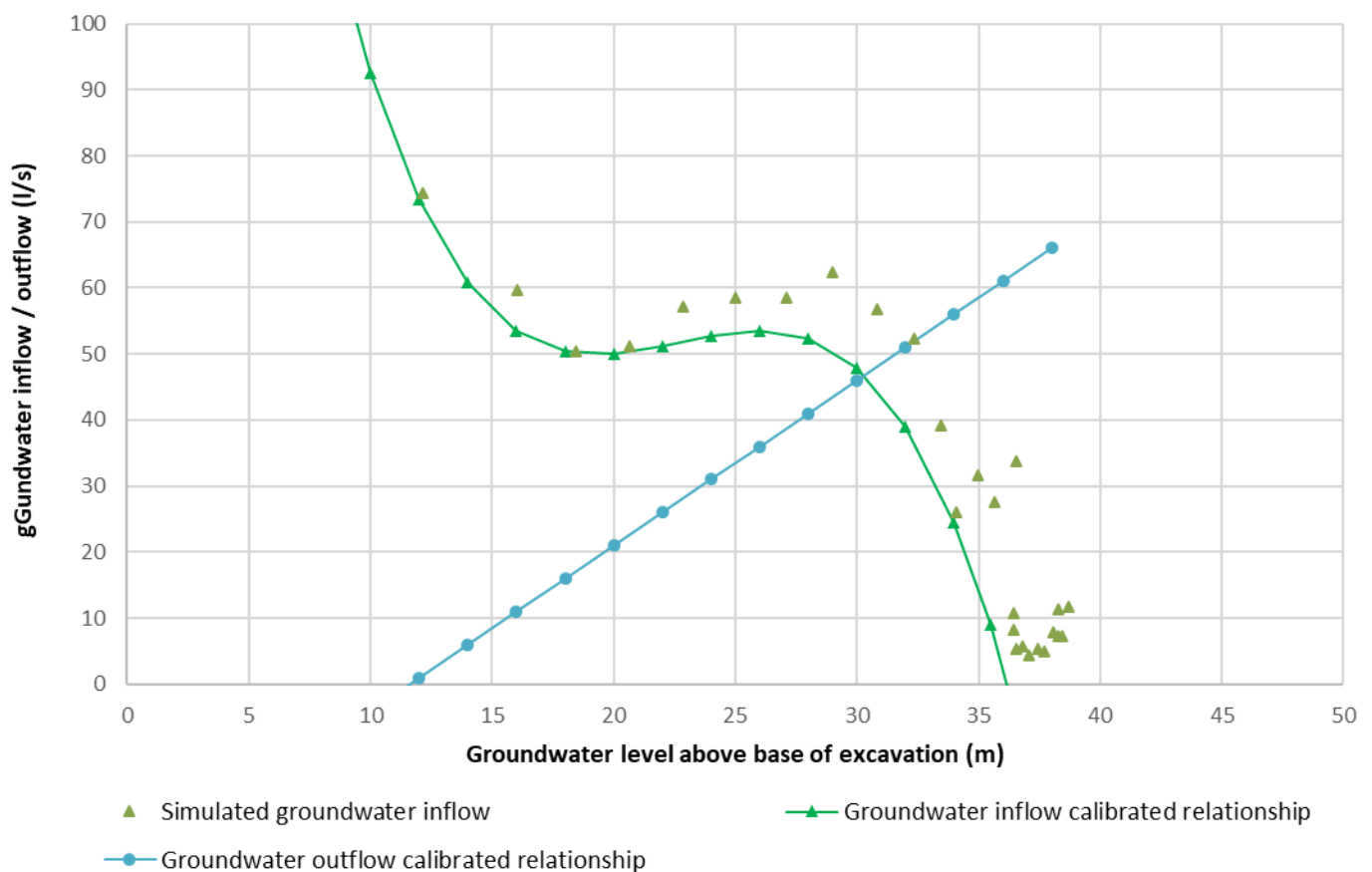
## 5.2 Development

The pit lake water balance is a spreadsheet-based tool that operates on a daily timestep and tracks the water level and volume within the pit void in response to climatic inputs and user-defined relationships between pit lake stage and groundwater inflow/outflows. The conceptual cross-section presented in Figure 14 reflects the main conceptual elements incorporated within the model.

Model inputs and parameters include:

- HADUK rainfall dataset for the period 1982 to 2024. This comprises the main rainfall input to the model. During the calibration period (August 2023 to December 2024) recorded rainfall data from Cwmbargoed weather station, situated within the site boundary, were used instead.
- EA PEt data for the period 1982 to 2024. This comprises the sole evaporative input to the model.
- Pit lake stage vs groundwater inflow/outflow relationships.. Final calibrated relationships for both stage vs groundwater inflow and stage vs groundwater outflow are presented in Figure 33. The groundwater model demonstrated a strong relationship between groundwater inflow and pit lake stage, showing that groundwater inflow reduces as the elevation of the pit lake above the pit base increases. The shape of the curve is a consequence of the shape of the pit, which means that the reduction in groundwater inflow rate associated with a decrease in gradient between the pit lake and surrounding groundwater is offset by the increase in wetted contact area between 15 and 30 m above

the pit floor. The groundwater outflow vs stage relationship was determined through the process of model calibration to best fit observed records of lake level. It was not possible to disentangle a meaningful relationship for this term from the model owing to the absence of outflows from the lake during the early part of the lake recovery, and relationship with recharge. However, from a conceptual perspective, groundwater outflow is likely to be related to the lake level and gradient between the lake and surrounding groundwater and therefore a simplified linear outflow vs stage was included in the model and calibrated to provide a best fit to observed data.



*Figure 33 Relationships linking pit lake stage to groundwater inflow (green) and groundwater outflow (blue) (pre-calibration)*

- Runoff is calculated using the SCS-CN (Soil Conservation Service Curve Number method) approach (K.X. & Valiantzas, 2012).
- Stage/ pit lake area / volume relationships for both the current pit void geometry and the proposed restoration landform.

## 5.3 Calibration

The approach to model calibration involved fitting the simulated pit lake level to observed records available from August 2023 to December 2024. Quality of fit is based on how well the model simulates the general trend of pit lake level evolution through the calibration period, but also to what extent it can mimic responses to larger rainfall events, such as Storm Bert in November 2024 (Figure 11).

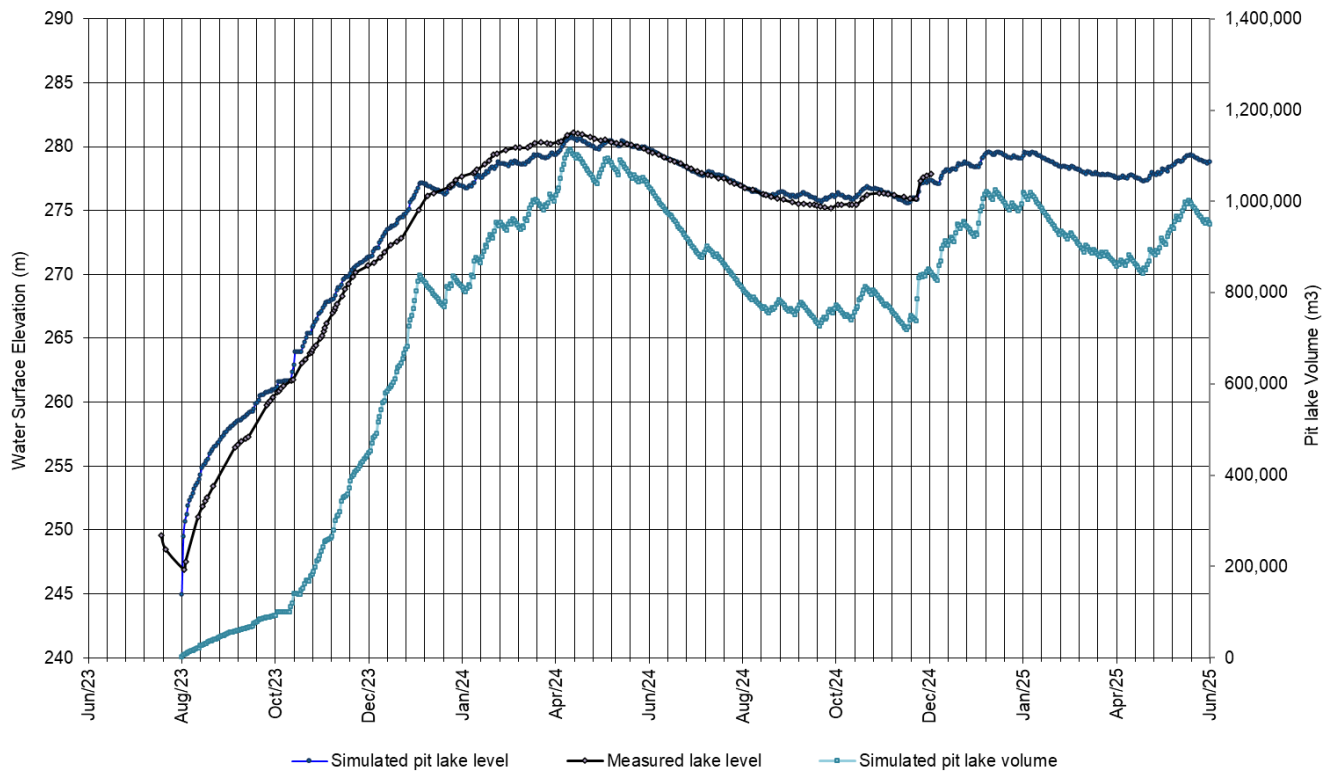
Additional mechanisms were needed in the mass balance model to achieve a good fit to the observed data. These included:

- Groundwater inflow rate is limited to 1300 m<sup>3</sup>/d (15 l/s) below a pit lake elevation of 266 mAOD. This was included to limit the groundwater inflows at low pit lake level elevations, namely during the initial recovery.
- At pit lake elevations above 270 mAOD, groundwater outflows can only occur if the sum of calculated outflows from the pit (groundwater outflow and evaporation) exceeds inflows (rainfall, runoff, groundwater). Conceptually this was implemented to reflect how rainfall events can result in a net groundwater gradient into the pit, and therefore groundwater only flows in. Although this represents a simplification, and in fact groundwater outflows will almost always occur, this mechanism was required to maintain an outflow rate sufficiently high to fit the pit lake recession data, whilst replicating the pit lake level highs during periods of significant rainfall.
- Runoff is only applied when runoff is calculated to occur in the SWAc runoff/recharge model, which accounts for soil moisture conditions. In addition, a multiplier of 0.1 was applied to all runoff generated during the months of June to September. These mechanisms were implemented to reduce the volume of runoff reporting to the pit during

the drier months and reflects how runoff is generated preferentially at the site when the soil is saturated during wetter, colder times of the year.

The simulated pit lake level and volume are shown relative to measured levels in

Figure 34. Simulated levels track measured levels well through the duration of the monitoring period, both during the rising limb and ensuing recession. The model can also simulate discrete responses to rainfall events, such as Storm Bert in November 2024. Regression analysis, as shown in Figure 35, demonstrates that the overall fit between simulated and observed lake levels is very close. These metrics lend confidence to the use of the model for projections of potential future behaviour. Any further improvements should focus on increasing simulated lake levels in the 276 to 277 mAOD range and reducing the frequency of level over-estimation in the 278 to 280 mAOD range. The model would also benefit from further lake level monitoring data. It is also important to note that, as with all models, the reliability of its projections is strongly affected by the quality, quantity and nature of the data that have been used during development and calibration. Although the model responds well to current extremes relative to what has been observed (for example Storm Bert), there is greater uncertainty associated with the model response to conditions that were not present within the calibration dataset, such as extremely dry or wet periods. This emphasises the need to continue improving the model using climatic data and pit lake levels recorded at the site.



*Figure 34 Simulated pit lake level and volume relative to measured lake level*

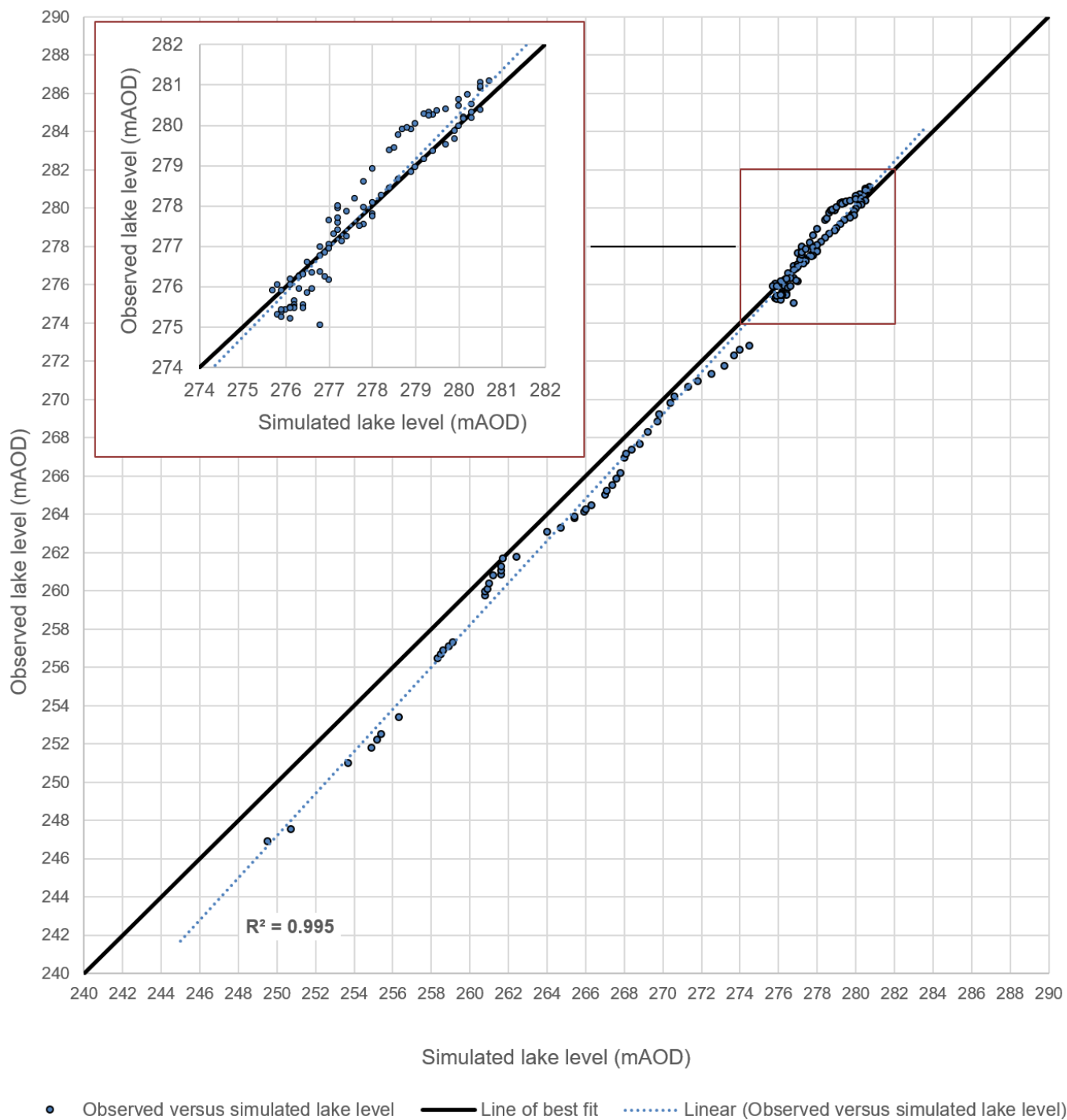


Figure 35 Regression analysis, observed versus simulated pit lake levels

## 5.4 Model projections

Two sets of model projections were run to simulate the long-term evolution of the pit lake water level and volume within the pit void. Projected lake levels were evaluated with consideration for the risk of the lake overtopping the pit void. The breach level for the proposed restoration landform is 331 mAOD, equivalent to a lake volume of approximately 9,550,000 m<sup>3</sup>. The breach elevation of the current pit void is 333.7 mAOD, which is equivalent to a lake volume of approximately 10,900,000 m<sup>3</sup>.

- **Historical climate:** Baseline runs were used to estimate the likely future range of pit lake levels assuming that the current climate records reflect future trends. This baseline suite consisted of two models representing both the current pit topography and the proposed post-restoration landform to highlights differences in pit lake level range and trends.
- **Climate change scenarios:** The pit water balance model for the post-restoration scheme topography was also run using selected synthetic climatic timeseries from an ensemble of projections; these account for potential climate change effects on rainfall and temperature in the future. The development of these projections is document in Chapter **Error! Reference source not found.** The climate change projections were derived using the UKCP 18 RMP 8.5 (high emissions) ensemble as a conservative assumption. Three climate change timeseries were selected from the ensemble to reflect a range of conditions:
  - Driest: Lowest hydrologically effective rainfall (precipitation – potential evapotranspiration).
  - Average: Mid-range scenario with average hydrologically effective rainfall.
  - Wettest: Scenario with the most hydrological effective rainfall.

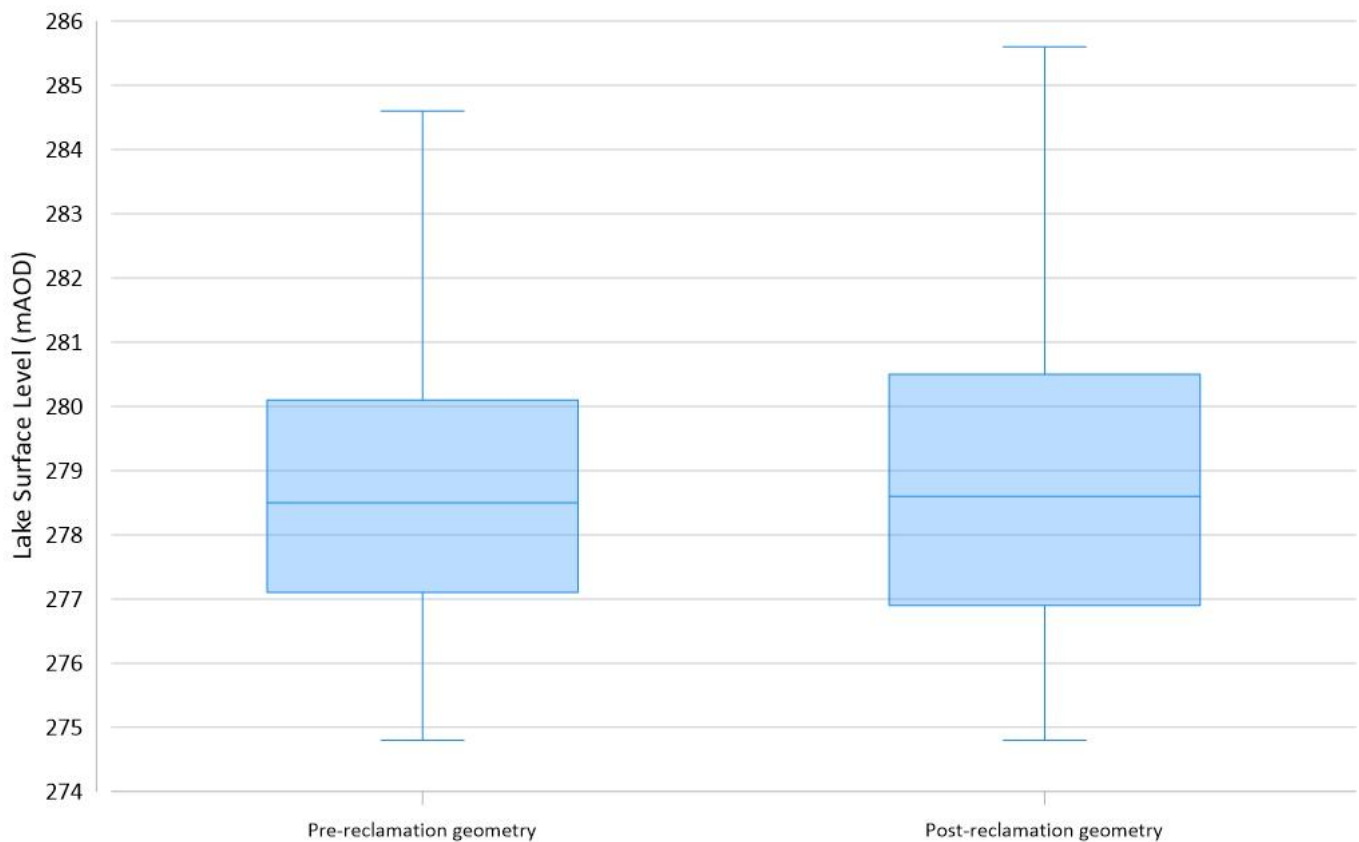
Findings from this assessment are also presented in the 2025 ES (RML, 2025).

## 5.5 Baseline runs

### *Level*

The median, interquartile range, along with minimum and maximum values for the simulated pit lake level in both scenarios are plotted in Figure 36. The maximum simulated pit lake water level (285.6 mAOD) is higher in the post-restoration landform scenario than in the current pit topography scenario (284.6 mAOD). The simulated maximum of 285.6 mAOD for the reclaimed landform is 45.9 m below the theoretical void breach water level of 333.7 mAOD.

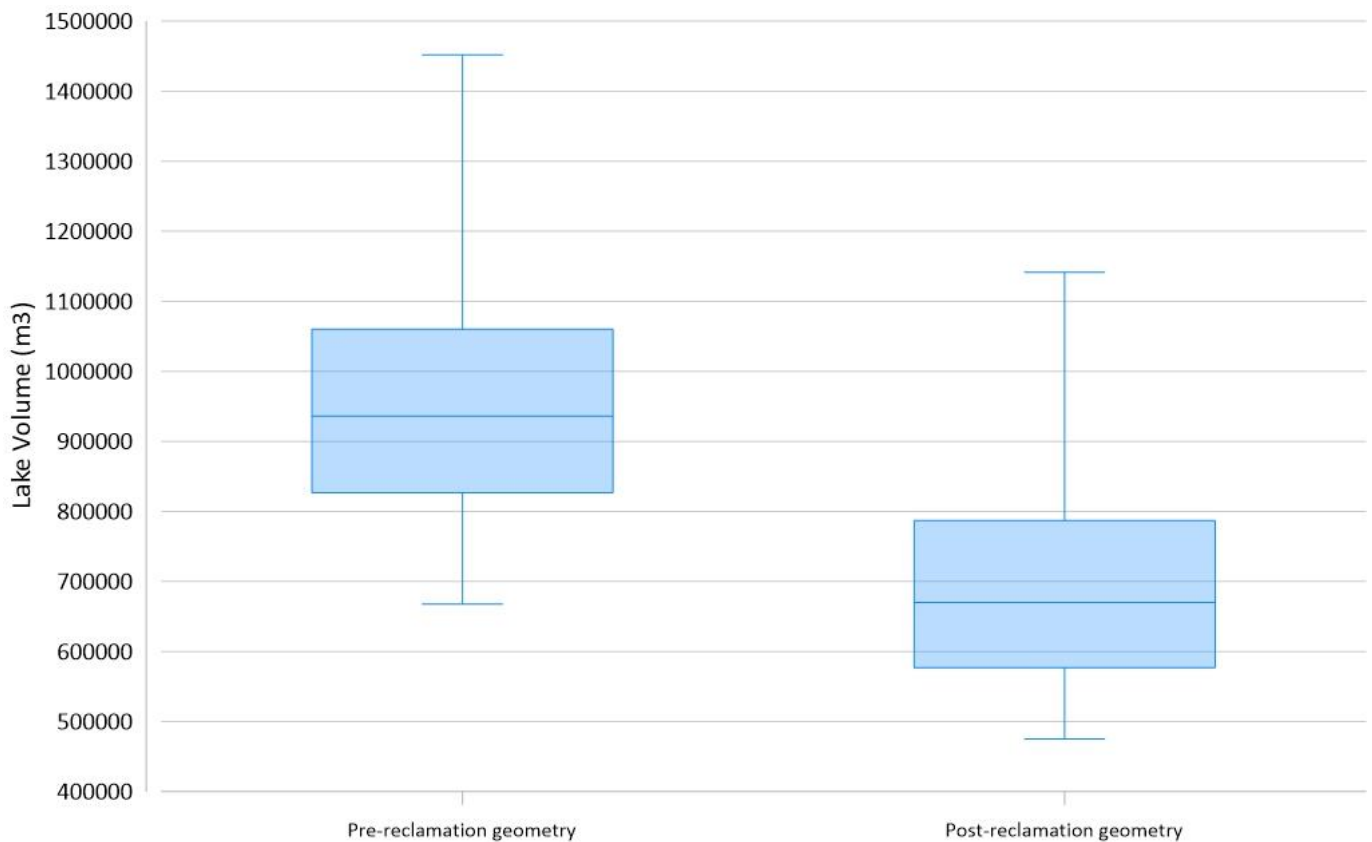
Similarly, the simulated minimum levels and median ranges do not vary substantially between the scenarios. However, the interquartile range is greater in the post-restoration scenario, implying more substantial seasonal variation in water level. This reflects a reduction in storage capacity within the former pit void, producing larger changes in water level for a given volume of added/removed water.



*Figure 36 Statistical distribution of simulated lake level ranges for pre-restoration and post-restoration pit geometries*

### Volume

The simulated statistical distribution of pit lake volumes for each scenario is shown in Figure 37. The simulated lake volume range is reduced in the post-restoration water balance model, owing to the reduced volume of the landform relative to that of the present day. Median simulated volume is reduced to 670,000 m<sup>3</sup> from 935,000 m<sup>3</sup>, and the simulated maximum volume is reduced from 1,450,000 m<sup>3</sup> at a lake level of 284.6 mAOD to 1,140,000 m<sup>3</sup> at a lake level of 285.6 mAOD. The maximum simulated lake volume post restoration is 8,405,000 m<sup>3</sup> less than the volume of the pit void at the spill elevation. Alternatively, the maximum simulated post-restoration pit lake volume can be expressed as 12 % of the total void volume.



*Figure 37 Statistical distribution of simulated lake volume ranges for pre-restoration and post-restoration pit geometries*

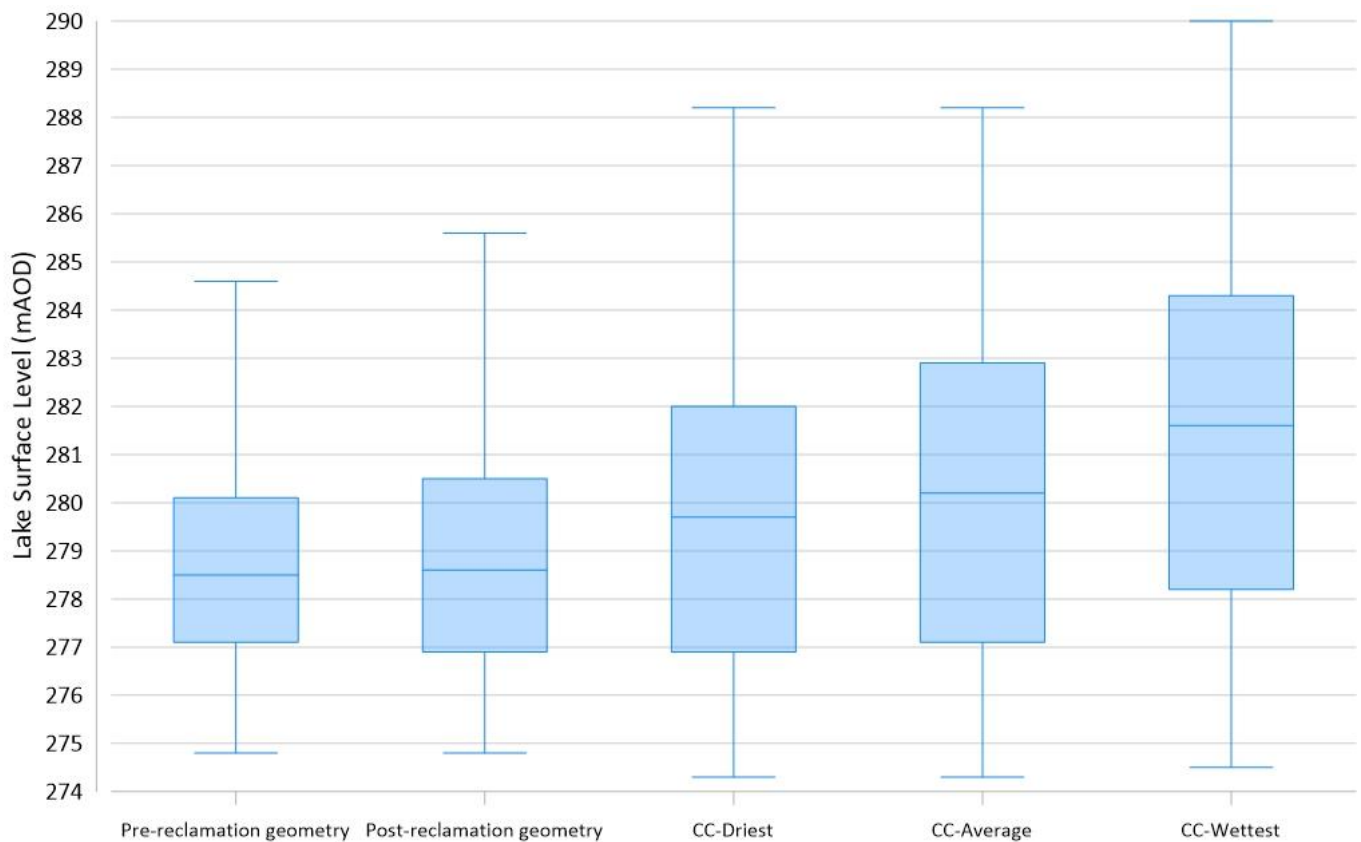
The water balance model indicates that a maximum post-restoration pit lake level of approximately 286 mAOD may be expected, with a corresponding volume of 1,140,000 m<sup>3</sup>. Assuming that the groundwater regime behaves in a manner consistent with the present day and that the surface water catchments remain unchanged relative to those associated with the current proposed landform, the findings suggest that there is negligible risk of the pit lake overtopping post-closure.

## 5.6 Climate scenarios

### *Level*

The statistical distributions of water levels for the climate change water balance models are shown in Figure 38 in relation to the “historical climate” scenarios. All three future climate scenarios result

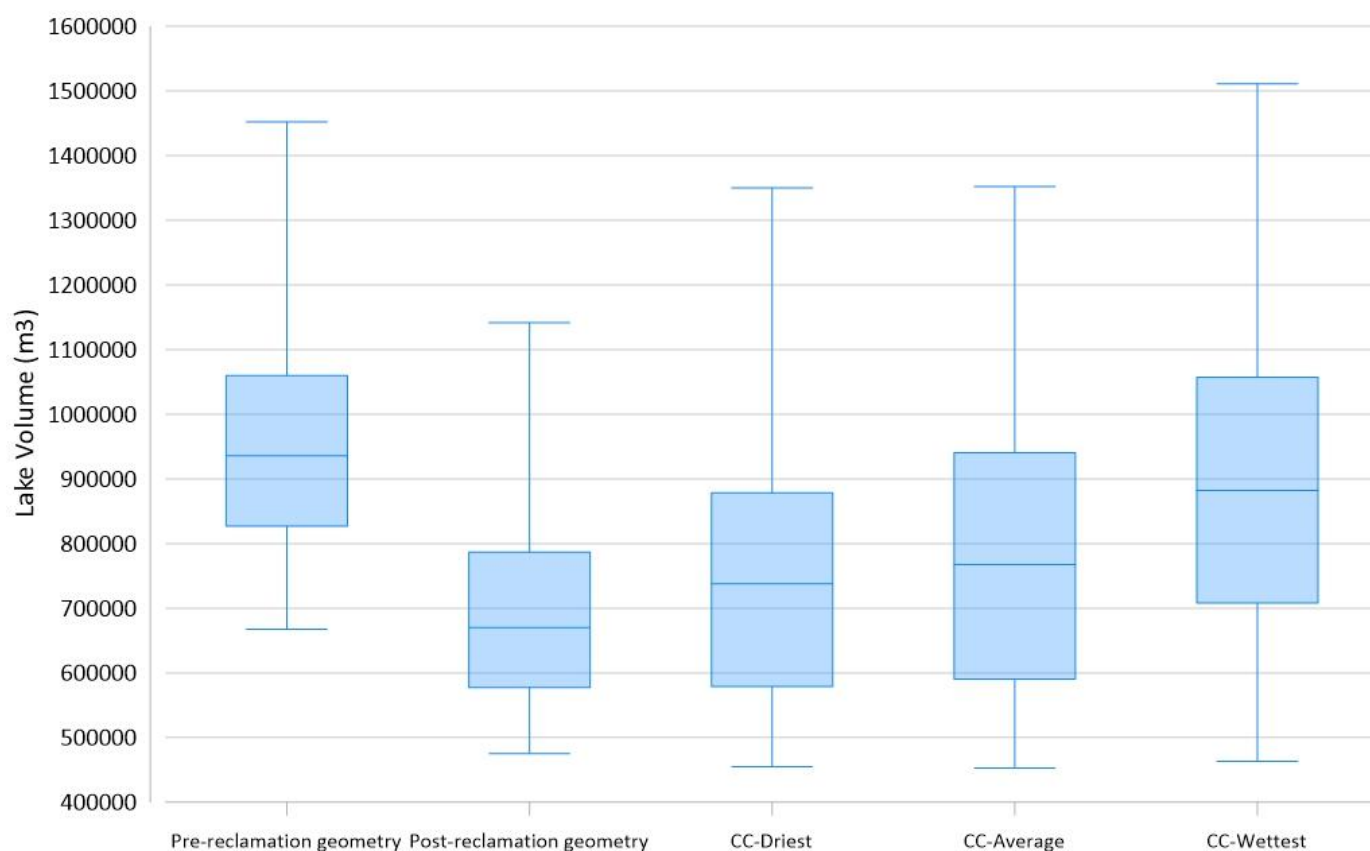
in an increase in the maximum simulated pit lake level. The highest lake level of 290 mAOD is simulated in the wettest climate change projection. Whilst median pit lake levels are higher across all climate change scenarios, it is notable that both the interquartile range and minimum/maximum ranges are also increased. This reflects more variability in seasonal climatic trends (temperature, rainfall), a wider long-term range in annual rainfall and temperature, due to the progressive effects of climate change, increases in the frequency and intensity of extreme rainfall events but also the increased prevalence of hot, dry periods, leading to lower simulated pit lake levels than would be expected using historical climatic records.



*Figure 38 Statistical distribution of simulated lake level ranges for pre-restoration and post-restoration pit geometries, including climate change scenarios.*

## Volume

A similar picture emerges with respect to the pit lake void volume, which is apparent in Figure 39. Maximum simulated pit lake volumes are greater in all climate change scenarios relative to the post-restoration historical climate scenario, reaching a value of just over 1,500,000 m<sup>3</sup> for the wettest projection. This represents 16 % of the available storage within the void. The range of simulated pit lake volumes is greater in the climate change scenarios, reflecting greater climatic variability and increased occurrence of extreme temperature and rainfall events.



*Figure 39 Statistical distribution of simulated lake volume ranges for pre-restoration and post-restoration pit geometries, including climate change scenarios*

The water balance model climate change scenarios indicate that a future, wetter climate that experiences more extreme rainfall events may result in an increase in maximum water levels and lake volumes within the void. If the assumptions made in the development of the water balance

model remain valid, these findings indicate that the lake stage should remain below the spill elevation of the void, and as such that there is negligible risk of the pit lake overtopping.

## 6. SUMMARY

The potential for hydrogeological impacts related to the implementation of the proposed restoration scheme has been evaluated using a multi-faceted approach, supported by a review of existing knowledge of the site that benefits from recent site investigations to address conceptual uncertainties.

Spatial hydrogeological impacts to nearby receptors were evaluated using a 3D numerical groundwater model founded on the conceptual site hydrogeological model and calibrated to groundwater heads, mine discharges and pit lake levels.

Long-term future evolution of the pit lake level, and assessment of the risk of overtopping, was evaluated using a pit lake water balance model. The effects of climate change, namely changes to rainfall patterns and potential evaporation, were accounted for through the inclusion of three climate change scenarios.

This chapter summarises the potential effects related to implementation of the scheme, the significance and risk level, and any mitigation or monitoring that is suggested. Furthermore, a cumulative effect assessment is provided to account for the compound effect of the scheme on mine water and groundwater discharges to surface water flows.

### 6.1 Summary of effects

Hydrogeological impacts and effects of the proposed restoration scheme are summarised in

Table 10. This summary table also provides an evaluation of the significance of any impacts and the risk posed by the assessment outcomes, as well as suggested actions including mitigation measures and environmental monitoring.

*Table 10 Summary of impacts, significance and risk level, and any mitigation or monitoring that is required*

| Assessment                      | Impact                                                                                                                                                                                   | Significance / Risk | Mitigation / monitoring required                                                                                                                                     |
|---------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Regional groundwater users      | No effect on groundwater users or groundwater supply within the search area. Limited to the immediate pit void area and of <1m change in groundwater level for both wet and dry periods. | Insignificant       | Continued monitoring of the pit lake level as a proxy for groundwater level.                                                                                         |
| WFD groundwater bodies          | No change in groundwater level or aquifer dynamic resulting in change to flow that could affect quantitative WFD indicators.                                                             | Insignificant       | None                                                                                                                                                                 |
| WFD surface water bodies        | No change in groundwater discharge to surface water bodies, either through the groundwater system or groundwater pathways, that are large enough to affect quantitative WFD indicators.  | Insignificant       | None                                                                                                                                                                 |
| Post-restoration pit lake level | Simulated maximum pit lake level remains > 40 m below the spill point.                                                                                                                   | Highly unlikely     | Continue pit lake level monitoring through restoration and closure. Continual validation and update of the pit lake water balance model with latest monitoring data. |

|                                          |                                                                                                                         |                 |                                                                                                                                                                      |
|------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Climate change effects to pit lake level | Projected climatic changes lead to higher maximum pit lake levels that are still > 40 m below the lake spill elevation. | Highly unlikely | Continue pit lake level monitoring through restoration and closure. Continual validation and update of the pit lake water balance model with latest monitoring data. |
|------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|

## 6.2 Cumulative effects

Cumulative effects relevant to this assessment relate only to the compound change in groundwater discharge to surface water bodies via the groundwater pathway and the DFDS, discussed in Sections 4.4.2.

Conservatively assuming that the maximum cumulative effect can be calculated as the sum of the maximum changes at any given time in the assessment period of the groundwater model simulation, it can be said that the greatest cumulative effect to groundwater discharge to surface water occurs to the Nant Morlais culvert. This involves an increase of 0.6 m<sup>3</sup>/d attributed to groundwater flow through the groundwater pathway, and an increase of 173 m<sup>3</sup>/d through the DFDS. Given that the increase in the flow through the DFDS is three orders of magnitude greater than the change simulated through the groundwater pathway, it can be said that the impact of the cumulative effect is essentially the same as the impact owing to the change to DFDS discharge in isolation. Therefore, it can be said that the cumulative impact represents an acceptable range of flow deviation, as presented in the JNCC Common Standard Monitoring for Rivers (<5% deviation at <Q95, <10% deviation at >Q95).

## 6.3 Summary of significant effects

The hydrogeological impact assessment of the proposed restoration scheme implementation does not identify significant effects that require mitigation or adjustments to the proposed plans. The pit lake level should continue to be measured and reviewed on a regular basis in the future

regardless of whether the restoration scheme is implemented or not. These data, as well as climatological observations, should be used to update and validate the pit lake water balance model to increase confidence in future projections of potential pit lake level range. Furthermore, groundwater levels both within the site area and within the hydrogeological search area should continue to be monitored to confirm the absence of impact to groundwater users.

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# Appendix 1: Climate change modeling

## Overview

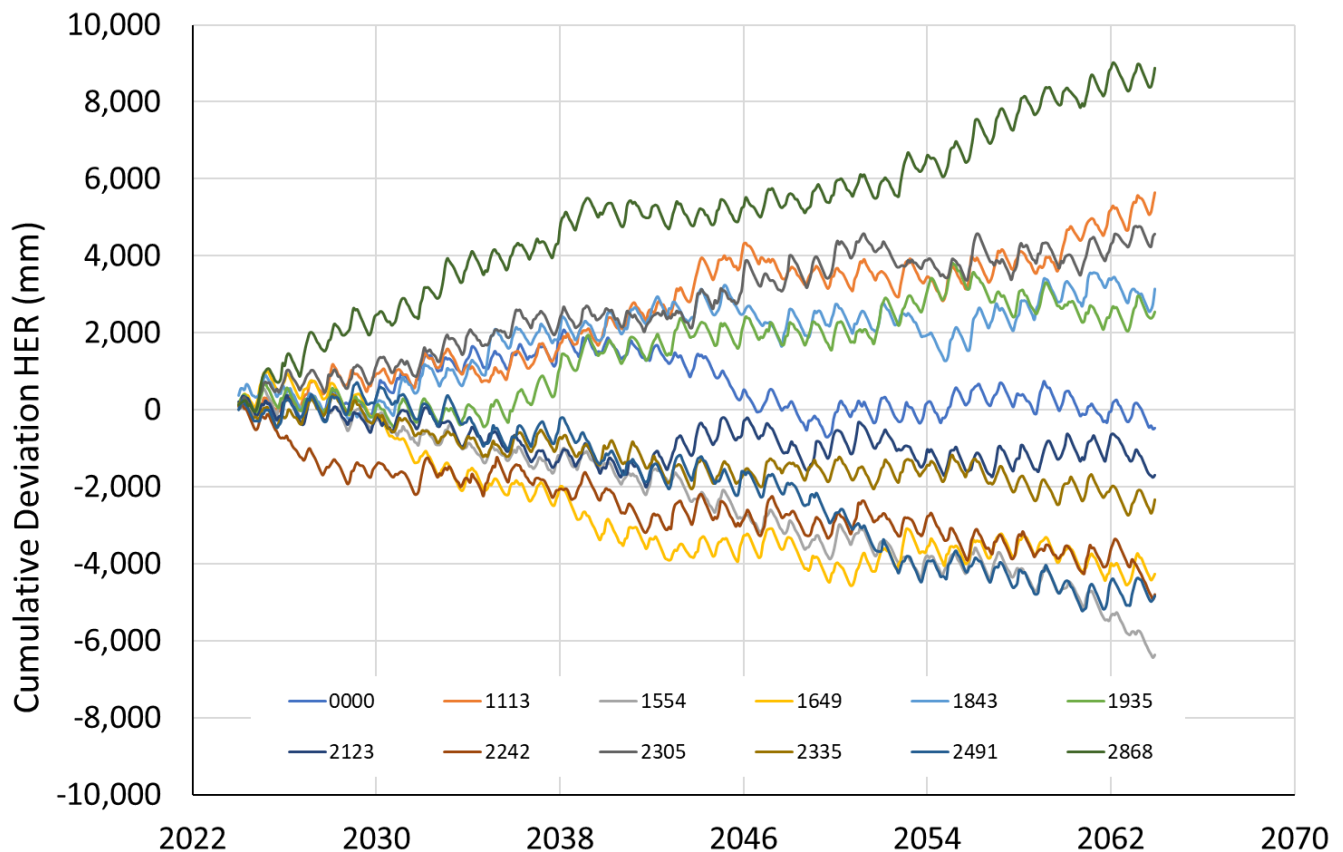
The pit lake water balance model described in Section 5.6 was used to investigate the potential future pit lake level range under a variety of climate change projections. These projections are taken from the UKCP18 (United Kingdom Climate Projections) ensemble (Met Office Hadley Centre, 2019). The following chapter describes how climate change projections for rainfall and PE were generated, provides a comparison against the historical rainfall and PE datasets and summarises important assumptions and limitations.

## UKCP18 regional projection ensemble

The recharge model uses all 12 members of the UKCP regional projections ensemble, which provide projections of daily rainfall and PEt for the period 1980 to 2080. These projections are based on the RCP8.5 (Representative Concentration Pathway 8.5) high emissions climate scenario, which represents a conservative projection of future climate (IPCC, 2019). This scenario is often used in climate research to explore the upper bounds of climate impacts without mitigation.

To facilitate comparison between these projections over the 2024-2064 simulation period, the UKCP rainfall and PEt data were converted to daily Hydrological Effective Rainfall (HER) values and an average HER per month was calculated across the ensemble. This was used to calculate cumulative deviation from the mean on a monthly basis for each projection, with the results shown in Figure 40.

Projection 2826 represents the wettest of the projections and 1554 the driest, although the relative positions of ensemble members vary over time, highlighting differences in the underlying assumptions on climate forcing mechanisms (Hannaford, et al., 2022). For example, 1554 is the driest projection from 2061 onwards, whilst 1649 is the driest from 2034 until 2052. 2491 is also one of the drier projections from 2052 until 2061. 2826 is consistently the wettest simulation.



*Figure 40 Cumulative deviation of HER from monthly mean of all UKCP projections (2024-2064)*

The x-axis represents the mean HER for each month, when averaged across all projections. Projections with an HER higher than the mean will show as an increase for that month (lower than the mean gives a reduction). At any point in time, projections are shown as the sum of monthly differences from the mean up to that point.

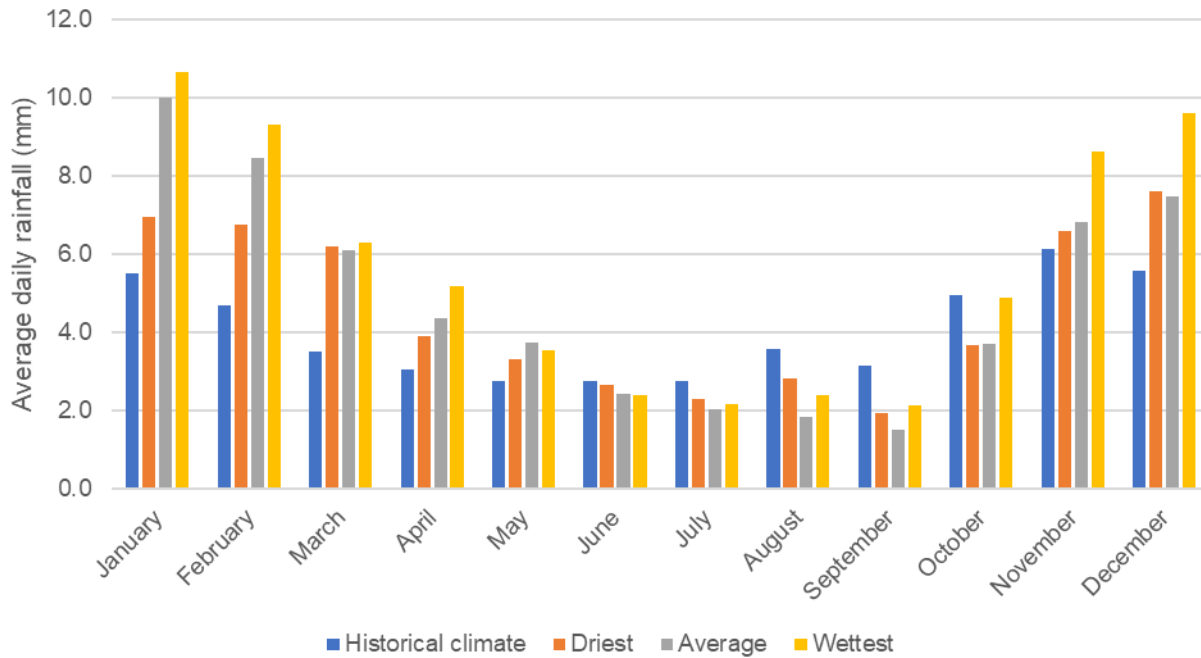
Three climate change timeseries were selected from the climate change modelling ensemble to reflect a range of conditions:

- Driest: Lowest cumulative hydrologically effective rainfall (precipitation – potential evapotranspiration). Projection 1554 was selected for this scenario.
- Average: Mid-range scenario with average cumulative hydrologically effective rainfall. Projection 1113 was selected for this scenario.
- Wettest: Scenario with the highest cumulative hydrological effective rainfall. Projection 2868 was selected for this scenario. Comparison against historical climate data

Daily average HER totals for the three selected climate change scenario timeseries (1554, 1113 and 2868) were compared against the HADUK rainfall and EA PEt datasets used in the model for an overlapping period of 1984 to 2024. This is presented in **Error! Reference source not found.** The average daily HER for the historical climate data is lower than all future climate projections, suggesting a bias in favour of a wetter climate. The additional rainfall in the climate change projections relative to the historical dataset generally occurs from November to May. Conversely, historical average rainfall is generally higher between June and September than in the climate change projections. These patterns are apparent in **Error! Reference source not found.**, which shows seasonal variation in average daily rainfall for both the historical dataset and climate change projections. Overall, the climate change projections suggest that the future climate in the site area will generally be wetter overall, but characterised by wetter winters, with more frequent and intense storm events, and drier summers.

*Table 11: Comparison between average daily HER for historical HADUK and EA PEt and future climate timeseries for the period 1984 to 2024*

| Climate dataset  | Average daily HER |
|------------------|-------------------|
| HADUK and EA PEt | 3.53              |
| Dry (RCM05)      | 3.61              |
| Average (RCM01)  | 3.93              |
| Wet (RCM15)      | 4.65              |



*Figure 41 Comparison of average daily rainfall for historical data and climate change projections*

## Assumptions and limitations

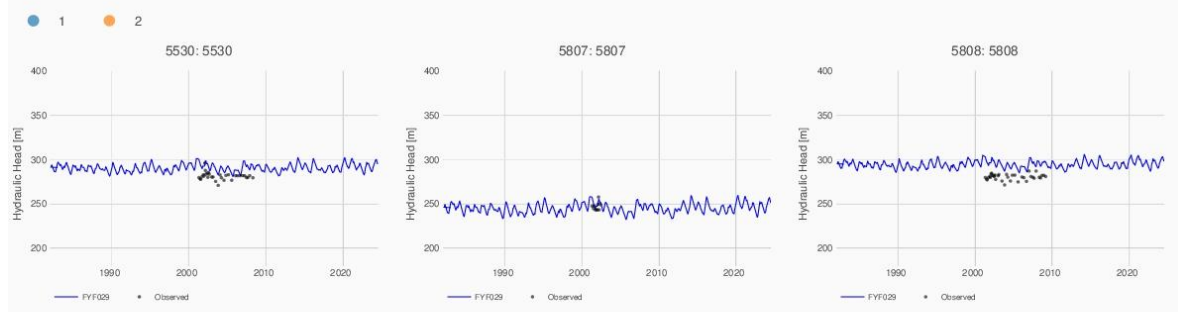
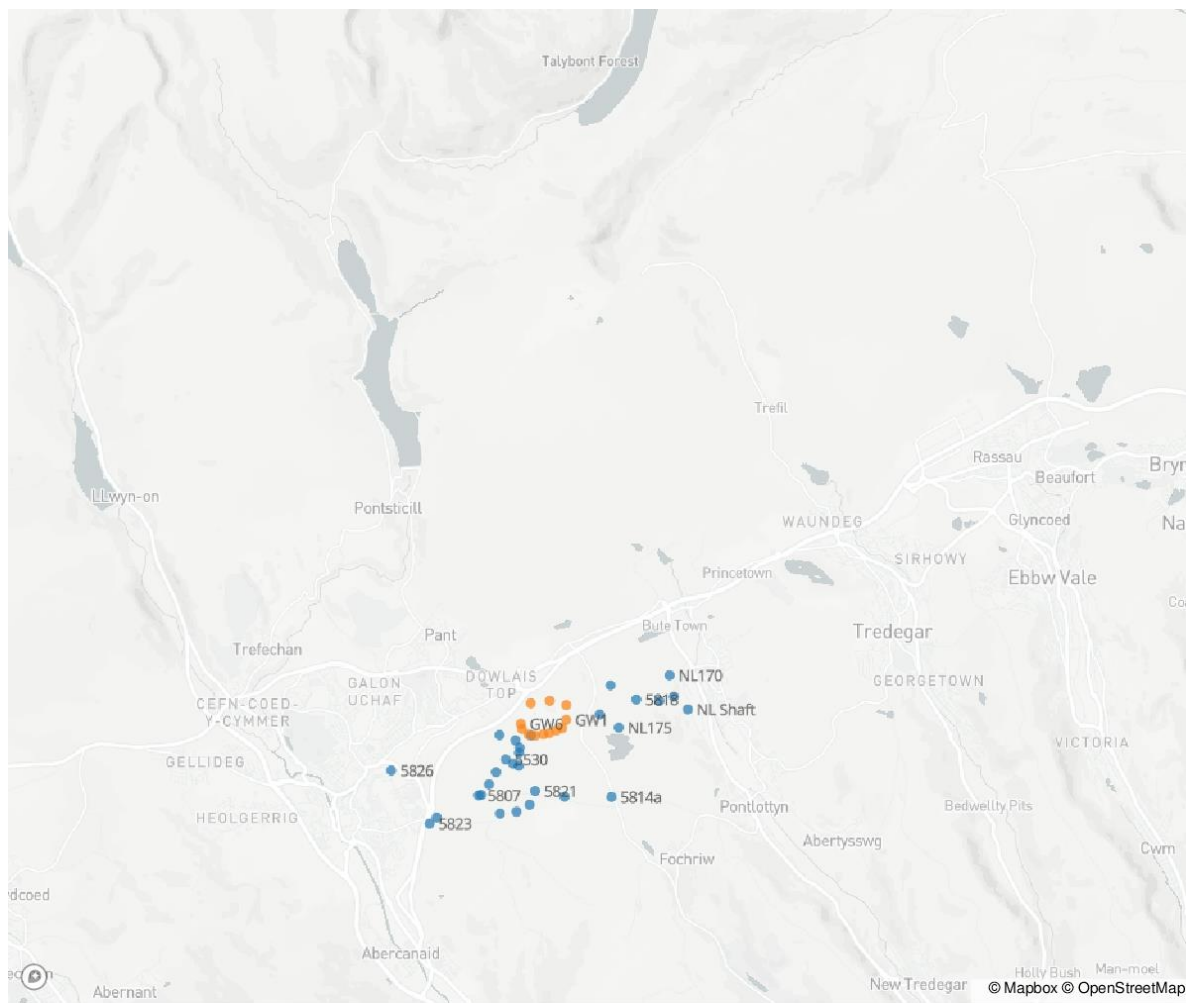
As with any model it is important to understand the assumptions that were made during model development and its limitations:

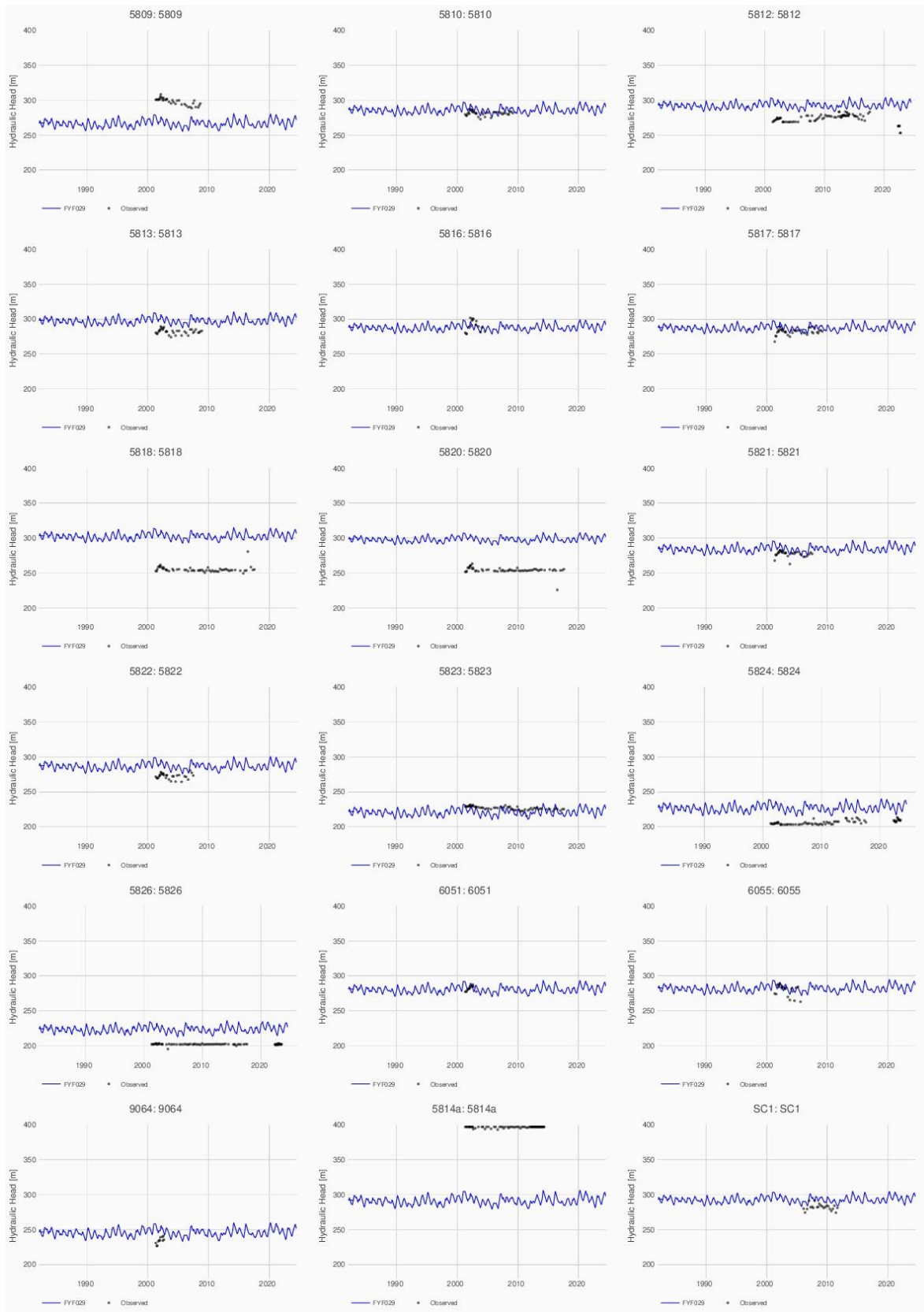
- The UKCP climate change projections are available as averaged daily rainfall for each month of the projection period (generally 1981 – 2080 although this does vary). However, this does not reflect the day-to-day variability inherent in the climate, such as short duration storm events, and is therefore unsuitable to be used directly in the pit lake water balance model. Instead, the monthly projections of rainfall were used to adjust the original HADUK rainfall and EA PEt datasets to generate modified climate change projections at a daily resolution, which also reflect longer-term trends in rainfall and evapotranspiration in the UKCP18 projections.
- The UKCP rainfall projections are mostly based on the CEH-GEAR rainfall historical dataset. This differs from the HadUK dataset as used in the groundwater and pit lake water

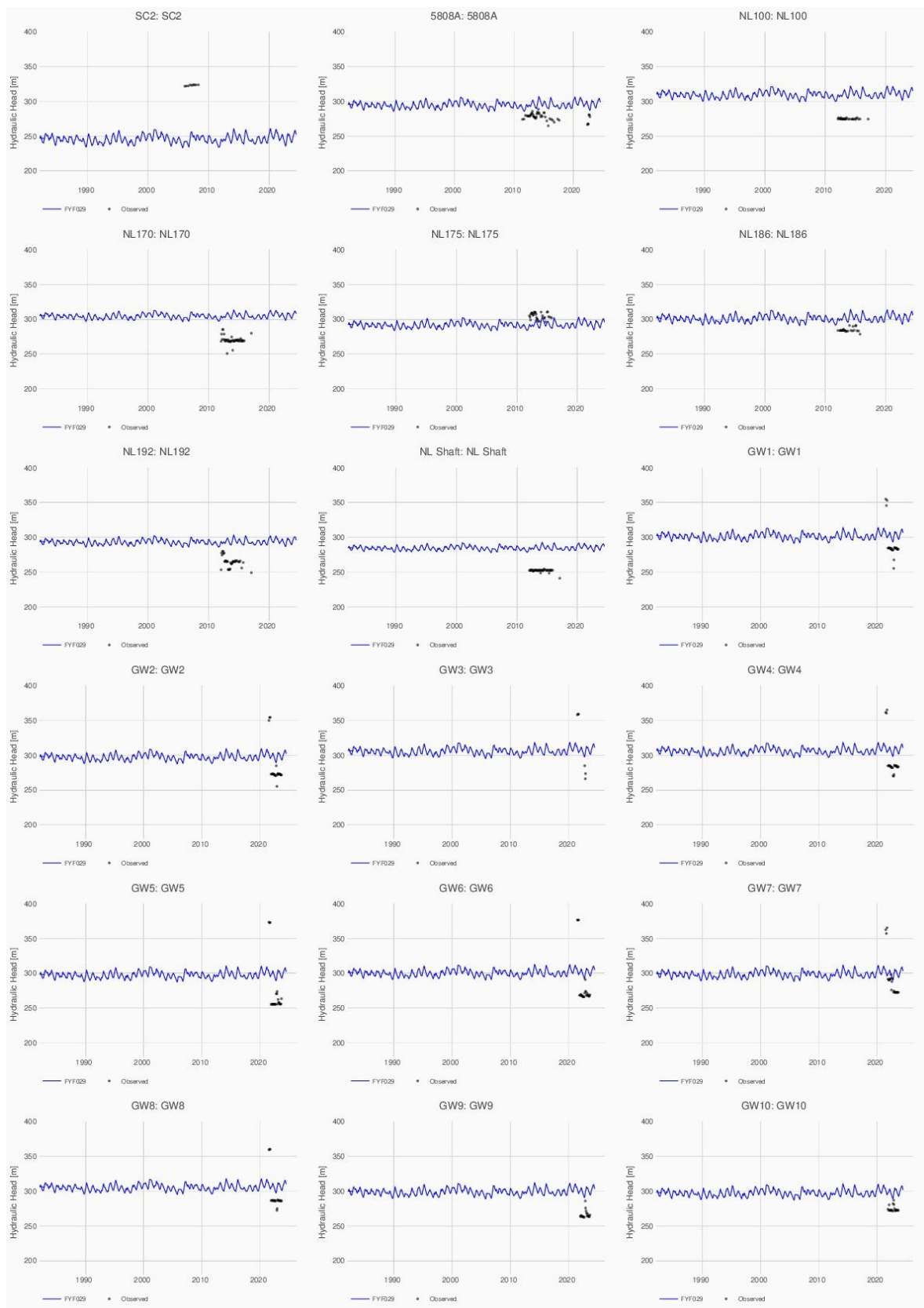
balance models and as such a bias in the projections may be present depending on the relationship between the CEH-GEAR and HaDUK datasets.

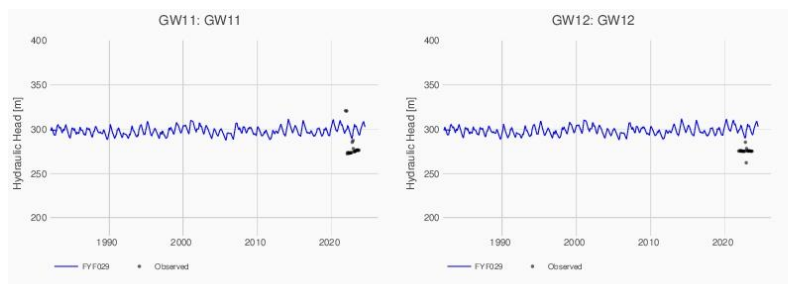
- For PE<sub>t</sub>, the UKCP18 projections are based on UKCP18 (United Kingdom Climate Projections 2018) projections of temperature, wind speed and relative humidity. Although the method used to develop the EA PE<sub>t</sub> dataset is not reported, it is likely that the UKCP18 dataset shows changes in PE from a different historical baseline. As such, a bias towards wetter or drier conditions in the climate change projections may exist depending on the relative difference between the UKCP18 baseline PE dataset and the EA PE<sub>t</sub> dataset.

## Appendix 2: Observed and simulated hydrographs

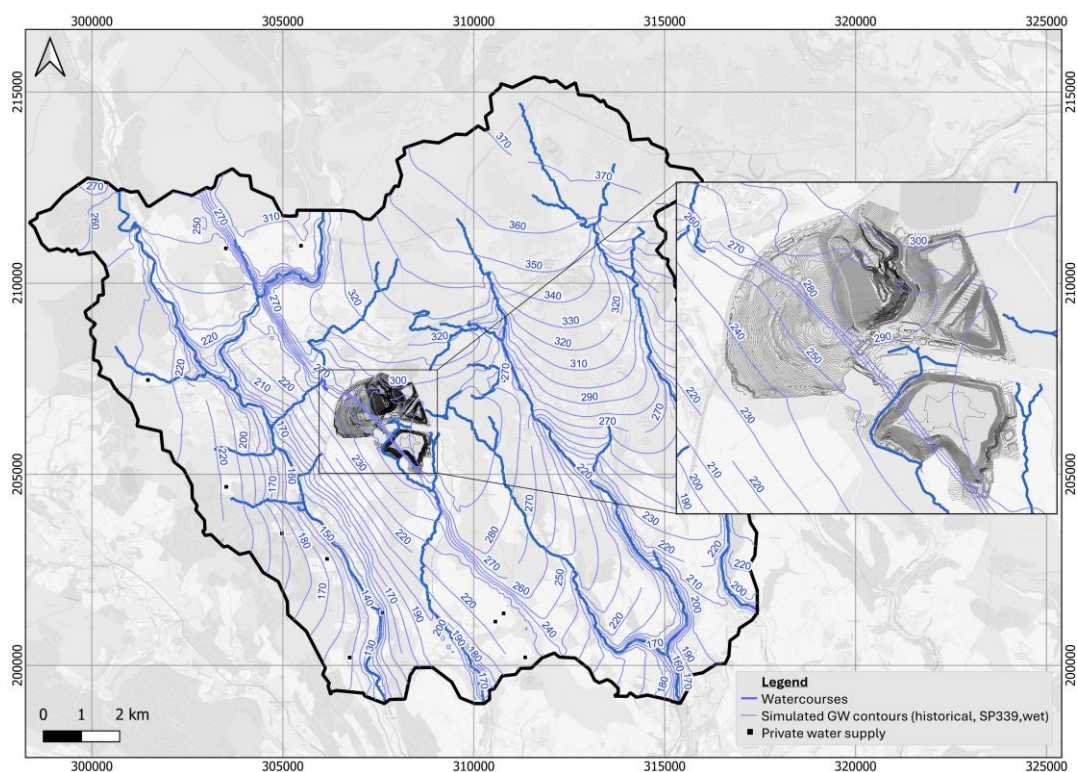




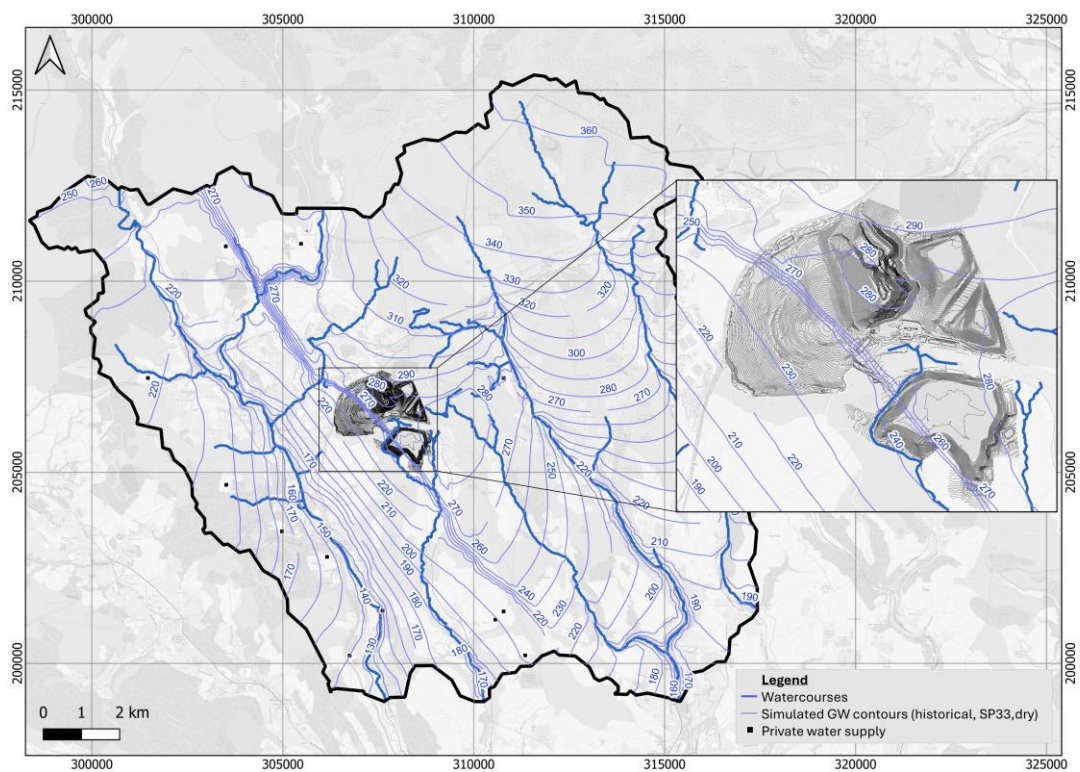




## Appendix 3: Historical spatial heads for wet and dry period



Wet period



Dry period

