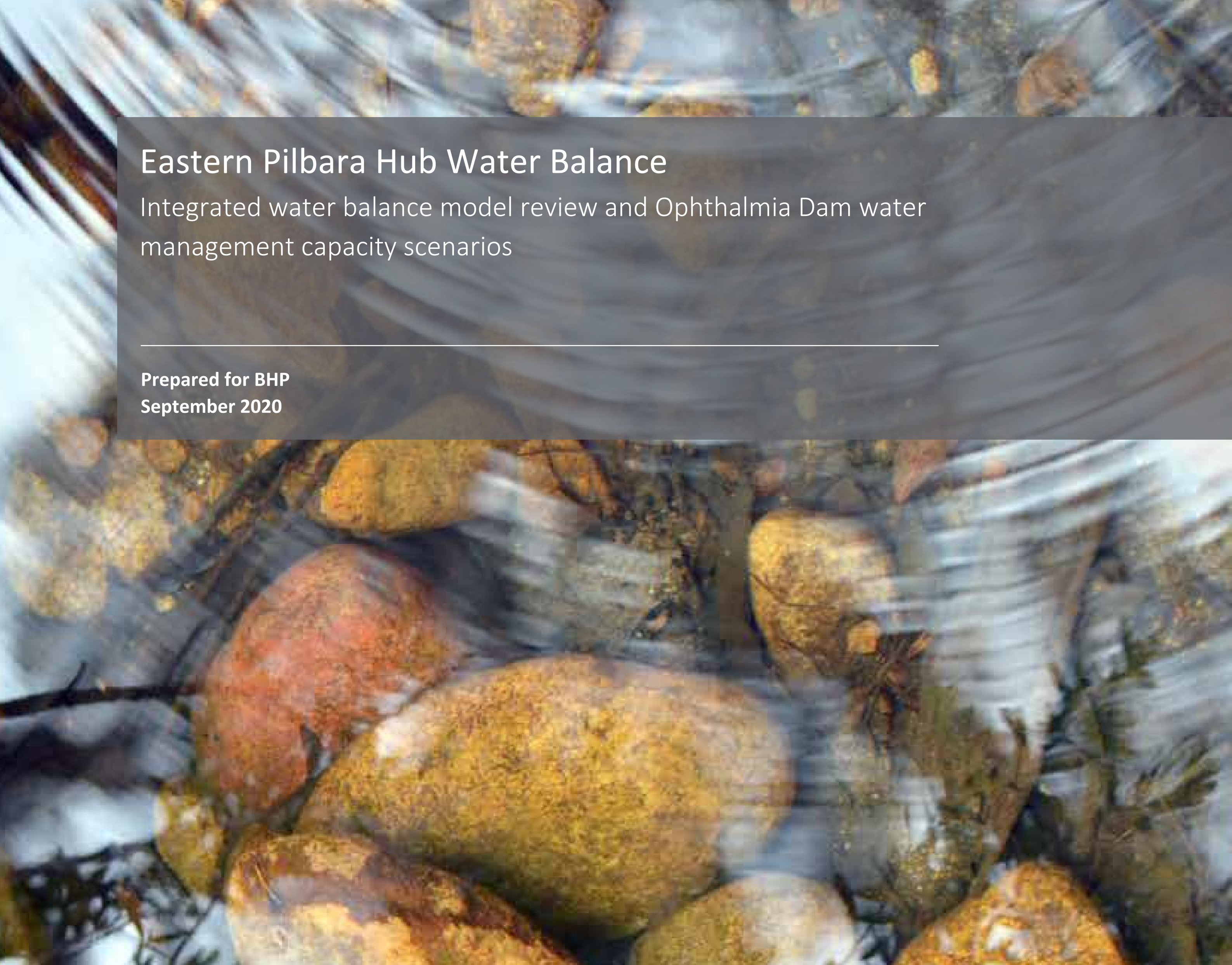

Eastern Pilbara Hub Water Balance

Integrated water balance model review and Ophthalmia Dam water management capacity scenarios

Prepared for BHP
September 2020

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Eastern Pilbara Hub Water Balance

Integrated water balance model review and Ophthalmia Dam water management capacity scenarios

Report Number

P200123 RP1

Client

BHP

Date

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Prepared by	**Approved by**
Steven Boxall Associate Hydrologist 16 September 2020	**Wade Dodson** Associate Hydrogeologist 16 September 2020

Executive Summary

EMM Consulting Pty Limited (EMM) was commissioned by BHP to undertake a water balance review and hydrological assessment of the Ophthalmia Dam and downstream shallow aquifer system to support the Eastern Pilbara Surplus Water Strategy.

The key purpose of the project is to provide an improved and up-to-date estimate of the potential water management capacity of Ophthalmia Dam and to assess the potential impact of different operating and mine water surplus discharge scenarios on hydrological and water quality conditions of Ophthalmia Dam and the downstream Ethel Gorge aquifer system. Predicted changes in the groundwater system are assessed against criteria set out in the BHP (2018) Eastern Pilbara Water Resource Management Plan (EPWRMP) and summarised in Section 5.3.1.

The two groundwater criteria (trigger levels) relevant to the scenario modelling assessments and defined in the EPWRMP are:

- Groundwater TDS concentration: trigger = 3,000 mg/L, threshold = 4,000 mg/L; and
- Groundwater level: trigger = change of >6.0 m or >4 m/y, threshold = >12 m or >8 m/y.

The water impact assessment represents a key requirement to support both the design capacity requirements for future surplus schemes and support a Part IV environmental approval for surplus discharge to Ophthalmia Dam from the OB32 East below water table mine and will inform peer reviews associated with surplus water infrastructure development projects.

The integrated GoldSim water balance model for the Ophthalmia Dam and Ethel Gorge aquifer system was developed for BHP by Golder Associates (2016, 2019) based on earlier assessments and conceptual model developments undertaken by RPS (2014a, 2014b). The model performance review and update process included updating and testing the model with input data up to early 2020 and also refining, where necessary, the model structure to more effectively represent and simulate natural and mine-related fluxes.

Key data and structural model updates undertaken in this performance review process included;

- correction of the location of recharge from the recharge ponds entering the groundwater component of the model;
- updating historic and recent groundwater abstraction information, particularly dewatering abstraction rates associated with OB23 adjacent to the Ethel Gorge palaeochannel, and
- updating the dam seepage estimation method to simulate predicted seepage losses and low dam storage conditions more effectively.

Through the review process the Goldsim water balance model has been shown to provide simulated dam water balance results that closely match historic Ophthalmia Dam water level and quality (TDS concentration) observations. Therefore, based on historic model performance, the modelling approach provides a higher level of confidence in the Ophthalmia Dam water balance predictions based on future surplus water discharge scenarios.

The groundwater component of the model representing the Ethel Gorge aquifer system downstream of the dam, has been shown to provide reasonable simulations of long-term observed groundwater level and salinity variability and trends. However, the modelling approach is acknowledged to have a number of limitations with respect to accuracy and reliability of groundwater balance simulations owing to the inherent spatial and temporal variability in groundwater levels and quality, in conjunction with model assumptions and numerical algorithms used to approximate (and simplify) the complex hydrological processes influencing the Ethel Gorge groundwater system.

Based on the model performance review, future surplus water discharge scenario model predictions and interpretation of model simulations for the groundwater system are recommended to be used to identify potential trends and the relative magnitude and/or direction of changes in groundwater conditions, rather than be considered accurate predictions of future groundwater conditions at a specific location.

Modelling scenarios undertaken to assess the theoretical management capacity of Ophthalmia Dam indicate that the potential maximum capacity of the dam to manage surplus water via infiltration, evaporation and controlled discharge, without overtopping of the Dam during the dry season, is approximately 115 ML/d (42 GL/a) without any controlled discharge and potentially up to 135 ML/d (49 GL/a) with a 3-month annual controlled discharge.

Three alternative surplus water discharge scenarios were run, with alternative dry, average and wet climate conditions, predicting discharge rates to Ophthalmia Dam and the associated recharge ponds over a projected 20-year period. The assessed alternative surplus water discharge scenarios include:

- Scenario 1: Continue recent surplus discharge rates (50 ML/d) over 20-year period (scenario defined as a conceptual ‘business-as-usual’ case);
- Scenario 2: Predicted surplus discharge from all existing pits with a maximum discharge rate of 85 ML/d over the 2022 to 2026 period; and
- Scenario 3: Predicted surplus discharge from all existing pits and OB32, with a maximum discharge rate of 145 ML/d over the 2022 to 2026 period, to assess incremental impact of OB32 surplus water contributions relative to Scenario 2.

The water balance model simulations of the Ophthalmia Dam storage conditions and groundwater level and salinity are estimated to remain within (ie below) the criteria specified within the EPWRMP (BHP, 2018) throughout the simulated 20-year model period and under varying hydrological scenarios.

The increasing suplus water discharge sceanrios are predicted to result in higher dam storage volumes, relative to historic or ‘business as usual’ case which is reflected as potentially more frequent and longer duration of active flows over the service spillway and a requirement to actively manage dam storage levels through controlled dry season water releases from the C wall valve each year.

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Table of Contents

Appendices

Tables

Figures

1 Introduction

1.1 Project objectives and approach

To support the Eastern Pilbara Surplus Water Strategy, BHP require an understanding of the capacity of Ophthalmia Dam with respect to accepting future mine water surplus discharge. An improved estimate of the sustainable water management capacity of Ophthalmia Dam represents a key requirement to support both the design capacity requirements for future surplus schemes and environmental approvals.

The *Eastern Pilbara Water Resource Management Plan* (EPWRMP) (BHP, 2018) contains criteria relating to groundwater salinity and groundwater levels within the Ethel Gorge aquifer system.

The key objective of this scope of work is to investigate the sustainable capacity of the Ophthalmia Dam under different operating scenarios (surplus discharge, climate, dam release), specifically:

- the capacity of the Dam to accept proposed volumes of surplus water without overtopping the spillway; and
- whether hydrological parameters in the Dam and Ethel Gorge aquifer system remain within the criteria set out in the EPWRMP.

Key outcomes of the work will:

- support a Part IV environmental approval for surplus discharge to Ophthalmia Dam from the OB32 East (OB32E) below water table mine; and
- inform peer reviews during the various phases of surplus water infrastructure development projects, and the Eastern Pilbara Surplus Water Management Plan.

The project approach comprises:

- updating the water balance model with operational data for the past 12 months (or more where available);
- updating model simulations and verification to assess and review model performance;
- defining, in conjunction with BHP, multiple surplus water discharge scenarios based on varying water inputs and key water balance factors, including alternative surplus water forecast scenarios, average, wet, dry climate sequences, dam operation and control rules; and
- running the scenarios, analysing the results and developing output summaries and visualisations.

1.2 Project background

1.2.1 Ophthalmia Dam

Ophthalmia Dam and the associated recharge facilities were designed and constructed to increase the sustainable yield and security of water supply for the Mt Whaleback iron ore mine and Newman township (estimated population of 6,000 people). Water supply for the mine and township were primarily sourced from production bores located in the unconfined alluvial aquifers of Ethel Gorge.

Construction of Ophthalmia Dam commenced in June 1981 and was completed in December 1981. This represented the starting point for an integrated water management scheme that involved the detention of flood waters, from the Fortescue River and Warrawandu and Whaleback Creeks, allowing the silt and sediment to be settled out before controlled release of impounded water to selected recharge sites located below the dam walls (Clark & Kneeshaw, 1983). The total upstream contributing catchment area is estimated to be 4,139 km^2 (Golder Associates, 2019). Dam overflow conveyed via dam spillways, detailed below, downstream to the Fortescue River through Ethel Gorge.

The dam consists of three main earth-core embankments (Wall A, B and C, refer to Figure 1.1). The embankments total approximately 3.4 kilometres (km) and two lesser auxiliary embankments of 3.2 km length (Clark & Kneeshaw, 1983). The dam has three spillways, as service, auxiliary and fuse plug, set at elevations presented in Table 1.1.

Table 1.1 Ophthalmia Dam spillway elevations (BHP, 2014)

Spillway	Elevation (m RL)	Storage Volume (GL)	Storage Area (km^2)
Base	509.0	0.04	0.15
Service	513.5	25.33	14.76
Auxiliary	515.5	67.60	28.21
Fuse Plug	516.3	92.40	34.05

Notes: m RL metres relative level
GL gigalitre

Although the main dam embankments and spillways extend for a significant distance across the Fortescue River valley, Ophthalmia Dam has a shallow maximum operational water storage depth, to the invert elevation of the service spillway (RL 513.5 m), of approximately 4.5 m (RPS, 2014a). The maximum operating storage capacity of the dam is estimated to be 25.33 gigalitres (GL) at the service spillway elevation covering a total impounded storage area of approximately 14.76 km^2 (refer to Table 1.1) (BHP, 2014).

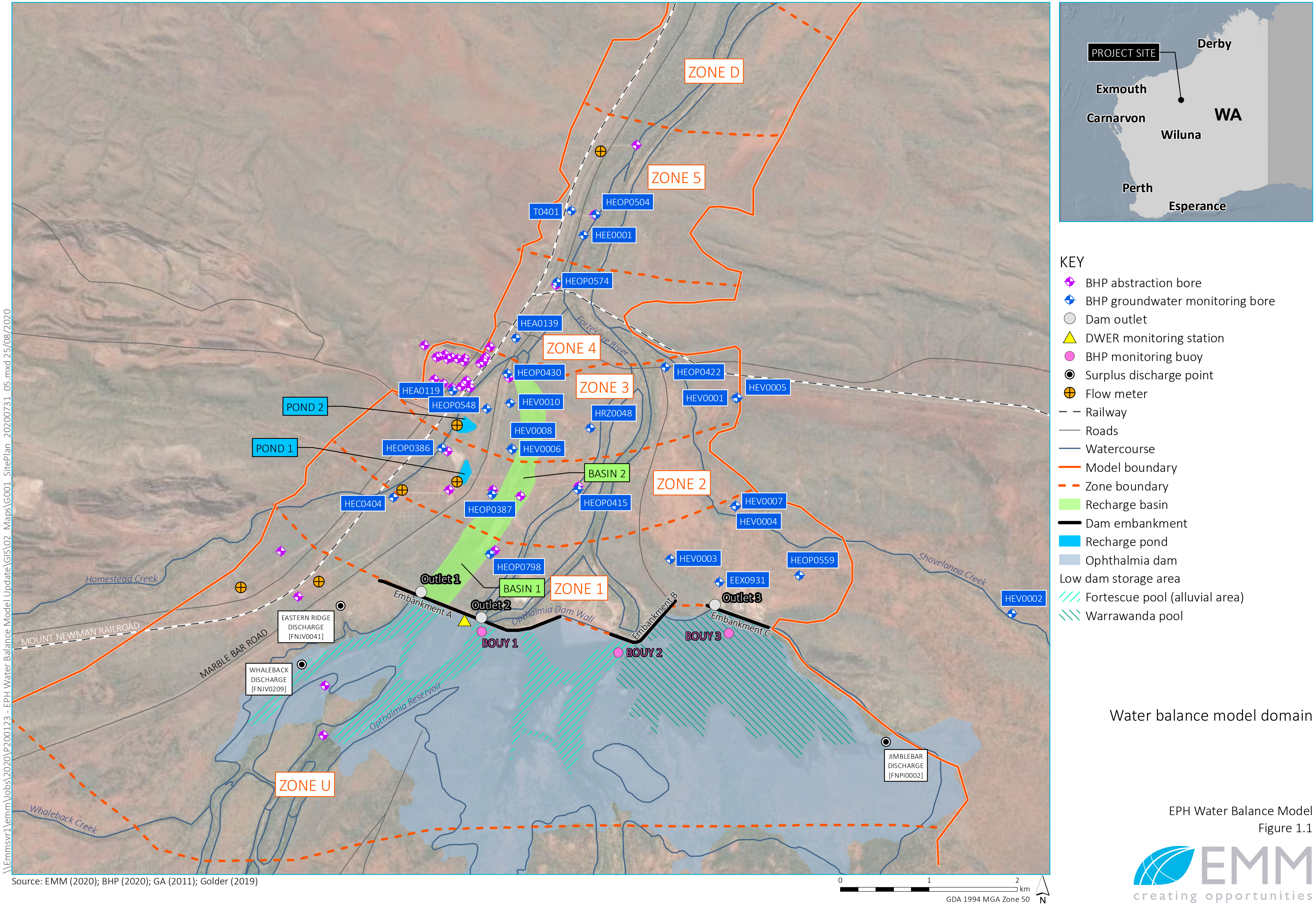
The design and proposed operation of the dam and associated recharge facilities was based on controlled releases from the dam, via gravity discharge, feeding directly to the two river recharge basins or to the four recharge ponds via an unlined canal (Clark & Kneeshaw, 1983). However, since completion of the dam, vertical seepage from Dam storage has largely been sufficient to maintain the downstream aquifers without the need to manually operate controlled releases from the dam to the recharge facilities. The recharge ponds have more recently been utilised independently of the dam to manage surplus mine water from the Eastern Ridge operations with measured flows provided from 2007 (refer to Section 3.5.2).

Ophthalmia Dam has three outlet valves providing controlled release options from the dam (Figure 1.1). Outlets 1 and 2 are located in Wall A and Outlet 3 in Wall C. It is understood that Outlet Valve 1 is not operational, Outlet Valve 2, when opened, directs water to recharge basins 1 and 2 and Outlet Valve 3 provides a release to Shovelanna Creek and into the downstream Fortescue River (BHP, 2019).

1.2.2 Ophthalmia Dam water balance modelling and related studies

Numerous studies of Ophthalmia Dam, and the downstream unconfined aquifer systems through Ethel Gorge, have been undertaken including, Clark & Kneeshaw (1983), Parsons Brinkerhoff (2013, 2015), RPS (2014a, 2014b) and Golder Associates (2016, 2019). These reports detail adopted modelling approach, concepts and provide input data, monitoring data, modelling assumptions and limitations.

The Goldsim model adopted for this assessment is the model developed as part of the Golder Associates (2019) study. This study was developed based on the water and salt balance concepts detailed in RPS (2014b). A brief summary of the modelling approach is provided in Section 2 of this report, the forementioned studies provide detailed references of the basis of the model structure, concepts and development process.



Water balance model domain

EPH Water Balance Model
Figure 1.1

Source: EMM (2020); BHP (2020); GA (2011); Golder (2019)

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2 Water balance structure and conceptual model

2.1 Overview

This section summarises the key components of the water balance model and the relevant conceptual models associated with the surface water and groundwater systems.

- Section 2.2 summarises the surface water system associated the Ophthalmia Dam water balance.
- Section 2.3 summarises the key features and processes associated with the Ethel Gorge groundwater system.
- Section 2.4 outlines the assumptions and limitations pertinent to the water balance model and the representation of the surface and groundwater systems.

2.2 Surface water system

A detailed characterisation of the Ophthalmia Dam water balance and the associated surface water systems is provided by RPS (2013). Ophthalmia Dam is located on the Fortescue River approximately 3 km upstream of Ethel Gorge. The dam forms the key element of the integrated water management system for the capture, controlled release, and recharge management of the downstream aquifer systems.

The key fluxes and stores associated with the Ophthalmia Dam water balance comprise:

- an upstream catchment of 4,140 km^2 with the Fortescue River and Warrawandu and Whaleback Creeks:
    - creek inflows to the dam are highly variable, both temporally and spatially, with significant catchment flow responses generally associated with seasonal, high magnitude and large-scale rainfall events such as those associated with tropical cyclones;
- a maximum operating storage capacity of the dam estimated to be 25.33 GL at the service spillway elevation (RL 513.5 m) covering a total impounded storage area of approximately 28 km^2:
    - the typical water storage regime consists of dam filling events dominantly during the wet season, although the dam does not fill every year, and rapid storage recessions during the dry season, due to seepage and evaporative losses. The dam usually reaches a near empty condition prior to the following wet season;
- evaporative losses, from open water evaporation and evapotranspiration, are significant given the shallow, but extensive nature of the impounded waterbody;
- seepage losses from the dam to the underlying and downstream groundwater system are significant;
- controlled releases from the dam to downstream recharge basins or Fortescue River via Shovelanna Creek;
- three spillways and the main service spillway discharging directly to the downstream Fortescue River; and
- over the more contemporary period, ie from 2010 onwards, surplus water from ore body dewatering has been discharged to the dam.

A schematic representation of the Ophthalmia dam water balance is presented in Figure 2.2.

2.3 Groundwater system

The Ethel Gorge groundwater system occurs in valley sediments bounded by low permeability basement rocks. The valley sediments infill a palaeodrainage feature comprising a palaeo-valley and channel. Parsons Brinkerhoff (2015) present a palaeo-surface map (after Tahal 1981) with the main palaeodrainage through the gorge concentrated on the western side, aligned with the modern flow path of Homestead Creek (Figure 2.1).

The valley sediments consist of a permeable alluvial aquifer comprising an upper unit of sandy-alluvium and calcrete (upper alluvial aquifer) and a lower unit of gravelly-alluvium (deep aquifer). The two units are separated by an extensive low permeability clay sequence (RPS 2014b). The deep aquifer and the low permeability clay are confined to the palaeo-channel morphology, whereas the upper alluvium extends across the palaeo-valley. In addition, the bed load of the modern drainages comprising Homestead and Shovelanna Creeks, which bypass Ophthalmia dam, and the Fortescue River and Warrawanda Creek downstream of the dam represent anastomosing, high permeable, high storage, unconsolidated gravel aquifers when saturated (Figure 2.1).

Ethel Gorge cuts across the east west trending basement rocks of the Hamersley Group. The different lithologies within the basement rocks have different resistance to weathering with resistant rock creating basement highs representing potential barriers to groundwater flow. Parsons Brinkerhoff (2015) provided a conceptual model of the basement highs and lows with potential impact on groundwater flow and salinity. They postulated that the basement highs represent potential barriers to groundwater flow, extending flow paths, raising groundwater levels with consequent higher evapotranspiration contributing to higher salinity associated with the eastern side of the gorge. It is also possible that the lower relief, lower topographic gradient, and smaller catchment area of Shovelanna Creek allow for greater evapo-concentration of salts relative to Homestead Creek.

The main features of the hydraulic conceptual model comprise:

- Ethel Gorge hydraulic gradient is from the south at ~510 to ~500 m Australian Height Datum (AHD) to the north where the gorge opens on to the Fortescue valley;
- depth to groundwater in the unconfined, upper alluvial aquifer ranging between 0 and 10 m below ground level (bgl);
- the deep aquifer is confined by the overlying clay and subject to hydraulic loading from Ophthalmia Dam where the underlying head in the deep aquifer is higher than the upper alluvial aquifer;
- surface water flow is a greater contributing factor to groundwater recharge than distributed rainfall (Parsons Brinkerhoff 2015); and
- groundwater is discharged via groundwater throughflow northward to Fortescue valley and via transpiration from riparian vegetation, and evaporation from disconnected surface pools.

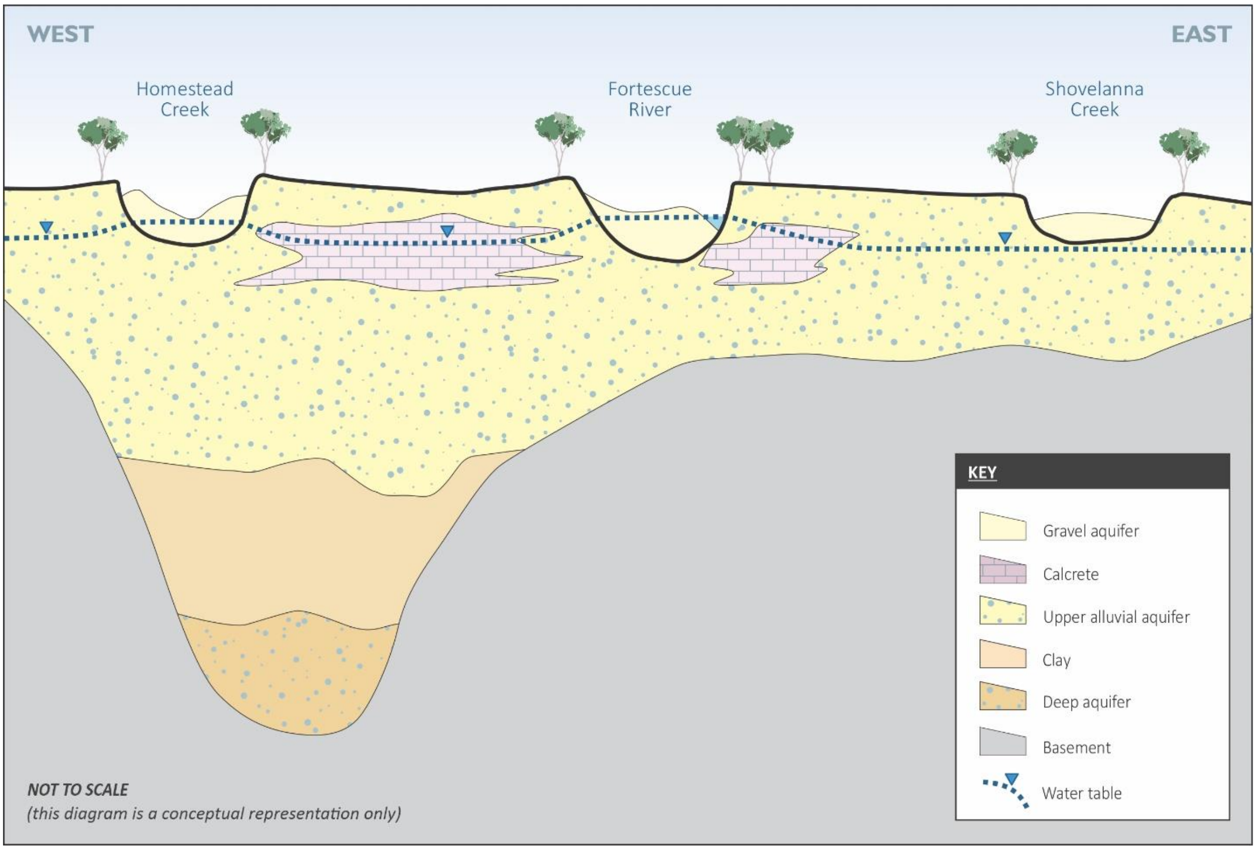


Figure 2.1 Ethel Gorge conceptual cross section

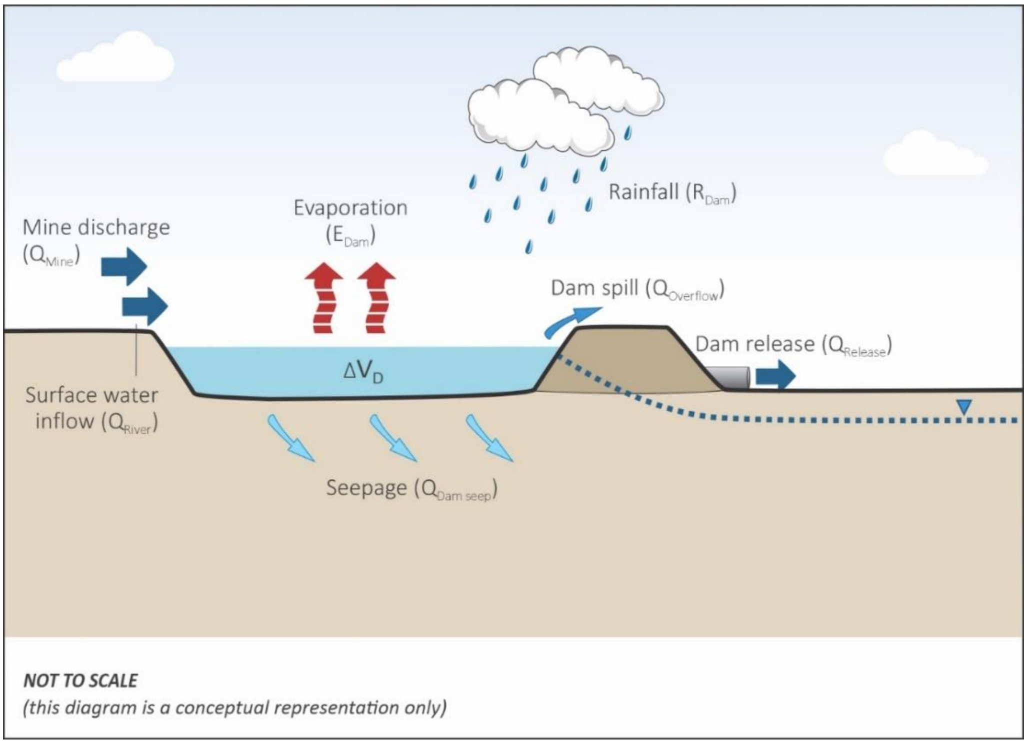
An Ethel Gorge annual quasi-steady state water balance (ie no change in storage) was estimated by RPS (2014b). They estimated the inflow components to comprise dam seepage at 50 ML/d, surface water recharge ~24 ML/d and diffuse rainfall recharge at ~2 ML/d. The outflow component of the balance comprised groundwater throughflow, given by a chloride mass balance indicating ~2 ML/d, groundwater abstraction for town water supply of 10.3 ML/d and evapotranspiration as the remaining balance at ~64 ML/d.

PB (2015) undertook a detailed balance of dam level and discharges with the measured salinity in the recharge basins and recharge ponds in the year 2000. The total change in storage in the dam over 85 days was in the order of 10.9 GL. Depending on the pan factor applied (1 to 0.54) between 5.4 to 8.0 GL of water was lost to dam seepage. This equates to annualised loss rates of between 23.2 and 34.3 GL/a (63.5 and 94.1 ML/d).

The numerical representation of the groundwater balance within Goldsim is documented in Golder (2019). There are three integrated components to the Goldsim water balance comprising:

- Ophthalmia dam water balance (Figure 2.2);
- unsaturated zone balance (includes evaporative loss) (Figure 2.3); and
- groundwater water balance (Figure 2.4).

The groundwater balance has contributions from both the Ophthalmia dam water balance and the unsaturated zone balance. Contribution to the groundwater balance from the unsaturated zone balance is predicated on a fixed total void volume within the unsaturated zone.



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(this diagram is a conceptual representation only)

Figure 2.2 Ophthalmia Dam water balance

$$\Delta VD = (Q_{River} + Q_{Mine} + R_{Dam}) - (E_{Dam} + Q_{Dam\ Seep} + Q_{Overflow} + Q_{Release})$$

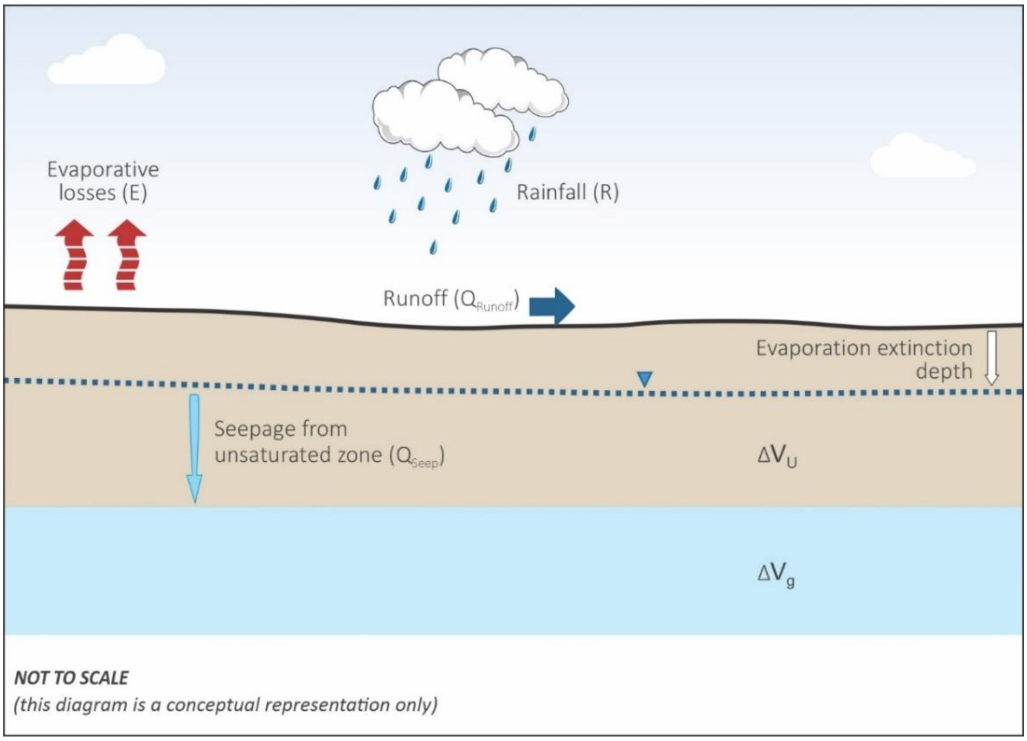

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Figure 2.3 Unsaturated zone water balance

$$\Delta VU = (R - Q_{Runoff}) - (Q_{Seep} + E)$$

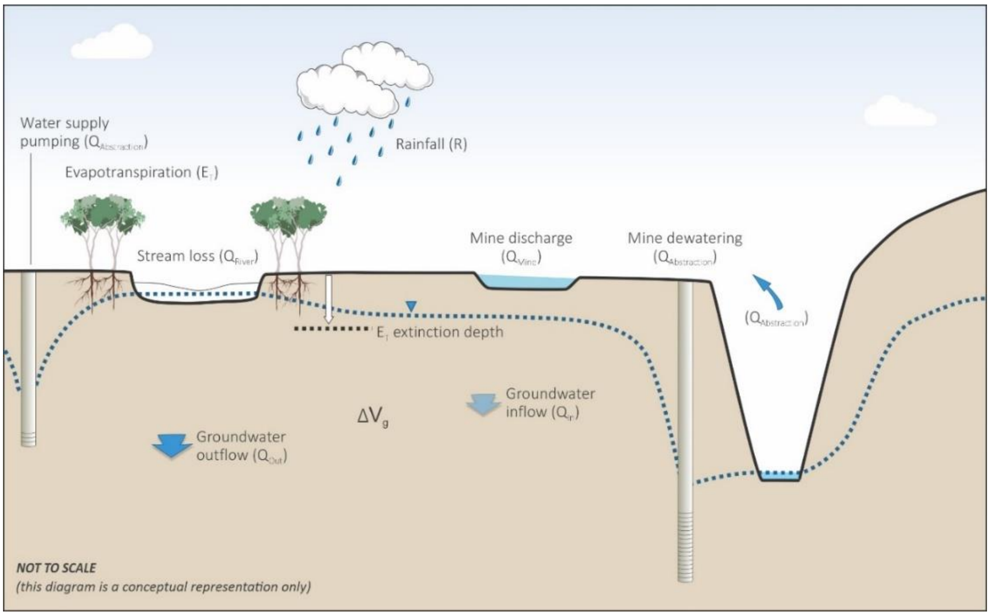


Figure 2.4 Groundwater water balance

$$\Delta VG = (Q_{In} + Q_{Seep} + Q_{Dam\ Seep} + Q_{River} + Q_{Mine}) - (Q_{Abstraction} + Q_{Out} + E_T)$$

2.4 Model assumptions and limitations

The pertinent assumptions and limitations of the Goldsim model are:

- the model is discretised into a strip across the width of each zone for the entire gorge, with predicted water levels representing the average of the stored volume within each east west strip. Similarly, predicted TDS represent the average across the east west zone strip, whereas spatial variability is apparent;
- the groundwater balance is represented with the one bulk parameter value for hydraulic conductivity and specific yield to approximate all three aquifers;
- the spatial discretisation of the model excludes the ability to represent the variations in TDS documented across the surface water catchment areas within each discrete zone, ie western groundwater quality versus eastern groundwater quality;
- the model only allows for seepage from rivers to groundwater, ie when the upper alluvium aquifer is full groundwater cannot discharge to surface pools or flow to the rivers. This is likely rare in the natural setting, but the system could become a gaining stream if dam levels remain high due to mine discharge;
- the algorithms used to represent the unsaturated zone water balance have a fixed total volume for each area of a sub zone within the zones, whereas the total volume should flex to represent rise and falls in groundwater levels which would likely buffer predicted TDS after long dry periods; and
- the topographic level is averaged across each model strip.

That is the model represents a ‘response prediction’ or ‘thinking’ model as opposed to a model that can be ‘accurately’ history matched to groundwater levels or TDS. As such the results from the model should be used to identify trends and/or the potential magnitude of change in key parameters of water level and TDS rather than absolute values as the spatial variability within a zone cannot be represented.

3 Model updates

3.1 Overview

This section summarises the model input that has been collated and reviewed prior to the water balance model performance review phase of the study (refer Section 4). The key model input information summarised include:

- climate and hydrological data;
- Ophthalmia Dam storage and water quality (TDS/EC) monitoring;
- groundwater system monitoring of water levels and TDS/EC;
- groundwater abstractions (water supply and dewatering related); and
- mine surplus water disposal rates to Ophthalmia Dam and recharge ponds.

3.2 Climate

Daily rainfall and evaporation data have been downloaded from the SILO database (Queensland DES 2020) for the period up to June 2020. These data have been collated for the same data drill location (Lat -31.30, Long 119.40) used in previous modelling assessments (Golder Associates 2016, 2019).

Monthly rainfall and Class A pan evaporation for the period 1979 to June 2010 are presented in Figure 3.1, highlighting the highly seasonal nature of rainfall and evaporative loss rates across the study area. Rainfall (and streamflow responses for the Ophthalmia Dam catchment – refer to Section 3.3) are dominated by wet season contributions, particularly for the period from December to March, which, on average, account for approximately 65% of annual rainfall. Mean monthly evaporation exceeds mean monthly rainfall for all months, by an order of magnitude over the summer months.

A summary of annual rainfall for the study area is presented in Figure 3.2 for the period 1980 to 2020. The rainfall data are summarised for September to August water years, consistent with the monthly rainfall distributions presented in Figure 3.1. Average annual rainfall for the 41-year period is 319 mm and ranges from a minimum of 121 mm (1993-94) to a maximum of 669 mm (1999-2000). As shown in the annual rainfall summary, and across the wider Pilbara Region, there is a large year-to-year rainfall variation (ie high inter-annual variability), which, combined with consistently high potential evaporation, results in significant hydrological variability (intra- and inter-annually) and large annual water deficits (Charles, et al., 2015). It is noted also that Charles et al. (2015) highlights the spatial heterogeneity of rainfall and climate with longitudinal, latitudinal, and coastal to inland contrasts, influenced by the complex topography of the Hamersley Ranges.

Tropical cyclones are a major source of large-scale rainfall across the Fortescue River catchment, although there are also many localised flooding events across the Pilbara Region that are not necessarily directly linked with tropical cyclones, ie approximately 50 % of significant catchment flood events (Rouillard, et al., 2014).

The period from 2018 through to January 2020 has been very dry, with below average monthly and annual rainfall (Figure 3.1 and Figure 3.2). Total annual rainfall measured for 2018-19 (122 mm) is 1 mm higher than the lowest annual rainfall (in 1993-94) over the past 41 years. The hydrological influence of this dry period, broken by significant rainfall across the region associated with tropical cyclone Blake, approximately 140 mm record on 9 January 2020, is clearly reflected in the streamflow records (Section 3.3) and the low water storage conditions of Ophthalmia Dam during this period (Section 3.4).

As highlighted in Section 4.2 below, the extremely low rainfall and absence of significant catchment flow response experienced in the 2018 to early 2020 period, combined with relatively high rates of mine water surplus discharges to Ophthalmia Dam, means that this period represents a relatively unique period for the review and assessment of the water balance model performance both in terms of water quantity and the TDS (mass) balance.

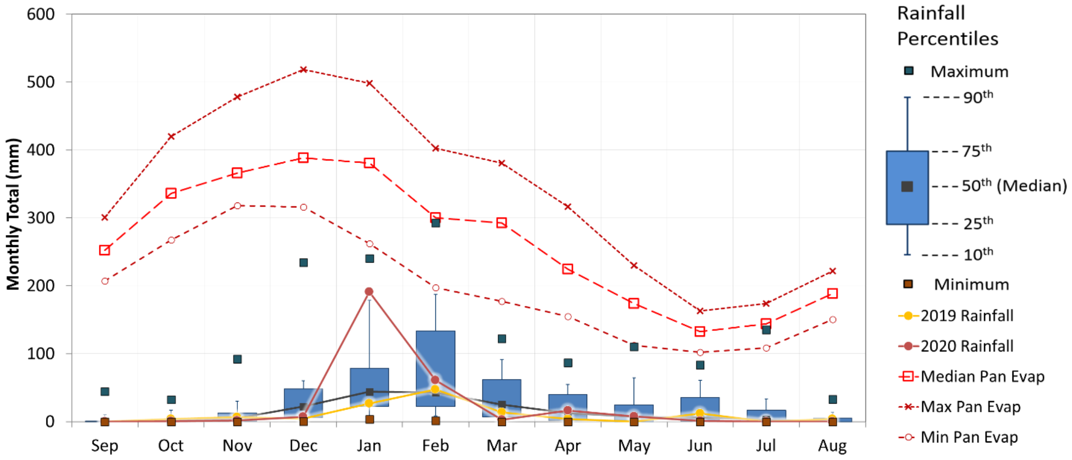


Figure 3.1 Monthly rainfall and evaporation statistics for period September 1979 to June 2020

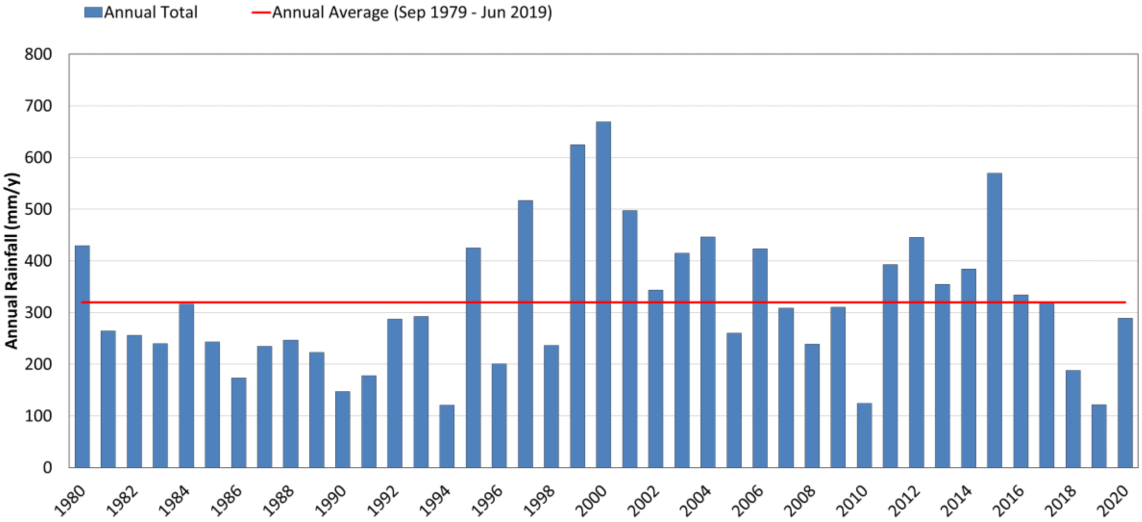


Figure 3.2 Annual and mean annual rainfall (September to August water year)

3.3 Creek inflows

The total contributing catchment area for Ophthalmia Dam is estimated to be 4,320 km^2 (Golder, 2019). Only the Fortescue River has a long-term gauged record (Newman) providing reliable estimates of potential catchment inflows to Ophthalmia Dam. The Golder (2019) water balance updates included gauged daily flows for the Fortescue River at Newman for the period up to September 2018.

Updated daily flows have been collated for the gauged record up to the end of March 2020 (Figure 3.3). These plots highlight the influence of the dry period on the hydrological response for the period since the end of the 2016-17 wet season. The 2017-18 wet season generated limited flows in the Ophthalmia Dam catchment and almost no flow response was recorded for the 2018-19 wet season resulting in only a very partial refilling of Ophthalmia Dam.

Only 51 ML of total flow was recorded for the year and this was limited to the three-day period from 15 to 17 February 2019. The catchment response to tropical cyclone Blake resulted in 20,590 ML/d recorded on 9 January 2020, sufficient to fill the dam from approximately 5% storage capacity to above the spillway capacity (25.33 GL refer to Table 1.1) by 10 January 2020.

Extremely dry hydrological years are observed across the historical record, particularly over the dryer, 1981 to 1994 period and the years of 1995-96, 1997-98, 2004-05 and 2006-08. The gauged flow record for the Fortescue River at Newman, as shown in detail for recent years in Figure 3.3 and total annual streamflow volumes in Figure 3.4, clearly reflects the significant hydrological variability, both through high intra- and inter-annually flow variability, driven by the high level of temporal and spatial rainfall variability, both locally and regionally, as detailed in Charles et al. (2015).

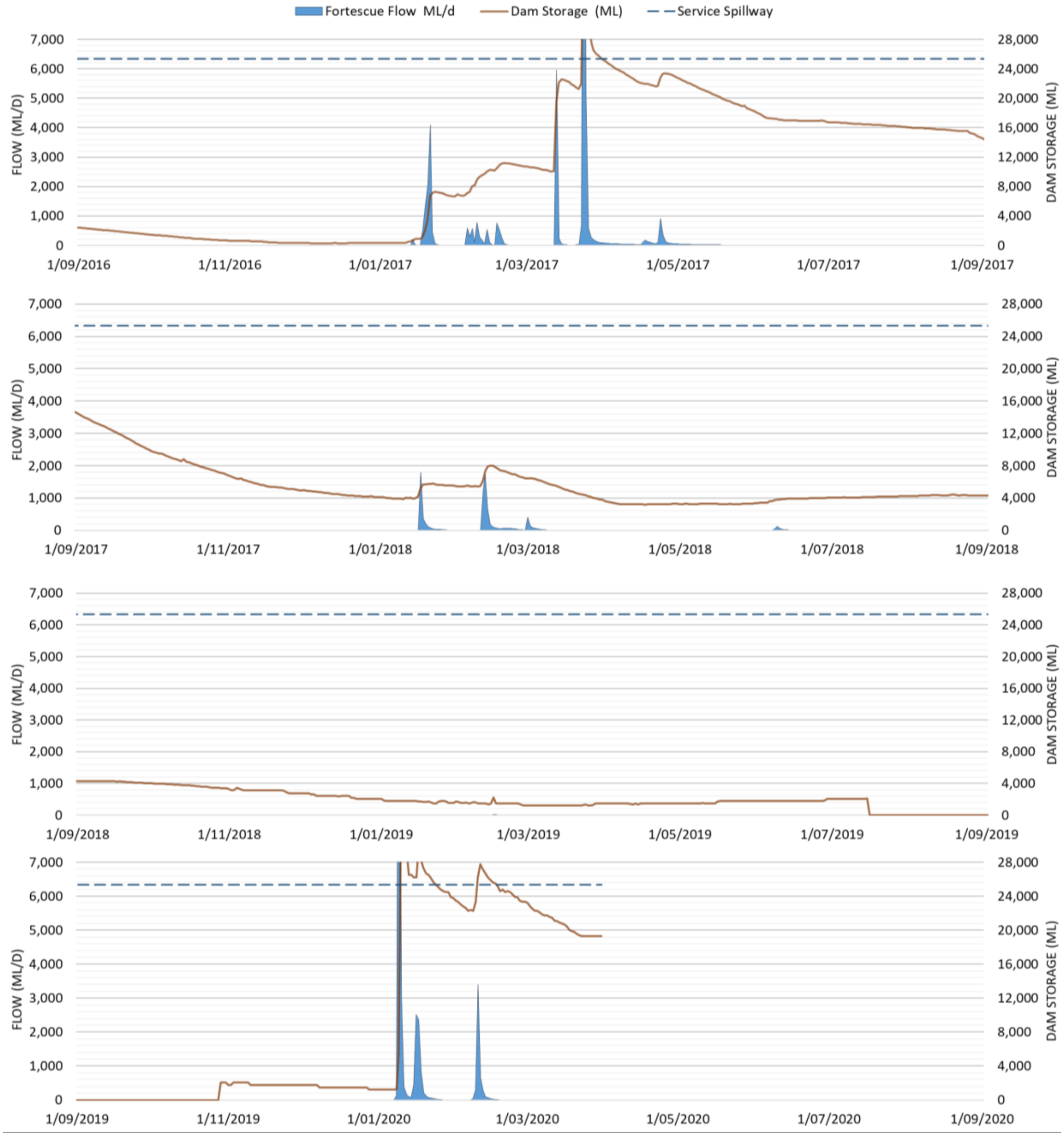


Figure 3.3 Gauged daily streamflow for Fortescue River at Newman and measured Dam storage volume

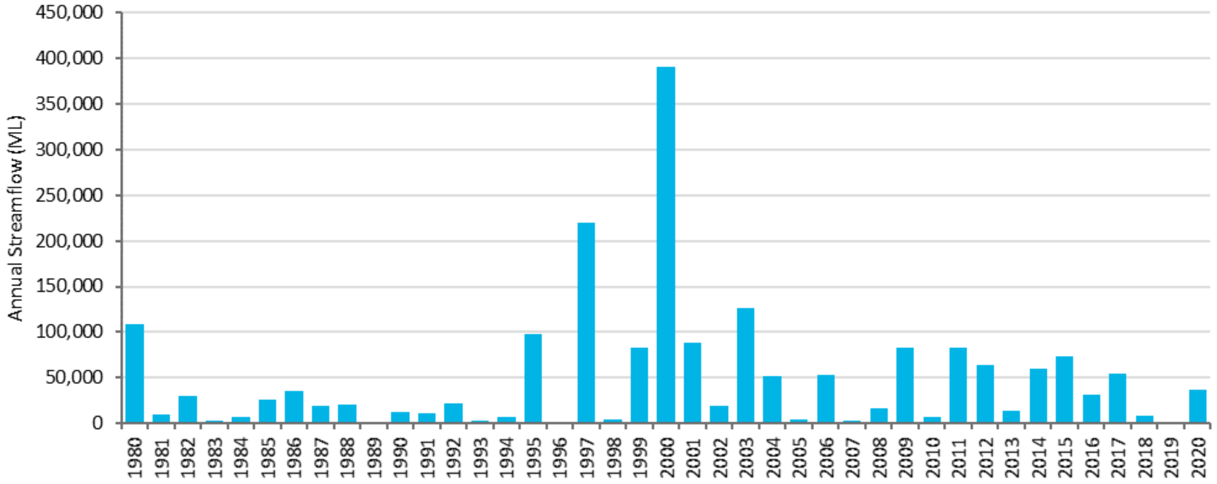


Figure 3.4 Annual gauged streamflow for Fortescue River at Newman

3.4 Ophthalmia Dam storage and salinity

3.4.1 Dam storage

Daily water level monitoring data for Ophthalmia Dam have been provided by BHP and include data for the period 26 June 2017 to 15 July 2019 and hourly measurements for the period from 29 October 2019 to the end of March 2020. Monitoring is for Buoy 1 located in the Fortescue Pool adjacent to Embankment A and close to the DWER monitoring station (708012) shown in Figure 1.1.

There are no water level measurements available for the period 16 July 2019 to 29 October 2019 (shown as zero storage volumes in Figure 3.3). Measured Ophthalmia Dam water levels are converted directly to storage volumes, as shown in Figure 3.3, based on the BHP (2014) derived Ophthalmia Dam stage- area- volume relationship.

3.4.2 Dam operation and controlled releases

No controlled releases are understood to have occurred in the period since the Golder (2019) water balance update up to the end of the available dam water level measurements (end of March 2020). This includes no controlled releases from following two operational outlet valves:

- Outlet Valve 2: Located in Wall A and used to fill recharge basins 1 and 2; and
- Outlet Valve 3: Located in Wall C and releases water to Shovelanna Creek and the Fortescue River.

Outlet 1, located in Wall A, is not operational and is believed to be unable to be physically opened due to lack of use (BHP, 2019).

The last recorded releases in the water balance modelling period occurred from the dam, through the C Wall valve occurred between 9 February 2018 and 5 April 2018. As shown in Figure 3.3 the low water storage volume of Ophthalmia Dam and absence of dam filling over the 2018-19 and 2019-20 periods appears to have negated the requirement for controlled releases from the dam. It is noted that, a controlled dam release from Outlet Valve 3 (Wall C) has occurred in early 2020, following the dam filling event associated with tropical cyclone Blake (refer to Figure 3.3), however, this occurred in the period after the water balance update data period and is therefore not considered in the modelling exercise.

3.4.3 Dam salinity

Historically the measurements of Ophthalmia Dam salinity (TDS) are only available for limited and discrete periods (Golder 2019). For this model update period electrical conductivity (EC) measurements have been provided by BHP for the three buoy monitoring locations in Ophthalmia dam covering the following periods:

- Buoy 1: 26 June 2019 to 8 October 2019;
- Buoy 2: 1 November 2017 to 8 October 2019; and
- Buoy 3: 9 November 2017 to 8 October 2019.

These data have been converted from EC (mS/cm) to estimates of TDS (mg/L) based on a conversion factor:

TDS (mg/L) = 670 x EC (mS/cm)

Historic salinity measurements for Ophthalmia Dam are presented in Figure 3.5 for the period January 2013 to January 2020. This plot highlights the gaps in the available monitoring record. The comparison to measured storage volumes (based on measured dam water level) highlights a key relationship between Ophthalmia Dam storage and salinity. Dam salinity increases, largely driven by evapo-concentration effects, as the dam storage is reduced over the dry season. Freshening wet season inflows to the dam result in rapid reductions in dam salinity.

PB (2015) reported that Ophthalmia Dam salinity (TDS) was between 20 and 500 milligrams per litre (mg/L) between 1982 and 2015. Typically, the dam salinity is less than 50 mg/L TDS shortly after filling, however it was acknowledged that the variability in antecedent conditions (ie dam storage and TDS, mine discharge) can impact dam water quality post surface flow events (PB, 2015).

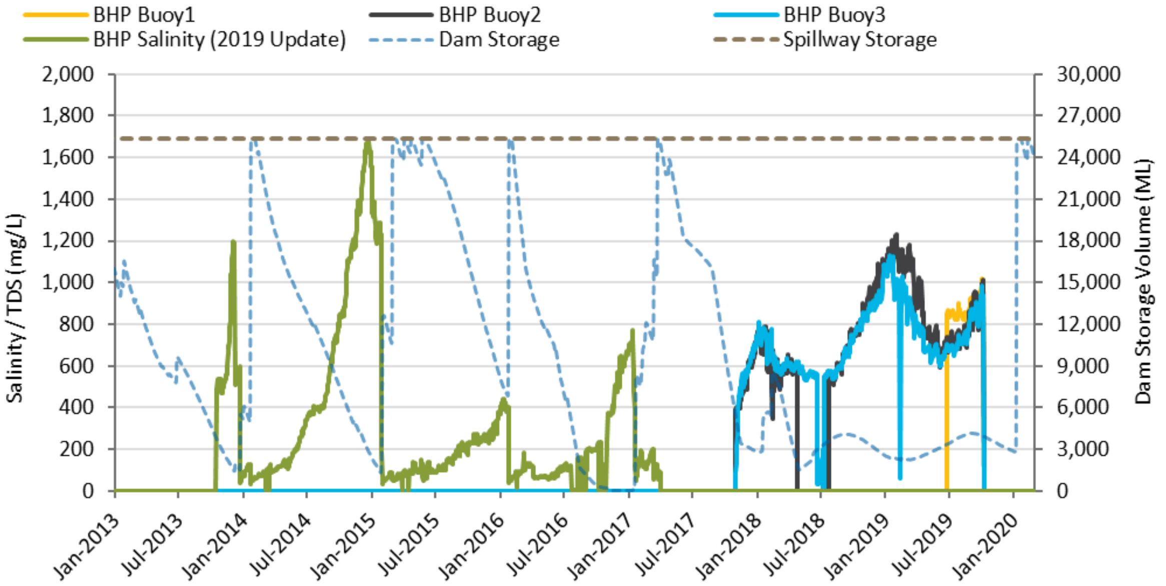


Figure 3.5 Monitoring record of Ophthalmia Dam salinity and storage volume (2013 to 2020)

3.5 Mine water discharge inflows

Surplus mine water from BHP operations are currently discharged via two options:

- direct discharge to Recharge Ponds 1 and 2, approximately 1.5 km downstream of Wall A; or
- direct discharge to Ophthalmia Dam, at one of three locations, upstream of the dam embankments.

The Recharge Ponds and Ophthalmia Dam discharge locations are shown in Figure 1.1.

3.5.1 Discharge to Ophthalmia Dam

Information on mine water discharge direct to Ophthalmia Dam has been derived from monthly meter readings for the three discharge locations (refer Figure 1.1 and Table 3.1). Monthly metered data are available at all three meter points to the end of January 2020 (Figure 3.6).

The Eastern Ridge discharge to Ophthalmia Dam (meter FNJV0041) has been operating since late 2006 with peak daily discharge rates of between 20 to 30 ML/d occurring during mid-2010 and subsequently during 2011 and 2012 (Golder, 2019). Additional contributions to total mine water discharge to the dam have occurred from Whaleback (meter FNJV0209) and Jimblebar (meter FNPI0002) mine hubs. The highest discharge rates are sourced from Jimblebar and range up to 38 ML/d since early 2018.

Total mine water discharge rates have been consistently above 40 ML/d since mid-2017 and up to a peak rate of 58 ML/d in August 2018.

Table 3.1 Ophthalmia Dam mine water discharge locations

Meter number	Description	Mine hub source
FNJV0041	TPS to Ophthalmia Dam (EDG01)	Eastern Ridge
FNJV0209	Tank Corner B to Ophthalmia Dam	Whaleback
FNPI0002	Ophthalmia Dam (OB31 Pipeline)	Jimblebar

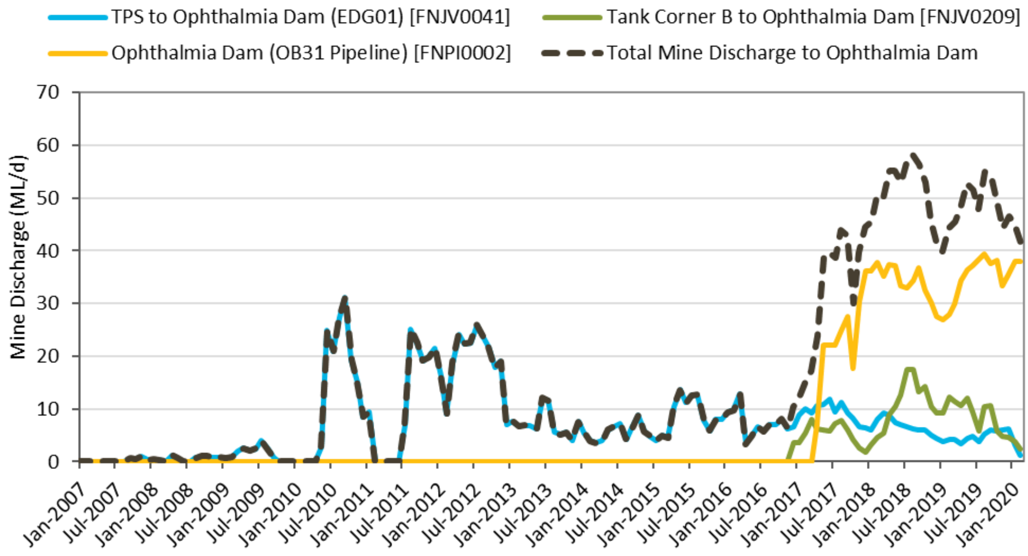


Figure 3.6 Measured mine water discharge to Ophthalmia Dam

3.5.2 Discharge to recharge ponds

Mine water discharges to the Recharge Ponds 1 and 2 (Figure 1.1) have been derived from monthly meter readings at two meters (Table 3.2). Monthly metered data are available up to the end of May 2019 (Figure 3.7).

Total surplus mine water discharge to the Recharge Ponds, from Eastern Ridge, has consistently ranged between 11 and 16 ML/d since early 2016.

Table 3.2 Recharge Pond mine water discharge locations

Meter number	Description	Mine hub source
FNJV0044	Recharge Pond 1 (EDG04)	Eastern Ridge
FNJV0045	Recharge Pond 2 (EDG04)	Eastern Ridge

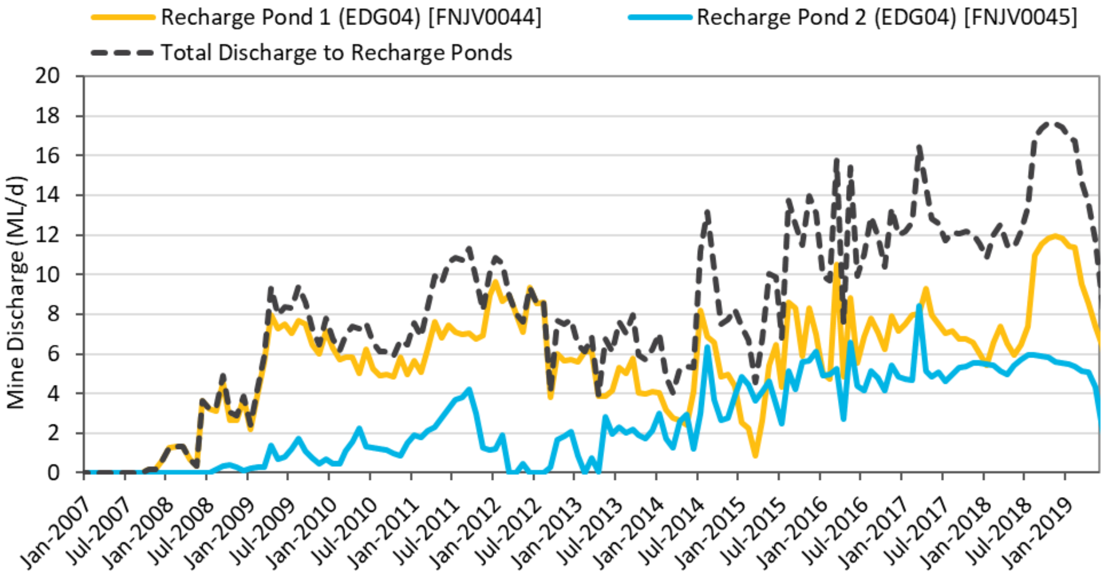


Figure 3.7 Measured mine water discharge to Recharge Ponds 1 and 2

A review of the model set-up for the recharge pond inputs to the groundwater system, assumed to provide direct groundwater recharge, indicates that these have historically been allocated to the wrong groundwater zones. As a result, the distribution of groundwater inflows from Recharge Ponds 1 and 2 have been updated to Zones 2 and 3 (refer to Figure 1.1), from the previous definition as inputs to Zones 3 and 4.

3.5.3 Surplus mine water salinity

Salinity data (TDS and EC) have been provided by BHP which are assumed to be representative of the salinity of surplus mine water discharges to Ophthalmia Dam. Available data for Whaleback, Eastern Ridge and Jimblebar hub surplus water are presented in Figure 3.8. The data has been used to refine assumptions on historic and predicted future surplus water salinity and provide a more representative estimate of the salt load inputs to the dam and groundwater system.

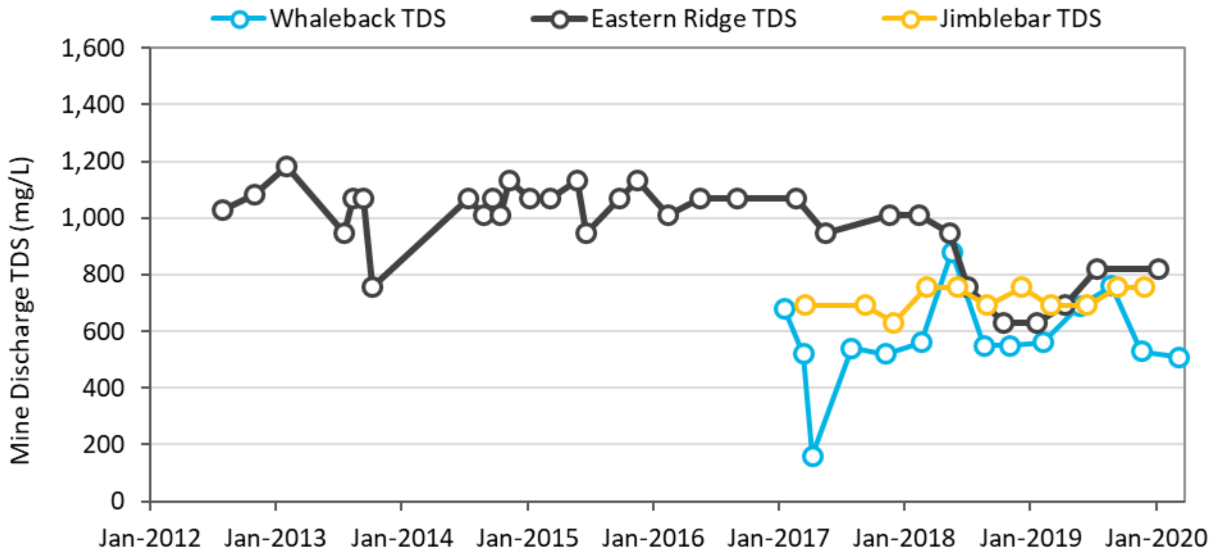


Figure 3.8 Surplus water salinity

3.6 Groundwater conditions

3.6.1 Groundwater level

Groundwater levels were provided at 27 monitoring points comprising groundwater bores (manual and automated measurements) and vibrating wire piezometers (automated measurements). Groundwater levels from automated loggers are collected daily (as a minimum) whilst manual levels are recorded approximately monthly.

Updated groundwater levels reflect the low rainfall period over 2018/19 with groundwater levels receding in most bores from August 2017 to early January 2020. However, groundwater levels did not decline to historic lows recorded in 1980 (pre Ophthalmia Dam). Post cyclone Blake groundwater levels recovered near instantaneously, shown by HEA0119M which increased by 7.75 m between readings taken on 16 December 2019 and 31 January 2020.

Groundwater levels have been updated in the model for the monitoring bores defined summarised in Table 3.3. These monitoring bores are consistent with those used in the previous model development and assessment studies (Golder 2016, 2019).

Table 3.3 Groundwater monitoring bore summary

Modelled groundwater zone	Monitoring bores
Zone 1	EEX0931M, HEOP0798M
Zone 2	HEOP0387M, HEOP0415M
Zone 3	HRZ0048M1, HEOP0548M, HEA0119M
Zone 4	HEA0139M, HEOP0574M
Zone 5	T0401M

3.6.2 Groundwater salinity

The observational records comprise groundwater analysis with laboratory measured EC in micro siemens per centimetre (µS/cm), laboratory TDS at 180°C in mg/L, samples with both EC and TDS, and field EC. Where both EC and TDS were measured in the laboratory the data has been used to generate a site-specific relationship for groundwater (Figure 3.9). This relationship was then used to populate all laboratory measured TDS and EC data to generate the longest time series possible. The field EC was not used.

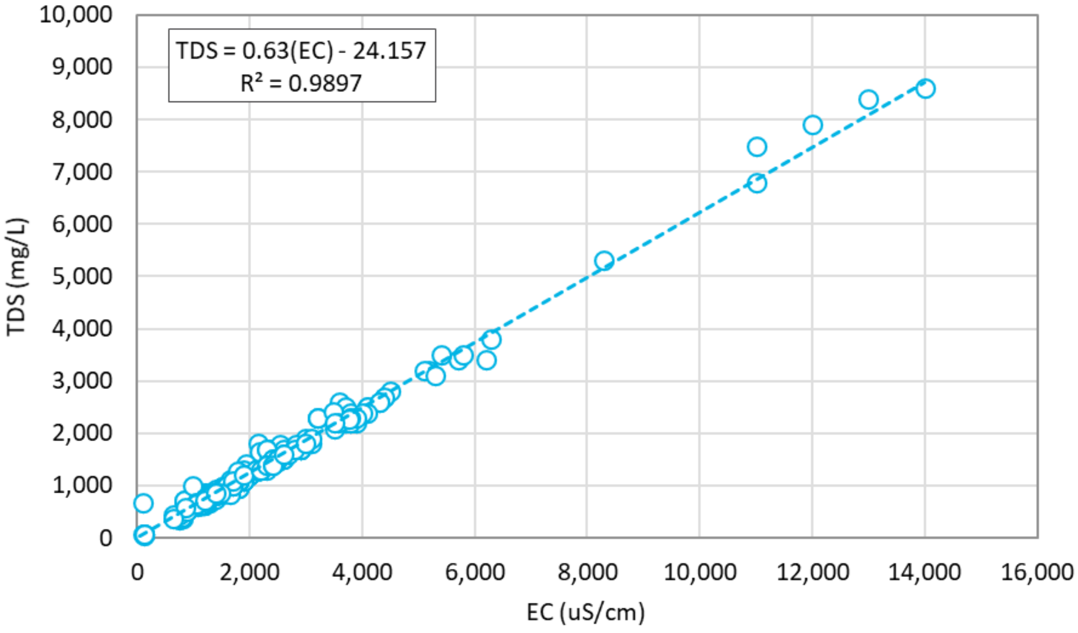


Figure 3.9 TDS to EC relationship for Ethel Gorge groundwater

The resulting salinity records are summarised in Table 3.4, with timeseries of TDS concentration for bores in model zones Upstream to Zone 2 and Zone 3 to Zone 5 presented in Figure 3.10 and Figure 3.11 respectively. The available groundwater salinity information are summarised as follows:

- 29 bores were provided with either TDS or EC data, of which only eleven had greater than 50 observations;
- the HNPIOP series of bores and HEOP469 have the longest TDS/EC records beginning in 1978 pre-dating construction of Ophthalmia Dam;
- three of the HNPIOP bores are located upstream of Ophthalmia Dam and are unlikely to be influenced by the dam or dam water management;
- there are very few bores in the monitoring record that have both a water level and TDS/EC measurement with which to determine potential cause and effect of changes in salinity; and
- of the 29 bores with TDS/EC records eight of them are missing location details.

Table 3.4 Summary of groundwater salinity monitoring in Ethel Gorge in mg/L

Bore	Catchment	Model Zone	No. observations	Mean TDS	Minimum TDS	Maximum TDS	Standard Deviation
EEX0917M	Unknown		9	2,779	2,268	3,276	313
EEX0931M		1	9	627	567	693	43
HEA0113M	Unknown		16	1,012	599	1,134	154
HEC0404M	Homestead	1	13	1,197	1,134	1,260	36
HEC0405M	Unknown		13	814	756	882	48
HEOP0313M	Unknown		5	490	466	510	17
HEOP0314M	Unknown		5	597	373	660	126
HEOP0417M	Unknown		3	1,176	1,134	1,260	73
HEOP0469P	Fortescue	Dam	84	1,010	69	2,329	422
HEOP0504M		5	6	1,040	756	1,449	300
HEOP0559M	Shovelanna	1	3	2,394	2,331	2,457	63
HEOP0574M		4	2	664	473	855	270
HEOP0798M	Fortescue	1	1	1,088	1,088	1,088	-
HEQ0022M	Unknown		11	693	630	765	40
HEV0003M	Shovelanna	1	12	1,817	1,764	2,016	96
HEV0004M	Shovelanna	1	11	3,688	3,339	3,969	274
HEV0005M	Shovelanna	3	10	6,999	5,229	8,820	1,323
HEV0006M		3	12	982	945	1,197	73
HEV0008M		3	12	908	819	1,134	95
HNPIOP0007P	Homestead	Upstream	109	661	314	1,386	122
HNPIOP0008P	Homestead	Upstream	128	672	69	1,008	107
HNPIOP0010P	Homestead	Upstream	94	659	133	882	115
HNPIOP0011P		2	186	927	95	1,363	154
HNPIOP0012P		2	177	895	229	1,443	299
HNPIOP0013P		1	165	1,153	226	2,205	391
HNPIOP0015P		3	119	750	91	1,156	233
HNPIOP0029P		4	57	887	630	1,380	168
HNPIOP0030P		5	91	1,194	789	2,255	308
HNPIOP0031P		5	96	1,469	836	2,375	372

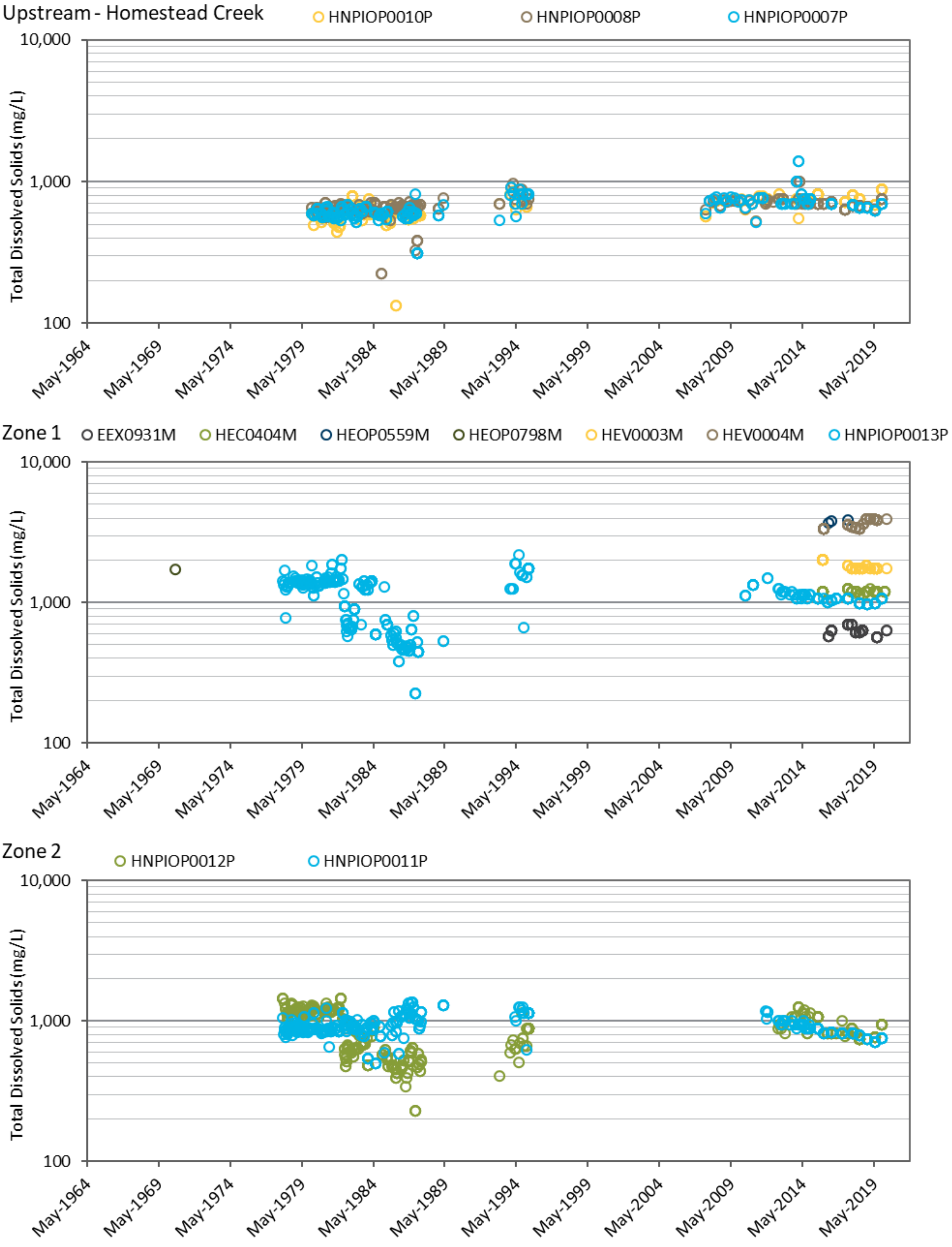


Figure 3.10 Measured bore TDS data records for Upstream (top), Zone 1 (middle) and Zone 3 (bottom)

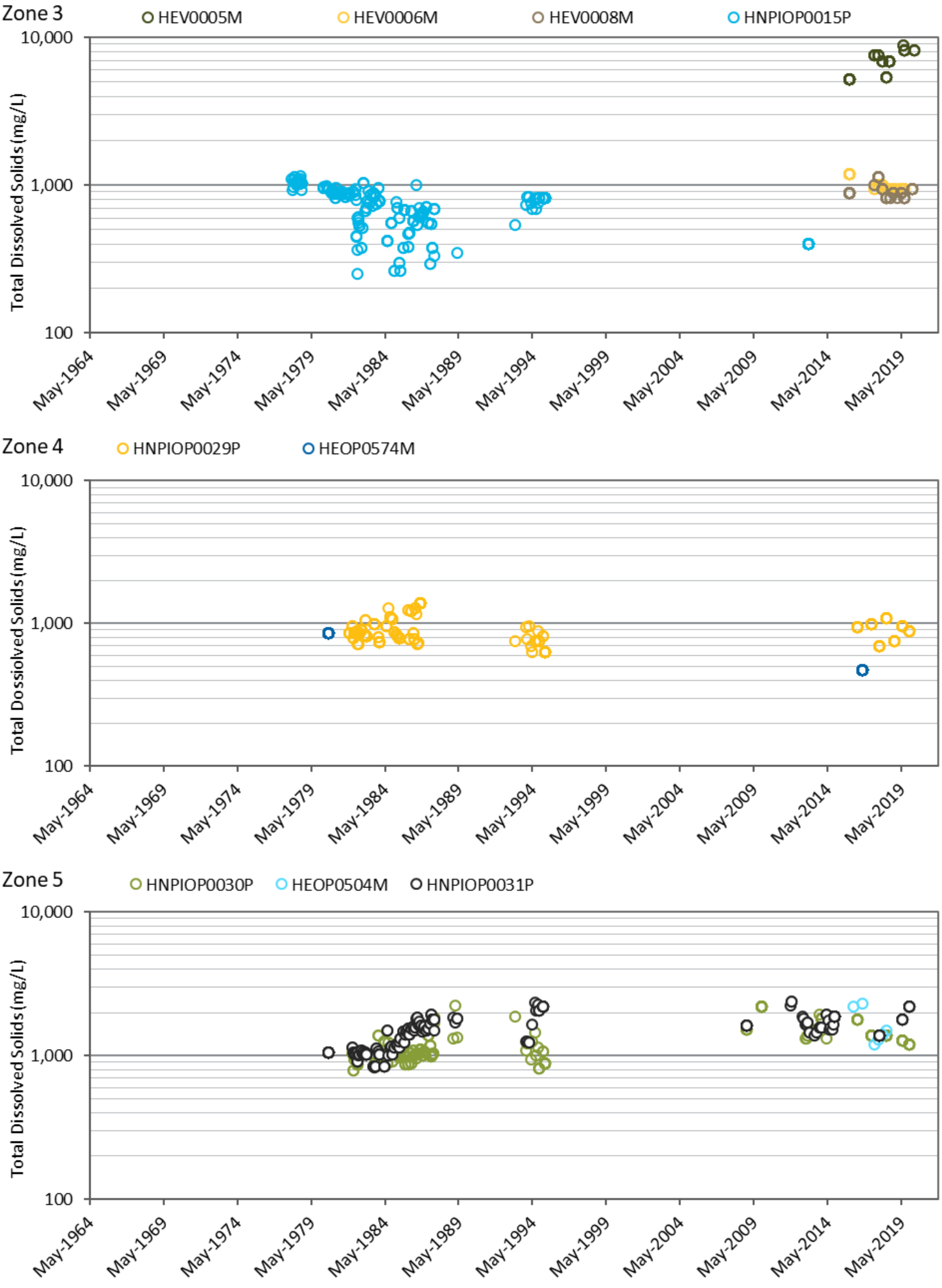


Figure 3.11 Measured bore TDS data records for Zone 3 (top), Zone 4 (middle) and Zone 5 (bottom)

The TDS and or EC observations, particularly the spatial and temporal TDS information presented in Figure 3.10 and Figure 3.11, indicate:

- TDS/EC have been measured periodically from 1978 to present, the irregular frequency of monitoring makes it difficult to confidently assess trends;
- there is considerable spatial and temporal variability in TDS/EC within each model zone (see Figure 3.10, Figure 3.11 and Table 3.5);
- support for the conceptual model of increasing TDS/EC through Ethel Gorge along the direction of groundwater flow (RPS, 2014);
- groundwater TDS near Shovelanna Creek is generally higher than groundwater TDS associated with Homestead Creek, consistent with Parsons Brinkerhoff (2015) assessment of higher salinity to the east side of the dam in comparison to the west; and
- overall the observational data does not support the expected increase in TDS/EC anticipated in conceptual and salt balance models, with the potential exception of Zone 5.

Table 3.5 Variability in groundwater salinity across model zones

Zone	No of bores[1]	No of observations	Minimum TDS (mg/L)	Maximum TDS (mg/L)
Dam	1	84	69	2,329
1	7	214	226	3,969
2	2	363	95	1,443
3	4	153	91	8,820
4	2	59	473	1,380

[1] There are seven bores of unknown location with 62 observations excluded from the table

3.6.3 Groundwater abstraction

Groundwater abstraction rates for each of the water balance model zones (Figure 1.1) have been estimated from meter readings. Monthly groundwater abstractions for the period up to the end of March 2020 and are presented in Figure 3.12.

Groundwater abstraction for dewatering of Orebody 23 adjacent to the Ethel Gorge palaeochannel and for water supply to Newman results in a reduction in local groundwater levels that would have multiple effects on groundwater TDS. It is expected that groundwater TDS will decline locally around the dewatering centre and impacted area, given reduced groundwater levels would:

- result in a reduction in evapotranspiration in areas where the drawdown cone interacted with groundwater dependent vegetation; and
- allow for greater loss from surface water flow as lower groundwater levels provide for a greater unsaturated zone for infiltrating surface water.

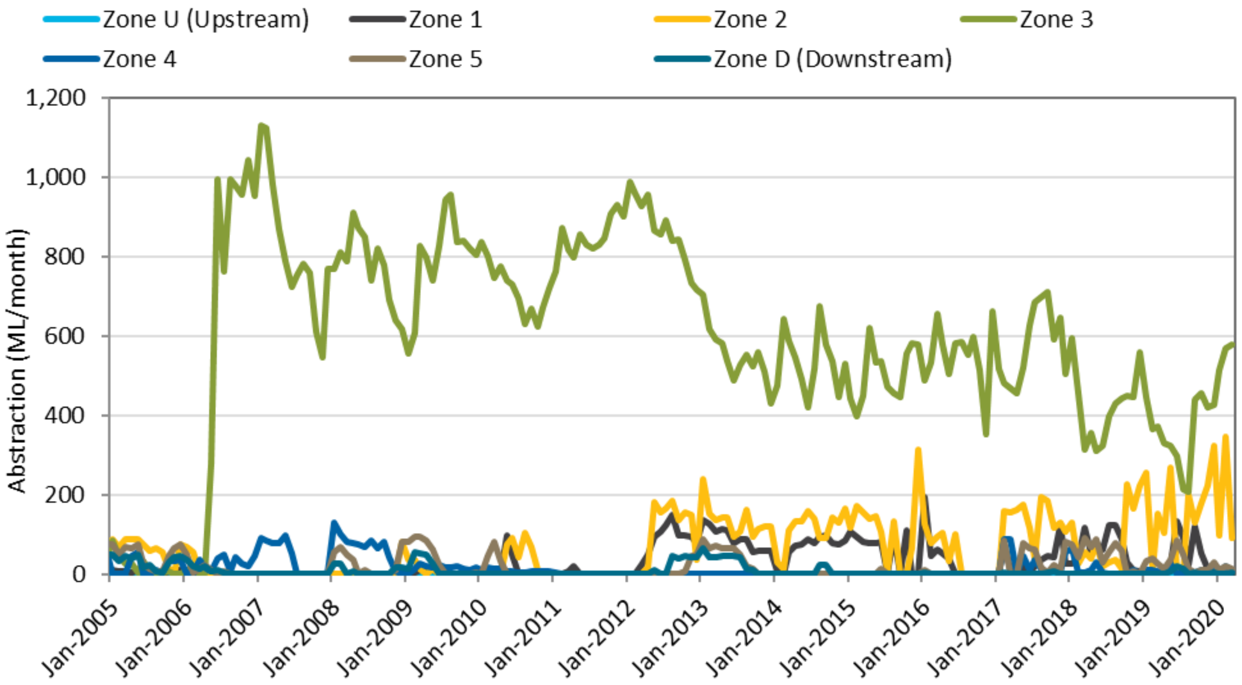


Figure 3.12 **Total monthly groundwater abstraction rates for water balance model zones**

4 Water balance performance review

4.1 Overview

This section summarises a review of the water balance model performance undertaken with the updated monitoring and operational data detailed in Section 3. The updated data allows the water balance simulations to be assessed for the additional 26-month period up to the end of February 2020. The updated model runs undertaken for the performance review adopt the same model parameters and input method defined in the Golder (2019) modelling assessment.

The performance review assesses the:

- Ophthalmia Dam water balance performance, with particular focus on the comparison of monitored and simulated water storage and TDS;
- dam seepage estimation approach in light of the outcomes of the dam water balance; and
- the shallow groundwater system water and salt balance.

Changes to the model structure have not been actively undertaken as part of the project scope. Any model updates have been, where possible, limited to changes to model parameters, input variables and/or model assumptions.

4.2 Ophthalmia Dam water balance review

The updated model period represents two consecutive dry years where, as a consequence of the absence of significant catchment flows, Ophthalmia Dam did not reach the spillway storage level between April 2017 and January 2020 (refer to Figure 3.3). The dam water level monitoring shows a general progressive reduction in dam water storage over this period.

The two-year flow period, 2017-19, represents the lowest two-year flow volume (8,451 ML) recorded at the Fortescue River gauging station over the 41-year flow record from 1980. The second lowest recorded two-year catchment flow volume was 8,854 ML recorded for the 1992-94 period. Therefore, in conjunction with the high rates of mine water surplus discharges to Ophthalmia Dam over the recent period, totalling 34,800 ML over the 2017-19 period (as detailed in 3.5.1), the water balance model update period represents a relatively unique period for the assessment of model performance both in terms of water quantity and the TDS (mass) balance.

4.2.1 Ophthalmia Dam storage

The Eastern Pilbara Hub (EPH) water balance model parameters defined in the Golder (2019) assessment have been adopted and the model has been run to simulate dam water storage and salinity for the extended period up to the end of February 2020. The one model update applied at this point was the adoption of measured TDS concentrations for respective surplus water discharge sources, ie Whaleback, Eastern Ridge and Jimblebar as presented in Section 3.5.3. This replaced an assumed surplus water TDS concentration of 1,000 mg/L which had been applied across all modelled surplus water discharges. A summary output presenting the simulated and measured water storage volume for Ophthalmia Dam is presented in Figure 4.1 and simulated and measured dam TDS in Figure 4.2.

The comparison of simulated and observed dam water storage is consistent with the Golder (2019) assessment for the period up to 2018. A good model fit is achieved for the period where controlled dam release information are available, 2016 to 2018. However, clear deviations are evident between measured and simulated dam storage for the earlier years of the simulation period. The rapid rates of dam recessions observed over the period 2011 to 2016 and the presence of inflections in the recession curves, suggest dam releases are likely to have been occurring (Golder, 2019). However, data relating to these potential releases are not available to include in the model at this stage or in previous iteration of the water balance model development.

The simulated and measured dam TDS presented in Figure 4.2 shows a good level of agreement between modelled and measured dam TDS concentrations. It is noted that that the simulated concentration is inherently a function of the effectiveness of the model simulation of dam storage volumes which may explain some deviations. Additionally, the dam mass balance calculations assume full and instantaneous mixing of water and mass, whereas TDS (or EC) measurements may to some degree be influenced by the proximity of the sampling point to the mine water discharge location. This is of relevance at high water storage conditions as the dam has a maximum surface area of approximately 15.31 km^2 at the service spillway elevation.

For the model update period, 2018 onwards, the simulated dam storage (shown in Figure 4.1) and simulated TDS (shown in Figure 4.2) indicates a deviation from both the measured storage and TDS data. The result appears to show a consistent trend away from the observed data with simulated water storage showing an increasing trend over the update period (compared to a decreasing trend in the observed data) and simulated TDS appears to be increasing at a much higher rate than the observed data.

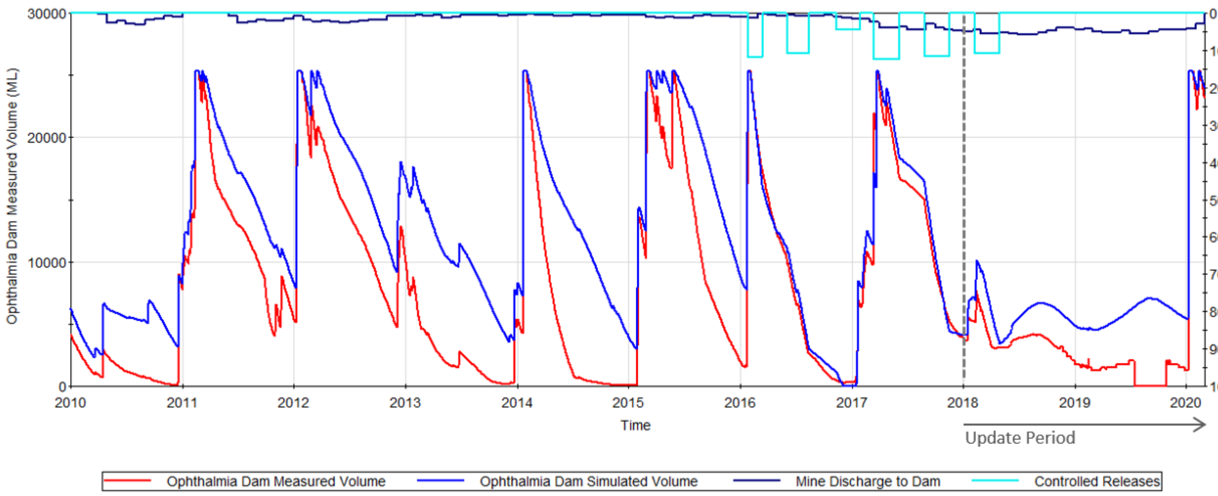


Figure 4.1 Simulated and measured Ophthalmia Dam water balance (2010 to 2020) – original parameters

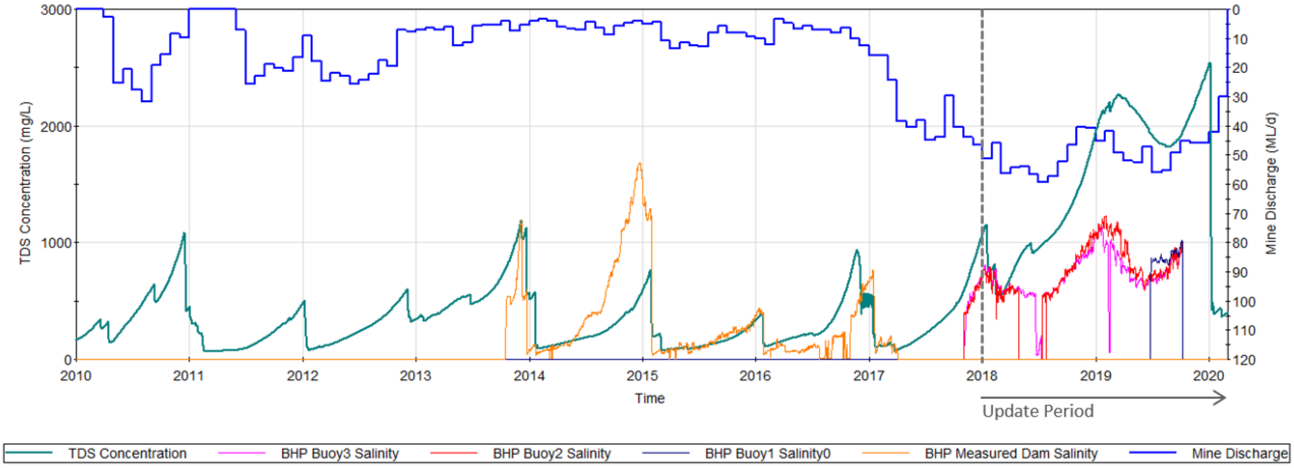


Figure 4.2 Simulated and measured Ophthalmia Dam salinity (2010 to 2020) – original parameters

Based on the comparison of simulated and observed dam storage, and TDS:

- the apparent consistent deviation between simulated and observed dam water storage (and TDS) indicates a potential deficiency in the model ability to represent dam water balance, particularly for dry hydrological periods;
- the increases in dam water losses in the update period cannot be attributed to controlled dam releases which has, indicatively, been identified as a potential cause of deviations in the simulated and observed water balance in earlier periods;
- the two natural, and ongoing water losses from the dam are through open water evaporation and seepage from the dam to the underlying and downstream groundwater system; and
- any further increase in evaporative losses over the update period, to try and reconcile the water storage deviation, would result in further increasing the rate of increase in TDS due to enhanced evapo-concentration.

Apparent deviations in the water and TDS balance for the dam, based on the observations for the update period, may potentially influence the level of confidence and accuracy of any proposed water balance scenarios applying future predictions of surplus water discharge to the dam. Therefore, further model review has been undertaken to explore the underlying assumptions and approaches applied to the dam seepage loss rates, particularly at low storage levels.

4.3 Dam seepage estimation method review

Further review has been undertaken to explore options to potentially improve the effectiveness of the water balance model to represent and simulate the dam storage and TDS balance over the update period.

As noted in previous studies Golder (2016, 2019), PB (2013, 2015) and RPS (2014), various estimates of dam seepage rates and pan factors applied to open water evaporation estimates have been defined through a number of dam water balance reviews and modelling assessments and each of these estimates has provided a relatively good level of fit between observed and simulated dam storage conditions. The most recent update of the model balance undertaken by Golder (2019) shows a good level of agreement between observed and simulated recession rates, ie total losses attributed to evaporation and seepage. This is evident for the periods where controlled release information are available as shown for the 2016 to 2018 period in Figure 4.1. It is noted, however, that all previous seepage estimates assume seepage rates are equal across the entire dam storage area and linearly related to dam storage area.

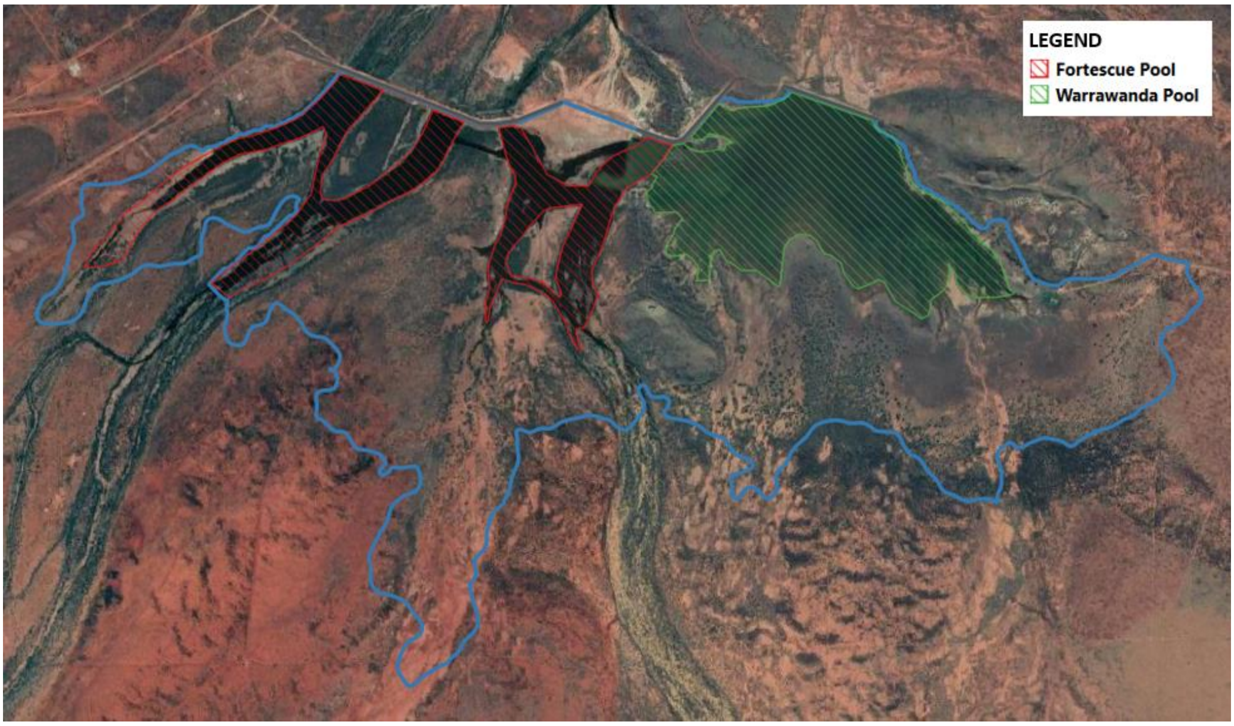
To achieve an equivalent reduction in simulated dam storage over the 2018-19 period an estimated increase in dam losses of 5 to 8 ML/d is required. As mentioned, increasing the assumed rate of evaporative loss from the dam is not an option therefore, an alternative (non-linear) dam seepage relationship, focusing on the low storage conditions, has been explored.

4.3.1 Preferential seepage area loss function

Aerial imagery shown in Figure 4.3 presents Ophthalmia Dam at a low storage level with an estimated ponded area of 3,800,000 m^2, as approximated by the delineated areas (referred to as the Fortescue Pool and Warrawanda Pool).The total delineated storage area is approximately equivalent to a storage volume of 2,500 ML or a storage elevation of RL 510.8 m.

As shown in the observed dam storage information (Figure 3.3 and Figure 4.1), this is within the lower end of the storage range that the dam has been within over the 2018-19 period (i.e. ranging from approximately 4,000 ML down to 2,000 ML). This image and storage delineations presented highlights preferential low dam storage in modern alluvial gravels (indicated as the red hatching), particularly in the western and central storage areas. These alluvial gravels are expected to have a significantly higher rate of seepage and hydraulic connectivity to the downstream shallow groundwater system.

A preferential seepage function has therefore been defined based on estimated area of alluvial gravels, which has been assumed approximately equivalent to the estimated Fortescue Pool area shown in Figure 4.3 which is largely constrained to the Fortescue River and Warrawanda Creek channel systems upstream of the dam wall. This preferential seepage area is estimated to cover approximately 1,600,000 m^2 (or around 10% of total dam storage area at service spillway level). The Warrawanda Pool, indicated to the east of the dam storage extent in Figure 4.3, is predominantly located outside of the alluvial system and, as defined by Parsons Brinkerhoff (2015), this area of the dam has a higher base elevation relative to the Fortescue Pool.



Source: Google Earth

Figure 4.3 Ophthalmia Dam at a low storage level

The preferential seepage approach has been developed based on:

- high seepage rate assumed for alluvial areas (up to 14.0 mm/d); and
- low seepage rate applied to remaining inundated area (approx. 1.2 mm/d).

These assumed rates result in a weighted average seepage rate of approximately 2.5 mm/d at maximum storage level (approximately 39.0 ML/d), which is consistent with the upper limit seepage rate estimates developed by Golder (2019). However, the approach results in significantly higher seepage at lower storage levels (up to a 15.0 ML/d increase at very low storage). A potential limitation of the approach at very low storage volumes may result in the simulated dam storage reaching an empty condition when localised storage volume may remain, albeit very limited volumes relative to total storage.

A comparison of the original (linear) seepage rate and the proposed preferential (non-linear) seepage relationship is presented relative to dam storage area and volume in Figure 4.4 and Figure 4.5.

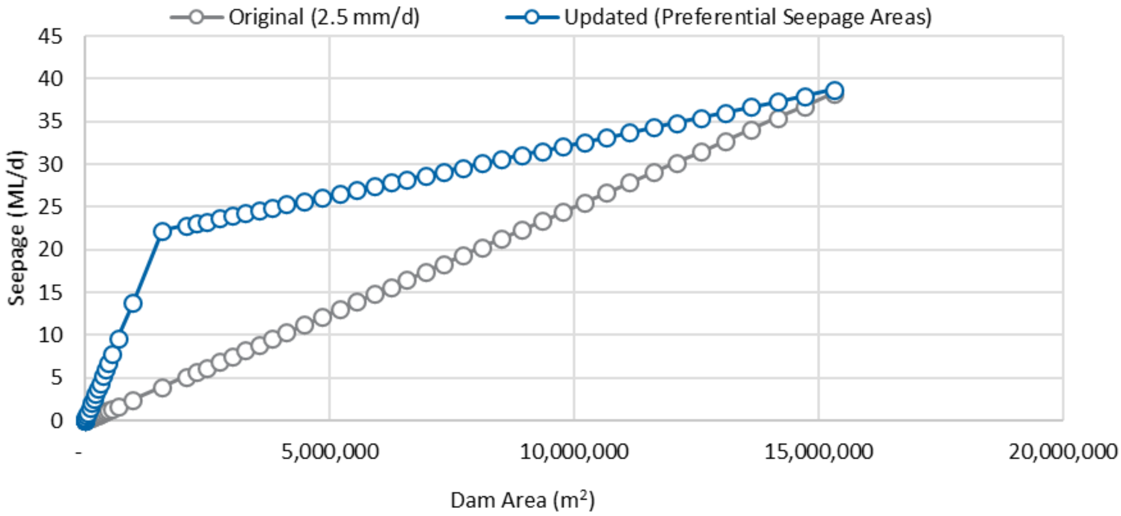


Figure 4.4 **Comparison of original and preferential seepage rate vs dam storage area relationship**

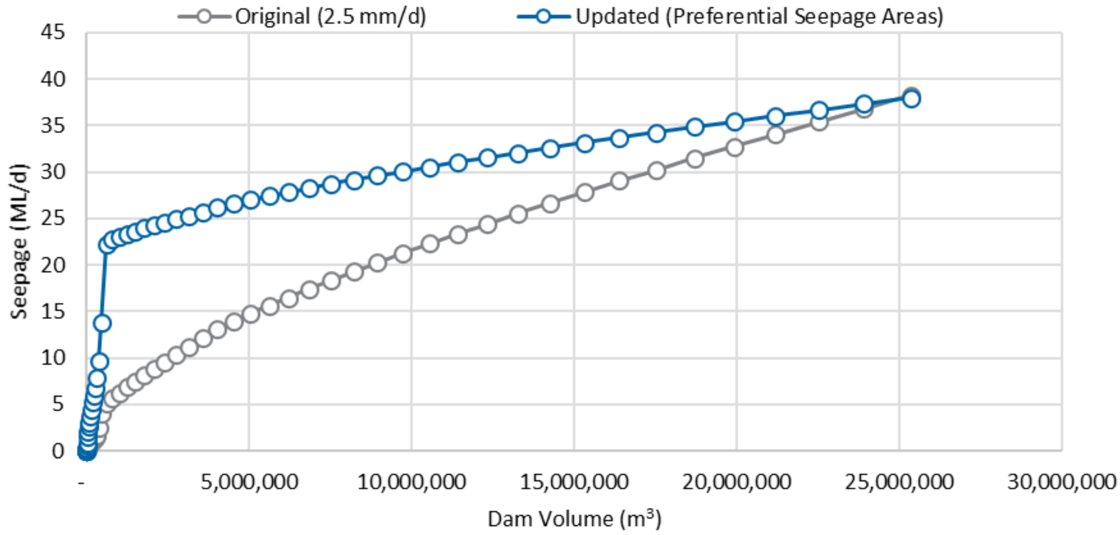


Figure 4.5 **Comparison of original and preferential seepage rate vs dam storage volume relationship**

A summary water balance output presenting the simulated and measured water storage volume for Ophthalmia Dam applying the proposed preferential seepage area loss function is presented in Figure 4.6 and simulated and measured dam TDS is presented in Figure 4.7. A comparison of simulated and measured dam storage volume for the full period of dam operation (since 1982) is presented in Appendix A. The simulated storage and TDS concentrations based on the original loss model parameters are included in the plots as a dashed line for comparison.

The results of the model update indicate:

- the preferential area seepage loss approach provides improvements in model performance over the update period, relative to previous seepage parameter assumptions, both in terms of water storage volume and TDS concentration;
- there is still some deviation between the simulated and measures dam storage and TDS concentration over the 2018 to 2020 period;
- differences between the seepage loss approaches are barely noticeable at high storage conditions;
- the preferential seepage area approach is reflected as a higher rate of dam storage recession, particularly at mid to low storage levels;
- the proposed seepage loss approach does not appear to result in a reduction in model performance based on the full historic record (as shown in Appendix A); and
- the preferential area seepage loss approach appears to show an improved representation and simulation of low storage volumes and dam recession rates during historic dryer years, i.e. during 1983, 1984, 1991 to 1994, 1996, 2002, 2007 to 2010, and 2018 to 2020.

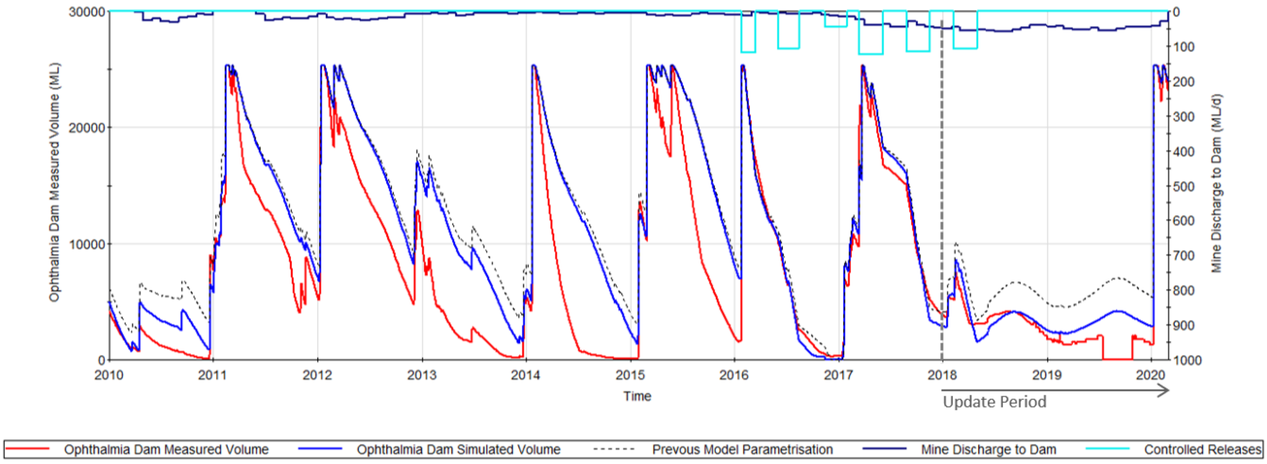


Figure 4.6 Simulated and measured Ophthalmia Dam storage (2010 to 2020) – updated parameters

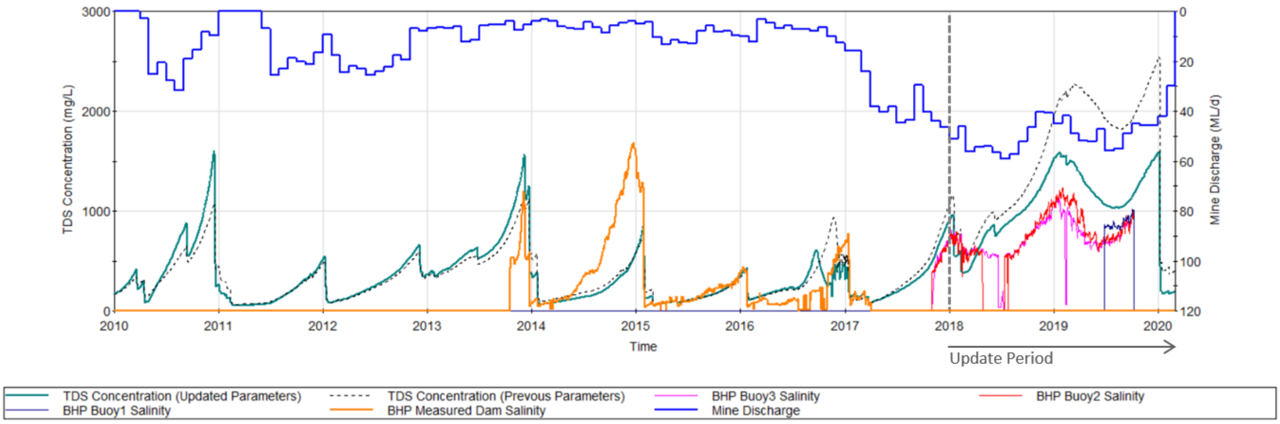


Figure 4.7 Simulated and measured Ophthalmia Dam salinity (2010 to 2020) – updated parameters

4.4 Groundwater system water balance review

4.4.1 Background

A review of the groundwater system water balance and performance has been undertaken as part of this assessment. However, there are limitations with respect to the water balance model's ability to effectively simulate groundwater levels, processes and quality in the aquifer system downstream of Ophthalmia Dam.

The groundwater system modelling approach attempts to incorporate a range of complex and highly variable fluxes (spatially and temporally), including groundwater abstraction, seepage recharge from Ophthalmia Dam and recharge ponds, rainfall-recharge, creek recharge, evapotranspiration losses and groundwater throughflow. This represents a simplification of processes and fluxes through the groundwater system. Modelled groundwater levels represent averages across the width of the aquifer model sub-zone extent and along the 150 m reach length. The monitoring bores (presented in Figure 1.1) are predominantly located along the western side of the modelled area and are potentially more affected by groundwater abstraction and mine dewatering activities in the adjacent mine areas (Orebodies 23 and 25).

The inherent limitations and assumptions associated with the groundwater simulations, specifically with relevance to those detailed in the conceptual model description (Section 2.3), should be taken into account and acknowledged when interpreting both the simulated historic (review) model runs and also the future (predicted) surplus water discharge scenarios. When using the model output trends are more important than the absolute values predicted.

4.4.2 Groundwater balance review summary

As part of the review process a number of updates to model parameters and inputs have been undertaken, including those relating to groundwater monitoring or operational information for the update period detailed in Section 3. The key updates and changes made to the groundwater component of the water balance model include:

- distribution of Recharge Ponds 1 and 2 inputs to the groundwater system updated to be to Zones 2 and 3 (refer to Figure 1.1). Previous defined as inputs to Zones 3 and 4. Placing the recharge pond within its correct zone has shifted results compared to the previous assessment but is aimed to improve the correlation in trends between the observed and predicted groundwater levels;
- updated groundwater abstraction information, particularly with reference to Orebody 23, have been integrated into the water balance and have an influence on simulated groundwater levels through Zones 2 to 5. The increase in groundwater abstractions will, by definition, influence changes in Recharge Pond 1 and 2 inputs detailed above;
- review and update of model zone areas and evapotranspiration areas;
- review of river seepage representation, including update of lower limit flow rate seepage assumptions;
- review and update of evaporation depth assumptions and parameters;
- review of key groundwater system parameters and initial conditions;
- review and update of zonal allocations of groundwater abstraction; and
- review of likely process and controls relating to potential changes in groundwater salinity.

The following sections provide a summary of the groundwater system outputs comparing observed and simulated groundwater levels (Section 4.4.3) and predicted changes in groundwater salinity over time (Section 4.4.4).

4.4.3 Groundwater levels

Simulated groundwater elevations are compared against measured groundwater levels for the monitoring bores summarised in Table 3.3. These monitoring bores are consistent with those used in the previous model development and assessment studies (Golder, 2016, 2019). Plots of observed and simulated groundwater elevations, based on the model update inputs and parameters, are presented for selected monitoring bores in Figure 4.8 to Figure 4.10. The simulated groundwater levels based on the original water balance model parameters are included in the plots as a dashed line for comparison.

The results of the groundwater level simulations with the updated water balance model parameters show:

- the groundwater balance shows a good level of agreement with observed data over the long-term and reflects the large scale processes and influences on groundwater levels and variability, ie increasing groundwater abstractions and dewatering from Orebody 23 and the influence of high groundwater recharge during the wetter than average periods around 1999-00;

- predicted trends and changes in groundwater levels are relatively consistent between the updated and Golder (2019) model parameters;

- deviation between the current modelling simulations and Golder (2109) (previous parameters) modelled groundwater responses from around 2008 onwards, particularly in Zones 2 and 3, are largely a reflection of the correction of the location of recharge from the recharge ponds entering the groundwater component of the model (refer to Section 3.5.2) and updated groundwater abstraction data, particularly for Orebody 23 dewatering, applied for the current modelling assessment (refer to Section 3.6.3);

- whilst the simulated groundwater response does reflect the expected response as defined by the model approach, the observed data does not necessarily reflect such a significant influence of groundwater abstractions and the recharge pond inflows through various periods of the observed datasets. This potentially highlights a key limitation of the model (refer to Section 2.4) whereby rapid groundwater flows may be bypassing the wider groundwater system; and

- the modelling approach does not effectively represent shorter-term variability and responses of the groundwater systems. This is a combined reflection of the simplification of the modelling approach relative to actual hydrological responses and the temporal resolution of many of the model inputs, such as discharge and abstraction rates, which are provided at a monthly timestep.

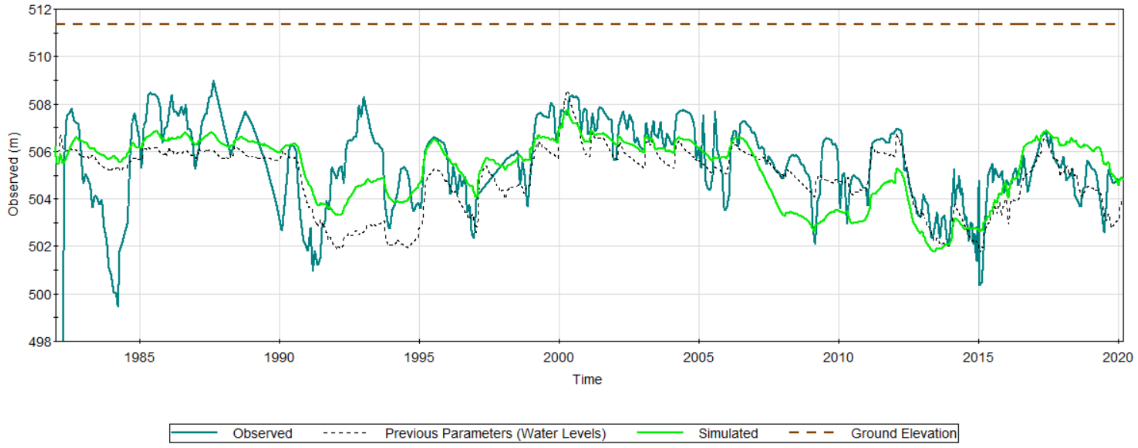


Figure 4.8 Zone 1, HEOP0798M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

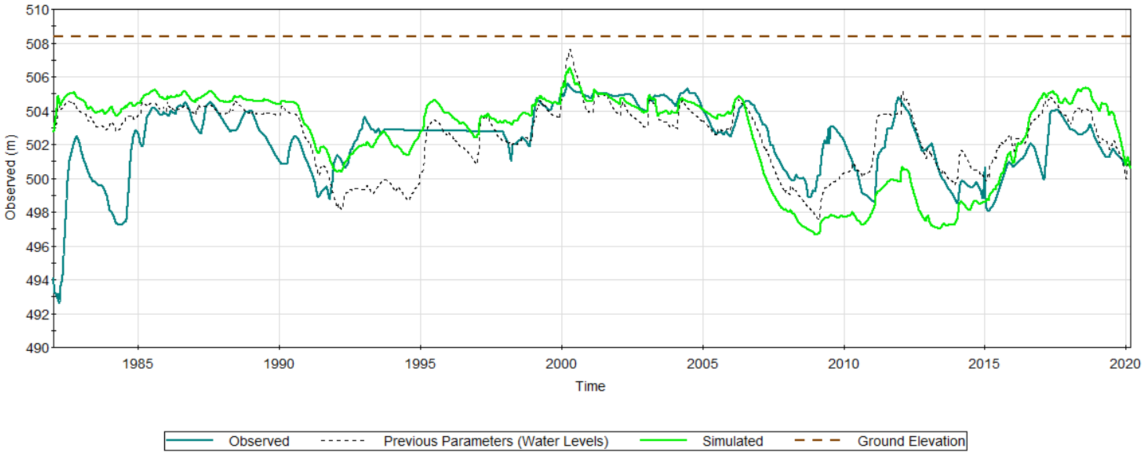


Figure 4.9 Zone 2, HEOP0415M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

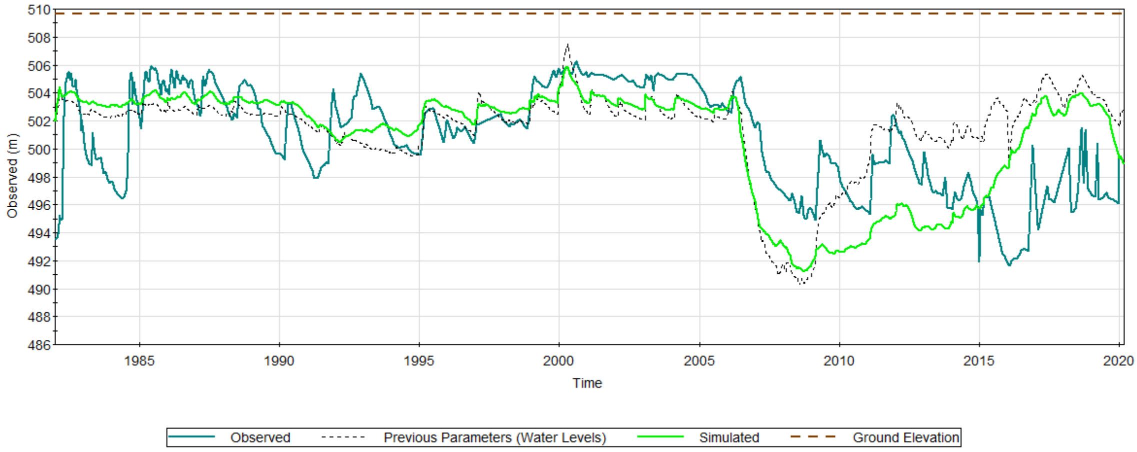


Figure 4.10 Zone 3, HEOP0548M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

4.4.4 Groundwater salinity

The Goldsim model has the assumption (and numeric limitation) that the only means of salt loss from the system is via groundwater throughflow and / or abstraction (dewatering orebodies and water supply). As groundwater levels rise, groundwater is removed via evapotranspiration, which increases the concentration of salt, and the model predicts a higher TDS as an outcome. However, this may be an over simplification of the system via the representation of the hydrogeology as a single aquifer with a lumped hydraulic conductivity (Section 2.4).

When groundwater daylights in discontinuous pools in the river bed, induced by management of the recharge basins, a wetter season or higher discharge from the dam; this will allow for increased groundwater throughflow in the river bed that will accelerate the removal of salt from zone to zone and from the system via overland flow. This mechanism for the removal of salt (and water) from the system is not adequately represented by the model with a single lumped hydraulic conductivity.

To counteract this short-coming in the model, the hydraulic conductivity of the aquifer was increased to allow for greater groundwater throughflow to remove more water and salt from the system. The effect on the predicted groundwater TDS is presented in Figure 4.11 (old model) and Figure 4.12 (updated model).

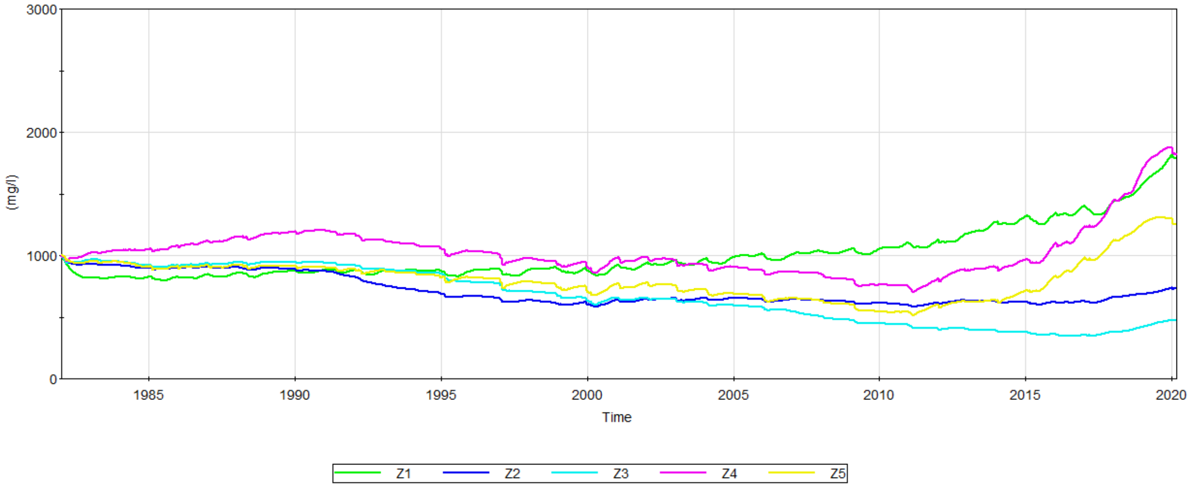


Figure 4.11 Original (Golder 2019) model parameters (Recharge Ponds to Zone 3 and 4), hydraulic conductivity at 2 m/d

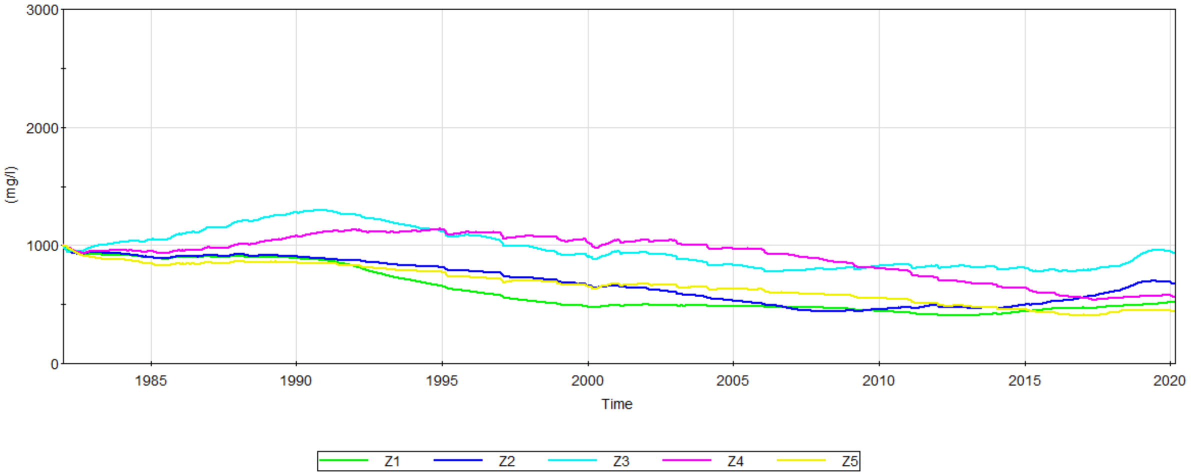


Figure 4.12 Updated model parameters (Recharge Ponds to Zone 2 and 3), hydraulic conductivity at 7 m/d

4.4.5 Model parameter summary

Water balance model parameters have been updated based on the outcomes of the model review and update process summarised above. Table 4.1 provides a summary of the updated model parameters with respect to the Ophthalmia Dam water balance, the groundwater balance and the TDS mass balance components of the model. These parameters are presented relative to parametrisation outlined in the Golder (2019) model update.

Table 4.1 Water balance model parameters

Parameter (units)	Previous Values (Golder 2019)	Updated Value	Notes
Ophthalmia Dam parameters			
Dam Seepage Rate (mm/d)	2.5	Non-linear area-based seepage function	Updated dam seepage estimates based on performance review. Refer to 4.3.1 for more details.
Pan Coefficient, Kp	NA	NA	Pan coefficient requirement removed by updated assumption of Morton's Lake estimated of open water evaporation in Golder (2019).
Catchment Inflow Factor	1.0	1.0	No change.
Stage-area-volume relationship	Defined from BHP (2014 stage-area-volume curves)		
Spillway elevation (mRL)	513.5	513.5	No change.
Controlled release rate (ML/d)	Defined based on outlet pipe rating curve (refer to Section 5.2.4).		
Groundwater model parameters			
Saturated hydraulic conductivity, Ks (m/d)	2.0	7.0	Increase Ks to account for rapid groundwater flow influence on bulk groundwater flow estimates.
Specific yield, Sy (%)	7.0	6.0	Minor adjustment based on model review.
Upstream boundary inflow (m^3/d)	1,500	1,500	No change.
Evaporation depth, De (m)	2.0	2.0	No change.
Evapotranspiration cut-off depth d2 (m)	5.5	4.8	Reduced to limit evapotranspiration effects.
Riverbed permeability (mm/d)	100	100	No change.
Recharge Pond seepage rate (ML/d)	Up to maximum historic flow rates (approx. 15.0 ML/d)		
TDS mass balance parameters			
River TDS concentration (mg/L)	40	40	No change.
Rainfall TDS concentration (mg/L)	2.2	2.2	No change.
Upstream groundwater inflow concentration (mg/L)	700	1,000	Revised to RPS (2014) assumed values.
Mine Discharge Concentration (mg/L)	1,000	Hub specific TDS concentrations	Defined for hubs based on historic monitoring.

4.5 Water balance summary

A schematic representation of the water balance for Ophthalmia Dam and the shallow aquifer system downstream of the dam is presented in Table 4.2. The data presented represents an annual summary of modelled fluxes, inflows and outflows, and net changes in storage, for both the surface water and groundwater within the model domain, for the 2018-19 period of the model update. The annual summary aims to provide a simple 'snapshot' of the water balance for the annual period and a visual presentation of the key simulated fluxes, based on the current water balance model structure and process representations.

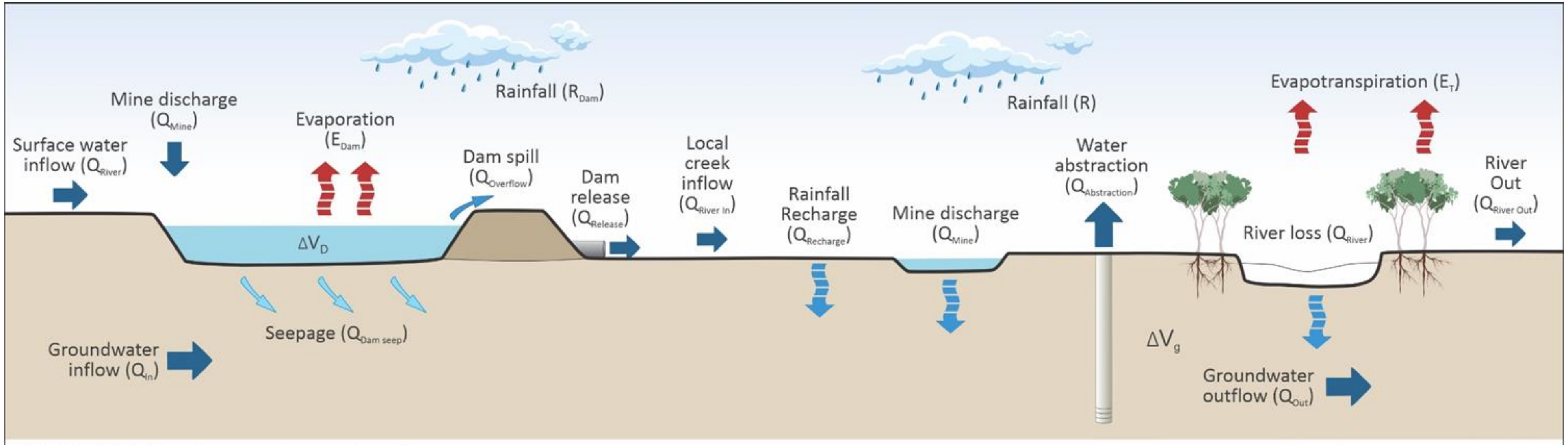
As detailed in Section 3.2 and Section 4.2, the extremely dry period occurring through the 2018-19 year represents a relatively unique period for assessing and reviewing the water balance. The dryness of the 2018-19 period is reflected in Table 4.2 by the almost complete absence of natural inflows to the system from creek systems, refer to Q_{River}, R_{Dam}, $Q_{\text{River In}}$ and Q_{Recharge}, and, therefore, the dominant influence on the water balance for the period are the mining and anthropogenic related discharge and abstraction fluxes, such as Q_{Mine} and $Q_{\text{Abstraction}}$.

The key observations from the simulated annual water balance summary in Table 4.2 include:

- the dominant (largest) water flux for the 2018-19 period was surplus mine water discharge to Ophthalmia dam (Q_{Mine}) of 48.7 ML/d;
- the Q_{Mine} discharge to the dam maintained the storage to a level where average daily evaporative (E_{Dam}) and seepage losses ($Q_{\text{Dam Seep}}$) are maintained at a rate of 23.8 ML/d and 25.7 ML/d, respectively;
- the dam water balance predicts a slight increase in surface water storage (ΔV_D) over the annual period (of 243 ML), as shown in Figure 4.6 above;
- seepage losses from Ophthalmia Dam ($Q_{\text{Dam Seep}}$) represents the largest predicted inflow to the groundwater system (25.7 ML/d) with groundwater recharge from the Recharge Pond discharge locations, downstream of the dam, accounting for 11.5 ML/d;
- rainfall recharge (Q_{Recharge}) and river recharge (Q_{River}) to the groundwater system was predicted to be almost zero for the 2018-19 period;
- predicted losses from the groundwater system from water abstractions ($Q_{\text{Abstraction}}$) and evapotranspiration (ET) of 13.7 ML/d and 27.6 ML/d respectively, exceed the predicted groundwater system inflows over the 2018-19 period;
- the groundwater balance predicts a reduction in groundwater (ΔV_g) storage of 1,732 ML over the entire model domain;
- compared to other years, the reduction in groundwater storage is likely to be significantly influenced by the absence of creek inflows (including local catchment, dam releases and dam spill) and creek recharge through the system which represents the dominant, but highly ephemeral, groundwater recharge flux; and
- downstream outflow from the model (Q_{Out}) of 2.4 ML/d is predicted to be marginally higher than the upstream groundwater boundary inflow (Q_{In}) of 1.5 ML/d.

The 2018-19 water balance summary presented in Table 4.2 can be compared directly with the equivalent water balance schematic and tabulated data presented in Section 5.3.4 (Table 5.5) for the 2018-19 period with alternative surplus water discharge scenarios.

Table 4.2 Annual water balance summary for 2018-19 (Dry Year)



NOT TO SCALE (this diagram is a conceptual representation only)

Dam Inflows (ML/d)			**Dam Outflows (ML/d)**				**Change in Storage (ML)**	**Local Creek Inflow (ML/d)**	**Groundwater Inflows (ML/d)**					**Groundwater Outflows (ML/d)**			**Change in storage (ML)**	**River Outflow (ML/d)**
Q_{River}	Q_{Mine}	R_{Dam}	E_{Dam}	$Q_{Dam\ Seep}$	$Q_{Overflow}$	$Q_{Release}$	ΔV_D	$Q_{River\ In}$	Q_{In}	$Q_{Recharge}$	$Q_{Dam\ Seep}$	Q_{River}	Q_{Mine}	Q_{Abs}	ET	Q_{Out}	ΔV_G	$Q_{River\ Out}$
0.1	48.7	1.3	23.8	25.7	0.0	0.0	243	0.0	1.5	0.1	25.7	0.0	11.5	13.7	27.6	2.4	-1,732	0.0

Notes: 1. Inflow and outflows presented as daily averages for the year
2. Change in storage (Ophthalmia Dam and groundwater system) presented as total change over the year

5 Surplus water discharge scenarios

5.1 Overview

This section summarises the water balance modelling scenarios based on projected surplus water discharge.

- Section 5.2 summarises the modelling scenarios adopted for the following water balance assessments:
  - a theoretical discharge capacity assessment for Ophthalmia Dam (described in Section 5.2.1); and
  - the assessment of potential changes in groundwater conditions downstream of the dam resulting from alternative surplus water discharge (three scenarios described in Section 5.2.2) and the definition of alternative hydrological (climate) scenarios (described in Section 5.2.3);
- Section 5.3 summarises the modelling results presented both graphically and with tables summarising key model outputs and statistics.

5.2 Summary of modelling scenarios

5.2.1 Ophthalmia Dam discharge capacity assessment scenario

Modelling scenarios were run to provide an assessment of the maximum ‘physical’ capacity of the dam. This scenario was undertaken to determine the potential capacity of the dam to manage surplus water through evaporation and infiltration losses, and with and without a 3-month controlled release.

The assessment applies a theoretical dam water balance scenario whereby the only inflow to the dam over the full period of the water balance simulation is surplus mine water discharge and creek inflow and direct rainfall contributions are excluded (ie set to zero). This aims to represent a ‘theoretical’ perpetual dry season for a 20-year simulation period upon which an incrementally increasing surplus discharge rate is applied up to the point at which the dam storage capacity is exceeded and overflow is predicted to occur. The capacity assessment does not consider predictions of TDS concentration.

The following modifications and adaptions are applied to the water balance model for the dam capacity assessment:

- no catchment inflow or direct rainfall input to the dam balance;
- surplus water discharge represents the only water input to the dam, applied at a constant rate starting at 50 ML/d ramping up to 240 ML/d in 10 ML/d increments;
- open water evaporation and seepage are included as losses from the dam balance;
- controlled release from the dam is included as an option (Capacity Assessment 2) based on a 3-month release duration from August each year; and
- the assumed ‘criteria’ (as detailed in Section 5.2.3) for the assessment is the estimation of the maximum surplus water discharge rate where the dam storage does not overtop the spillway.

The dam capacity assessment has been applied for the following two scenarios:

- Capacity Assessment 1: No controlled release; and
- Capacity Assessment 2: 3-month controlled release.

The results of the dam discharge capacity assessment are presented in Section 5.2.2.

5.2.2 Surplus water discharge scenarios

Alternative surplus water discharge scenarios were run predicting discharge rates to Ophthalmia Dam and the associated recharge ponds over a projected 20-year period. The assessed alternative surplus water discharge scenarios include:

- Scenario 1: Continue recent surplus discharge rates (50 ML/d) over 20-year period (scenario defined to assess reliability of results and review an ongoing 'business-as-usual' case);
- Scenario 2: Predicted surplus discharge from all existing pits. (Scenario 2 can be compared with Scenario 3 to show incremental influence of OB32 surplus); and
- Scenario 3: Predicted surplus discharge from all existing pits and OB32 (based on the high-case dewatering volume for OB32E generated by the numerical groundwater model). (Scenario to show incremental impact of OB32 surplus water contributions).

A summary of the predicted surplus water discharge rates for the three modelled water balance scenarios is presented in Figure 5.1. Scenarios 2 and 3 are positively skewed with higher predicted surplus water volumes in the first half of the forecast period. Both Scenario 2 and 3 surplus water discharge estimates drop below Scenario 1 (constant rate) after years 2026 and 2030 respectively.

Due to the nature of the surplus water discharge forecasts the model scenarios have applied a stochastic modelling approach (described in Section 5.2.3) to assess the potential sensitivity of the prevailing climate and hydrological conditions on the surface and groundwater balance.

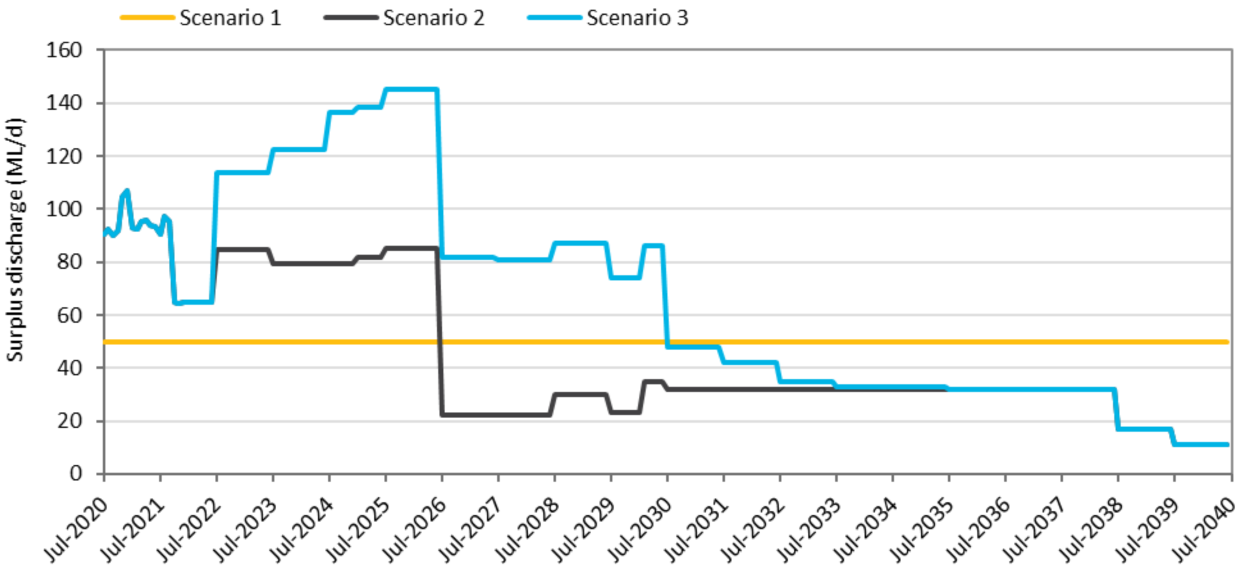


Figure 5.1 **Surplus water forecast summary**

The assumptions and considerations adopted for the development of the proposed surplus water discharge scenarios (listed above) and the associated modelling scenarios (detailed in the following sections) include:

- Jimblebar discharge to the Dam taken from detailed site water balance and distribution developed to support the Caramulla Surplus Scheme (managed aquifer recharge and/or discharge to Caramulla Creek). Discharge surplus water to the Caramulla scheme is maximised once it becomes operational in FY22;

- Ninga MAR takes a constant 10 ML/d from the Jim/OB31 pipeline to the Dam;
- water demand remains at current average levels throughout the future period;
- surplus water salinity for all hubs is defined at a concentration representative of current (or recent) actual surplus water salinity levels. Proposed surplus water TDS concentrations adopted for future discharge forecasts are presented in Table 5.1 and have been defined based on hub level TDS data for the period March 2017 to December 2019 for Jimblebar, July 2012 to January 2020 for Eastern Ridge and January 2017 to March 2020 for Whaleback;
- all scenarios will be run for 'dry', 'average', and 'wet' hydrological (climate) scenarios as summarised in Section 5.2.4 below;
- all scenarios include a controlled dam release from the C Wall valve (Outlet 3). The proposed operation of the controlled release, for the modelling scenarios, is based on a defined release start date, starting 1 August each year of the simulation period, and duration of release operation (3-month Release Period). The release period of August, September and October represent the driest months at the end of the winter season, refer to Figure 3.1, and provide opportunity to lower dam levels prior to the subsequent wet season and start of the tropical cyclone season. A description of the controlled release option and estimated rate of release is provided in 5.2.2; and
- all scenarios, the Ophthalmia Borefield is defined to abstract water at a continuous rate of 13 ML/d with the distribution of abstraction across zones presented in Table 5.2. The allocation of future abstractions are based on the average proportion of Ophthalmia borefield abstraction from the zone over the 2018 to 2020 period.

Table 5.1 Surplus water discharge TDS concentrations

Surplus water source mine hub	TDS (mg/L)
Jimblebar / OB31	750
Eastern Ridge	950
Whaleback	550

Note: Eastern Ridge TDS concentrations applied to recharge pond discharge as well as dam discharge

Table 5.2 Zonal allocation of Ophthalmia borefield abstraction

Groundwater modelling zone	Abstraction (ML/d)
Zone 1	2.7
Zone 2	7.4
Zone 3	0.0
Zone 4	2.8
Zone 5	0.1

5.2.3 Hydrological and climate scenarios

The water balance modelling of potential impacts and influences of future surplus water predictions has been undertaken applying three alternative 20-year future periods representing a 'dry', 'average', and 'wet' prevailing hydrological (climate) scenarios. These additional scenarios have been adopted to assess the potential sensitivity of the proposed discharge scenario influence on the water balance to the prevailing 'natural' hydrological conditions, particularly the inherent inter annual variation in climate and catchment responses (as detailed in Section 3.2). It is noted that the adoption of the climate scenarios is for the purpose of reviewing the potential sensitivity of the water balance assessment, based on alternative climate conditions, and not necessarily to assess the system water balance based on potential climate change forecasts, i.e. as detailed by Charles et al. (2015).

The 20-year hydrological scenario periods have been defined from the available 41-year hydrological record for the Fortescue River gauging station at Newman (detailed in Section 3.3). This gauged flow series has been adopted as the reference, and representative, data for the water balance as catchment inflow to the dam (as defined by historic gauged flows for the Fortescue River at Newman) represents the dominant water input to the water balance. The catchment is not modelled as a rainfall-runoff model and therefore the period of record is limited to the available gauged record, however, this period includes large inter- and intra-annual variation in flows as well as wet and dry periods. This approach to the modelling assessments means that the three scenarios are all based on periods that have been experienced in the past.

A summary of annual gauged flows for the Fortescue River at Newman, aligned to July-June water year for consistency with the proposed surplus water discharge modelling period, is presented in Figure 5.2. 20-year rolling averages have been defined for the available 41-year annual flow dataset. This provides a total of 22 options for the three hydrological scenarios. Due to the length of the modelled future period (20-years), relative to the length of the available flow record (41-years) it is noted that even dry 20-year periods will include one or more wet years. To retain consistency with the hydrological record, no splitting of periods or records has been applied.

A summary of estimated minimum, average and maximum 20-year hydrological periods is presented in Table 5.3. The estimated average 20-year flow statistic for the 'average scenario' was identified to include the extreme wet year of 1999-2000. Therefore, to exclude this extreme wet year the representative 'average' 20-year period has been defined (semi-qualitatively) for the period 2001 to 2020. As shown in Figure 5.2, this includes a number of dry and wetter years and therefore is considered to be reflective of a representative 'average' 20-year flow period. The associated 20-year flow periods, identified to represent the 'dry, 'average' and 'wet' hydrological scenarios are defined and also highlighted in Figure 5.2.

Table 5.3 Hydrological flow scenario summary (20-year periods)

Statistic	Annual average flow[1]	Period definition	Notes
Dry period	36,170	1980 to 1999	Skewed by 1980, 1995, 1997 and 1999 water years. Includes extended 'dry' period of water years 1981 to 1994 and consecutive dry years.
Average period	61,920	2000 to 2019	Representative average period shifted to the 2001 to 2020 period (annual average flow of 44,000 ML) to exclude the 2000 extreme wet year. Includes variable wetter and dry years.
Wet period	73,880	1997 to 2016	Includes wet years of 1997, 2000 and 2003.

1 averages defined for 20-year flow periods

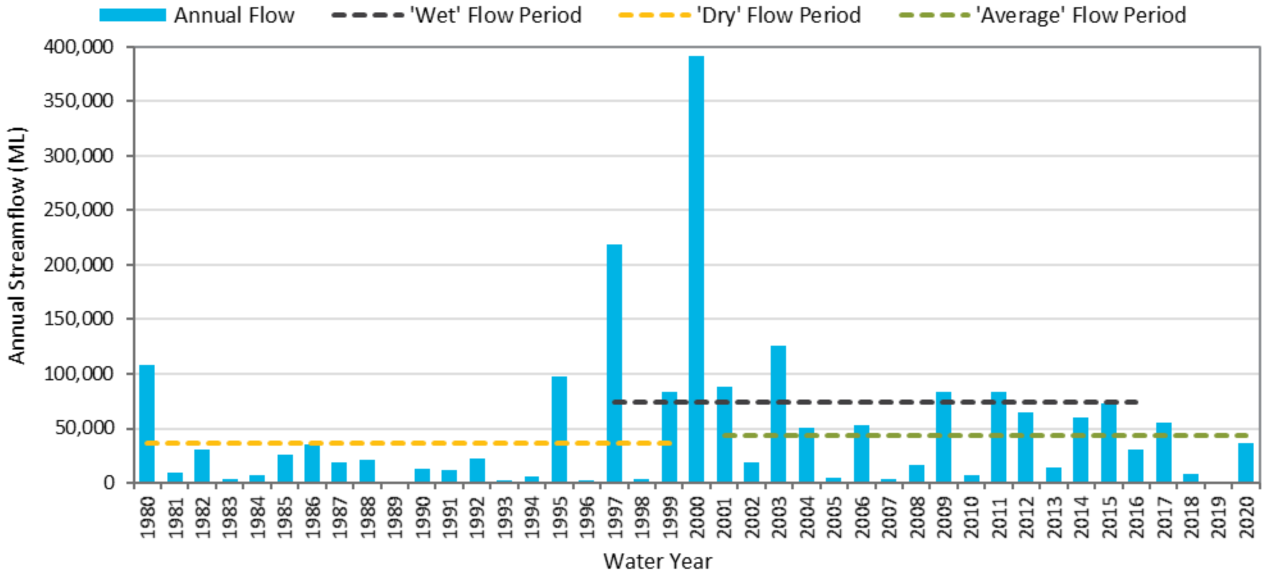


Figure 5.2 **Total annual Fortescue River flow (July to June water year) and defined 'wet', 'dry' and average 20-year flow periods**

Due to the skewed nature of the surplus water discharge scenarios, and the highly variable nature of the hydrological fluxes associated with the water balance, the water balance modelling applies a stochastic modelling approach whereby 20 individual model runs (referred to as model realisations) are undertaken with the start date of each run being shifted by one year along the 20-year climate scenario period. For instance, for the 'average' hydrology scenario the first realisation has a start date of July 2020, the second realisation then has a start date of July 2021, and so on. The 20-year periods are looped so when the end of the period is reached the model then links back to the beginning of the simulation period. Therefore, an equivalent climate scenario, including the inherent variability within each 20-year period, is applied for all years but the surplus water discharge scenarios remain the same for all 20 model realisations. The water balance model applies the prevailing daily rainfall, and evaporation for the defined for the 20-year 'dry', 'average', and 'wet'' periods.

5.2.4 Controlled release operation

As described in Section 1.2.1, Ophthalmia Dam has three outlet valves, as shown in Figure 1.1, providing controlled release options from the dam, with Outlets 1 and 2 located in Wall A and Outlet 3 located in Wall C. Outlet Valve 1 is not operational, Outlet Valve 2, when opened, directs water to recharge basins 1 and 2. Outlet Valve 3 provides a controlled downstream release of water from the dam to Shovelanna Creek and into the downstream Fortescue River (BHP, 2019).

The rating curve for Outlet Valve 3 (presented in Figure 5.3) was calculated by Golder (2019) and is consistent with estimated maximum discharge rate presented by BHP (2019) of approximate 136 ML/d at the service spillway storage capacity (RL 513.5 m). It is noted that the Golder (2019) rating curves have a defined minimum inlet (upstream) pipe invert of RL 509 m which is equivalent to an estimated dam storage capacity below the invert of 37 ML (or 0.15% of the operational dam capacity) as defined by BHP (2014) dam storage estimates.

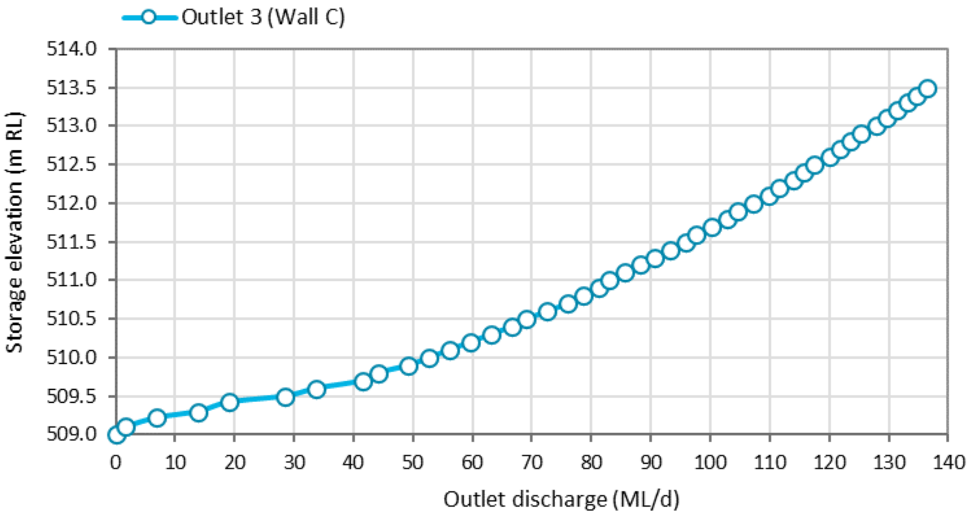


Figure 5.3 Estimated stage-discharge rating curve for Outlet 3

5.3 Modelling results

5.3.1 Assessment criteria

The overarching objectives of the water balance assessment, as detailed in Section 1.1, are to investigate the sustainable capacity of the Ophthalmia Dam under different operating scenarios (surplus discharge and climate) specifically:

1. the capacity of the Dam to accept the proposed volumes of surplus water without overtopping the spillway during the dry season; and
2. whether hydrological parameters, namely groundwater level and water quality, in the Ethel Gorge aquifer system remain within the criteria set out in the Eastern Pilbara Water Resource Management Plan (EPWRMP).

With respect to the assessment of the dam capacity to accept the proposed volumes of surplus water, the criteria of this assessment are simply defined by the surplus water discharge rate at which the dam is estimated to overtop the spillway. The proposed modelling approach is outlined in more detail in Section 5.2.1 above.

The modelling assessment of potential changes in groundwater and water quality conditions under alternative surplus water discharge scenarios adopts two criteria (trigger levels) identified by BHP (EPWRMP, BHP 2018) which are relevant to the scenario assessments:

- Groundwater TDS concentration: trigger = 3,000 mg/L, threshold = 4,000 mg/L; and
- Groundwater level: trigger = change of >6.0 m or >4 m/y, threshold = >12 m or >8 m/y.

These criteria are considered in the following section with reference to the summary results presented in Table 5.4 and the output summary plots for the simulated groundwater responses in Figure 5.8 to Figure 5.12.

The water balance modelling results for the three surplus water discharge scenarios, each assessed with dry, average and wet climate sensitivity runs. A summary of key results and statistics from the water balance model runs is provided in Table 5.4 and a discussion of the results is provided in Section 5.3.2.

Additional simulation results are presented to characterise the relative influence of the surplus water discharge scenarios on the water balance of Ophthalmia Dam, particularly relative changes in storage conditions and associated predictions of TDS concentrations. These results are presented for a selected Scenario 1, Scenario 2 and Scenario 3 simulation model run (Realisation 13), for the average hydrological condition with the 3-month controlled release operation. A comparison of key model outputs of simulated Ophthalmia Dam storage, controlled releases and TDS concentration are presented in Figure 5.6, a dam storage duration curve for the 20-year simulation period is presented in Figure 5.7 and groundwater levels and salinity are presented in Figure 5.8 to Figure 5.12.

5.3.2 Interpretation of results

As outlined in Section 2.4, there are a range of limitations and assumptions associated with the water balance model, particularly pertinent to the representation of the groundwater system, which should be acknowledged when interpreting the model results and outputs. The water balance modelling approach has largely been developed to:

- provide an efficient and integrated approach to simulate the 'linked' surface and groundwater systems; and
- understand the potential influence of changes to the dam water balance and therefore groundwater seepage from the dam, on the downstream groundwater system.

The modelling approach is not explicitly designed equivalent to a numerical groundwater model and, by definition, is a simplified representation of a complex system.

The model simulations and outputs relating to the groundwater system are best used to interpret potential trends and responses to changes in operations, particularly for comparing relative changes between scenarios, rather than to be interpreted as accurate predictions of future groundwater levels and TDS concentrations.

The water balance for Ophthalmia Dam has been shown to provide a good level of agreement between observed and simulated water volumes and TDS concentrations. This is particularly the case where good quality monitoring and operational information, including controlled releases from the dam, are available. The key components of the dam water balance are better defined, in general, and in most cases are measured and monitored effectively. The key uncertainties for the dam balance largely relate to the unmeasured components of inflow contributions from the ungauged portion of the dam catchment and seepage losses.

5.3.3 Ophthalmia Dam discharge capacity assessment results summary

The results of the dam capacity assessment are presented for the no-controlled release scenario (Capacity Assessment 1) in Figure 5.4 and the 3-month controlled release scenario (Capacity Assessment 2) in Figure 5.5. These model outputs present the minimum surplus discharge rate increment estimated to result in the dam storage reaching maximum capacity, ie overflow of the dam spillway. The simulated dam storage plots below indicate that:

- for Capacity Assessment 1 the simulated Ophthalmia Dam storage reaches a spilling condition at approximately 115 ML/d surplus water discharge (refer to Figure 5.4); and
- for Capacity Assessment 2 the simulated Ophthalmia Dam storage reaches a spilling condition at approximately 135 ML/d (refer to Figure 5.5).

The potential yield benefit, therefore, of the 3-month controlled release is equivalent to approximately 20 ML/d of additional constant surplus water discharge.

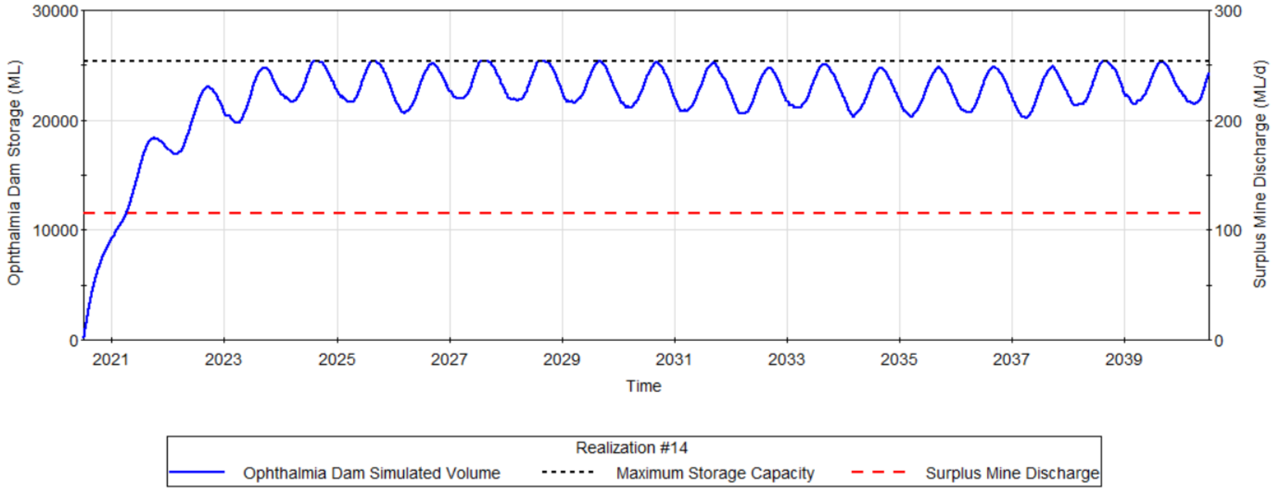


Figure 5.4 Capacity Assessment 1 – 115 ML/d surplus mine water discharge

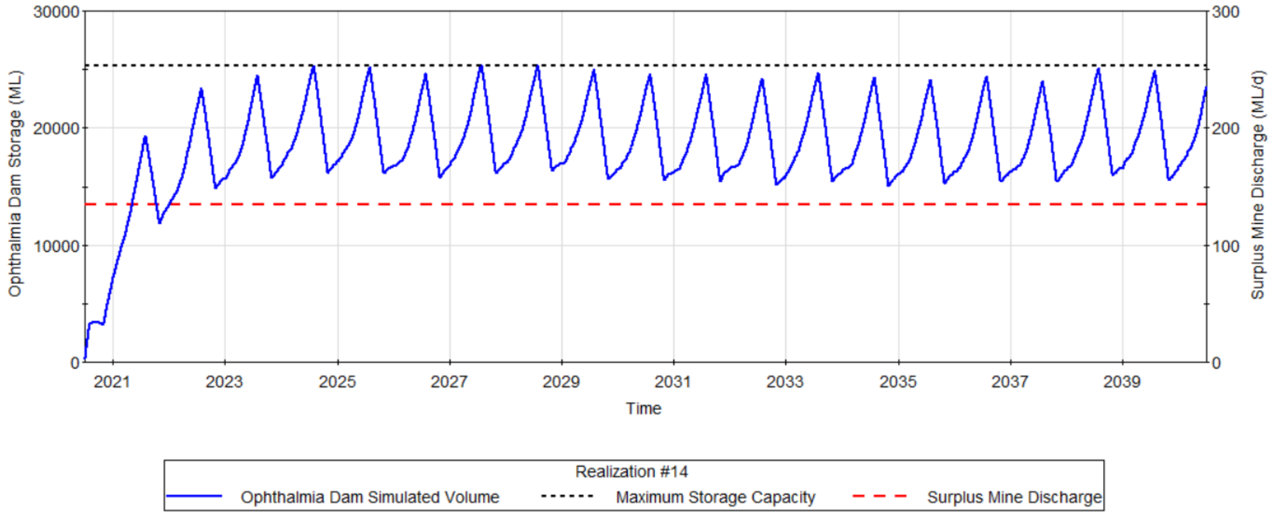


Figure 5.5 Capacity Assessment 2 – 135 ML/d surplus mine water discharge

5.3.4 Surplus water discharge impact assessment results summary

This section summarises the key water balance modelling results which have been based on the modelling scenario results presented below in various forms and the assessment criteria (Section 5.3.1). Water balance modelling results for the surplus water discharge scenarios, and hydrological and climate varying scenarios, are presented for review as follows:

- summary statistic of median storage and maximum salinity for dam and groundwater systems for all scenarios are presented in Table 5.4;
- a direct comparison of the Ophthalmia Dam water balance results for the three discharge scenarios for a single model run (realisation 13) are presented for the average hydrological scenario in Figure 5.6;
- a comparison of dam storage conditions for the three discharge scenarios for a single model run (realisation 13) are presented as storage duration curves in Figure 5.7;

- a direct comparison of the groundwater system water balance results (zone 1 to 5 water level and salinity) for the three discharge scenarios for a single model run (realisation 13) are presented for the average hydrological scenario in Figure 5.8 to Figure 5.12; and

- annual water balance summaries for Scenario 1, 2 and 3 surplus mine water discharge for the dry year (2018-19) and relatively wetter year (2000-01) are presented in Table 5.5 and Table 5.6 respectively.

Groundwater TDS concentration trigger conditions, 3,000 mg/L trigger condition and 4,000 mg/L threshold level (as outlined in Section 5.3.1) are included in Figure 5.8 to Figure 5.12, for reference. It is noted also that the groundwater level range (y-axis range) is 4.0 m, which is equivalent to the annual groundwater level change trigger condition of >4.0 m/y and lower than the maximum groundwater level change trigger conditions of >6.0 m/y (as outlined in Section 5.3.1).

The following points provide a summary of the model water balance scenario modelling result presented in Figure 5.6 to Figure 5.12 and key statistics presented in Table 5.4. Key observations from the Ophthalmia Dam water balance scenario results include:

- The model simulations and resulting outputs indicate that the assessment criteria conditions - TDS concentration triggers for the groundwater system, or groundwater level change, as detailed in Section 5.3.1 above – are <u>not exceeded</u> for any of the scenarios over the 20-year simulation period.

- The highest maximum dam TDS concentration of 2,000 to 2,200 mg/L (S2 Dry and Average scenarios) appear to be associated with very specific prevailing conditions relating to dam storage, low inflow rates and significant reductions in surplus water discharge. This TDS peak is shown for the S2 scenario in Figure 5.6 below.

- The absence of freshening inflow to the dam (natural and mine water discharge) results in potentially increasing TDS concentrations. Alternative operation of controlled releases, based on water quality, and monitoring could be defined to further mitigate increases in TDS.

- Historic measurement of relatively high TDS concentrations, i.e. in excess of 1,500 mg/L, are associated with low storage volumes (refer to Figure 3.5).

- High surplus water discharge rates for the early period of the S2 and S3 scenarios, i.e. for the 6-year period up to July 2026 as shown in Figure 5.6, results in consistently higher dam storage conditions over this period.

- Total annual surplus water discharge forecasts for the 6-year period (July 2020 to June 2026) period, 30,000 ML for S2 and 42,000 ML for S3, are higher than median annual flow (22,000 ML) recorded for the Fortescue River at Newman (refer to Figure 5.2), although it is noted that the distribution of catchment and surplus mine water inputs are very different.

- Modelling estimates highlight significant seasonal variation in evaporative losses from Ophthalmia Dam. Open water evaporation losses range from a peak of approximately 80 to 110 ML/d during the summer months down to a minimum range of 20 to 30 ML/d during the winter period.

- Estimates of maximum dam seepage rates, based on the updated preferential seepage area loss function, are up to approximately 38 ML/d at full storage level. At mid to low dam storage volumes the seepage losses are more commonly in the 20 to 30 ML/d range.

- Based on the estimates of dam losses, surplus water discharges in excess of 50 ML/d may exceed dam losses during low storage winter periods and discharges in excess of 120 ML/d may exceed or be equivalent to, maximum high storage, summer dam loss rates. Under these conditions, excluding natural dam inflows and without controlled releases from the dam, surplus water discharges will result in artificial filling of the dam and, ultimately, water flowing over the spillway.

- A summary comparison of dam storage conditions between Scenarios S1, S2 and S3 are presented as storage duration curves in Figure 5.7. These highlight that under the high discharge scenarios, and assuming equivalent operation of controlled releases, dam storage is predicted to be higher for longer periods, ie approximately 10% more time. This is particularly true for the higher surplus water discharge periods in the early part of the 20-year scenario (refer to simulated storage plots in Figure 5.6).

- The higher predicted dam storage conditions are reflected in longer duration of active flows over the service spillway.

Key observations from the groundwater system water balance scenario results include:

- Increased discharge to the dam and resulting increases in dam seepage to the groundwater system are reflected as an upward shift in average groundwater levels, (refer to simulated groundwater levels presented in Figure 5.8 to Figure 5.12).

- Reductions in the S2 and S3 scenario surplus discharge rates in 2026 and to a lesser degree in 2030 are reflected by downward trends in groundwater levels (refer to zone 1 and 2 simulated groundwater levels in Figure 5.8 and Figure 5.9 respectively).

- Surplus water discharge related shifts in average groundwater levels are predicted to be in the order of less than 0.5 to 1.0 m, which is within the predicted natural range of groundwater variability and are within the *Eastern Pilbara Water Resource management Plan* criteria.

- Historic groundwater monitoring, as shown in Section 4.4.3 and Appendix A -A.2, indicates that more significant variations in groundwater levels are associated with varying abstraction rates and dewatering activities rather than responses to shifts in more distributed and consistent fluxes such as seepage from the dam.

- Modelling indicates that increasing groundwater levels, driven largely by enhanced dam seepage, has the potential to lead to increasing groundwater TDS concentrations over the 20-year simulation period, indicated for realisation 13 scenario comparisons presented in Figure 5.8 to Figure 5.12. However, there is a high level of uncertainty relating to these predictions with considerable natural variable (spatially and temporally) in groundwater quality.

- Conversely, the modelling results show that high dam storage condition and related increases in controlled releases and spillway flows may result in an increase in river recharge fluxes to the downstream groundwater system (Table 5.5 and Table 5.6) which may act to freshen the groundwater system and buffer potential increases in TDS concentrations.

- Predicted maximum groundwater TDS concentrations are within the range that has been measured elsewhere through the Ethel Gorge system and are within the *Eastern Pilbara Water Resource management Plan* criteria.

The annual water balance summaries for a high surplus water discharge during a dry year (2018-19) and a wetter year (2000-01), summarised in Table 5.5 and Table 5.6, highlight the following key simulated responses, based on the water balance model structure, to increasing surplus water discharge:

- increasing dam discharge (Q_{Mine}) results in increased dam storage levels (and areas) resulting in increased open water evaporative losses (E_{Dam}), dam seepage ($Q_{Dam\ Seep}$) and dam spill ($Q_{Overflow}$), particularly under the S3 scenario discharge condition;

- evaporative loss rates (E_{Dam}) increase more significantly compared to seepage loss rates ($Q_{Dam\ Seep}$), ie the rate of increase of evaporative losses are more elastic to increase dam storage, based on the current seepage loss rate estimates;

- there is no predicted change in dam storage (ΔV_D), ie reduction during a dry year or increase during a wet year, for the high discharge S3 scenario as the dam is predicted to be full at the beginning and end of the year;

- increased controlled releases ($Q_{Release}$) and dam spill ($Q_{Overflow}$) result in increasing estimates of river recharge to the groundwater system (Q_{River}) downstream of the dam as well as increased river flows out of the model domain ($Q_{River\ Out}$);

- increasing dam discharge (Q_{Mine}) scenarios result in increases in estimated evaporative losses from the groundwater system (ET);

- the water balance scenario summaries indicate that a major component of the incremental increases in surplus mine discharge are potentially lost from the system through evaporation, from both Ophthalmia Dam (E_{Dam}) and the groundwater system (ET);

- increases in groundwater ET are largely driven by enhanced groundwater recharge from increases in dam seepage ($Q_{Dam\ Seep}$) and river recharge (Q_{River}); and

- surplus water released from Ophthalmia Dam, either as a controlled release ($Q_{Release}$) and/or dam spill ($Q_{Overflow}$), which is more than the river recharge rate (Q_{River}) downstream of the dam is likely to continue to flow further downstream.

Table 5.4 Water balance model results summary statistics

Scenario	Hydrological Scenario	Ophthalmia Dam			Groundwater System Maximum Salinity				
		Median Storage	Median Salinity	Maximum Salinity	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
S1	Dry	10,018	575	1,444	1,502	1,536	2,024	2,101	1,584
	Average	17,132	429	1,393	1,405	1,581	1,977	2,064	1,560
	Wet	18,410	371	1,319	1,353	1,637	1,974	2,046	1,569
S2	Dry	8,784	366	2,112	1,411	1,461	1,942	1,982	1,474
	Average	15,679	342	2,212	1,323	1,518	1,921	1,955	1,477
	Wet	18,012	296	1,990	1,290	1,586	1,924	1,928	1,488
S3	Dry	11,292	723	1,966	2,022	1,586	2,066	2,191	1,817
	Average	17,621	511	1,925	1,793	1,599	2,002	2,123	1,784
	Wet	19,739	427	1,711	1,750	1,658	1,983	2,097	1,793

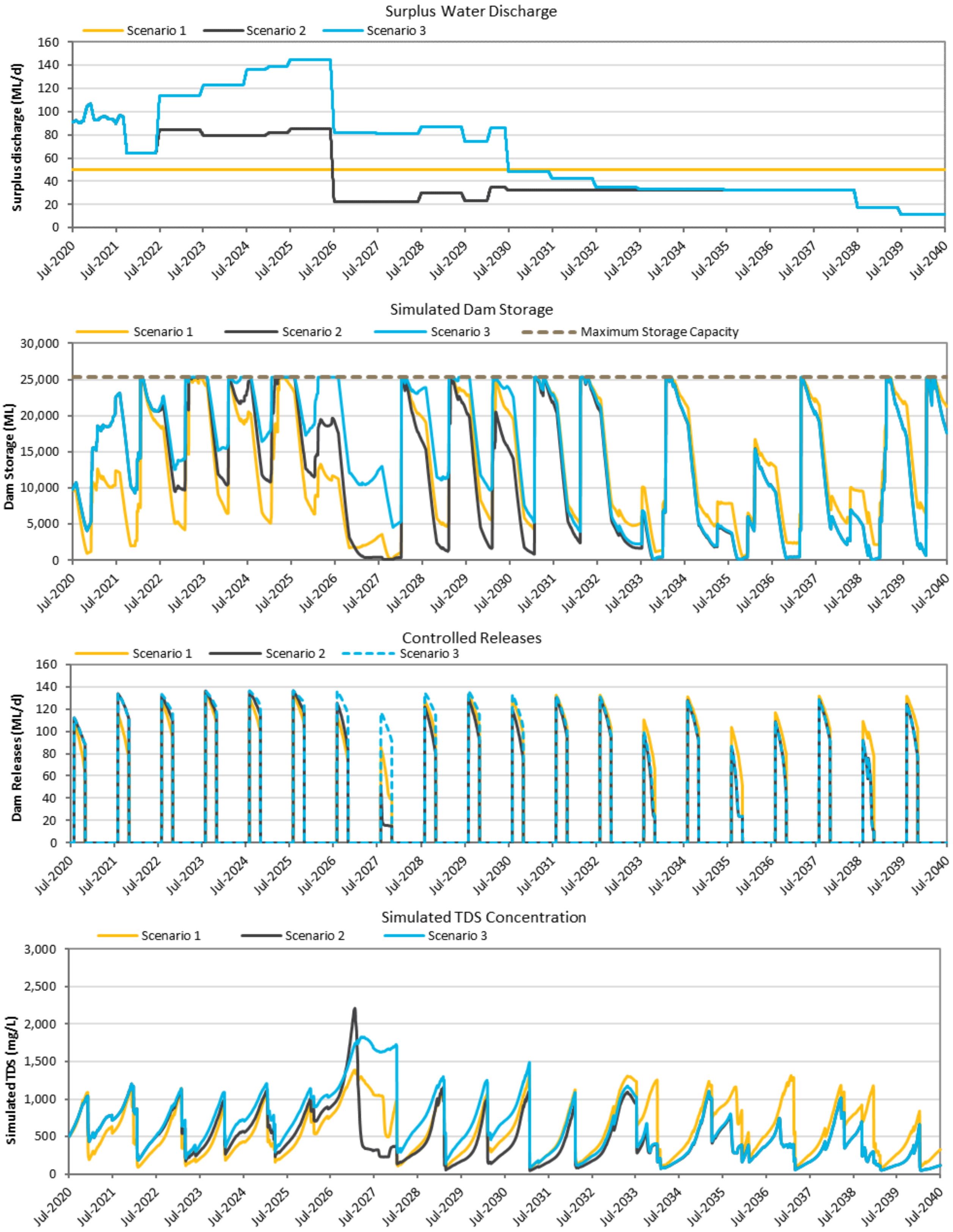


Figure 5.6 Ophthalmia Dam water balance comparison, Scenario 1, 2 and 3 (Realisation No. 13)

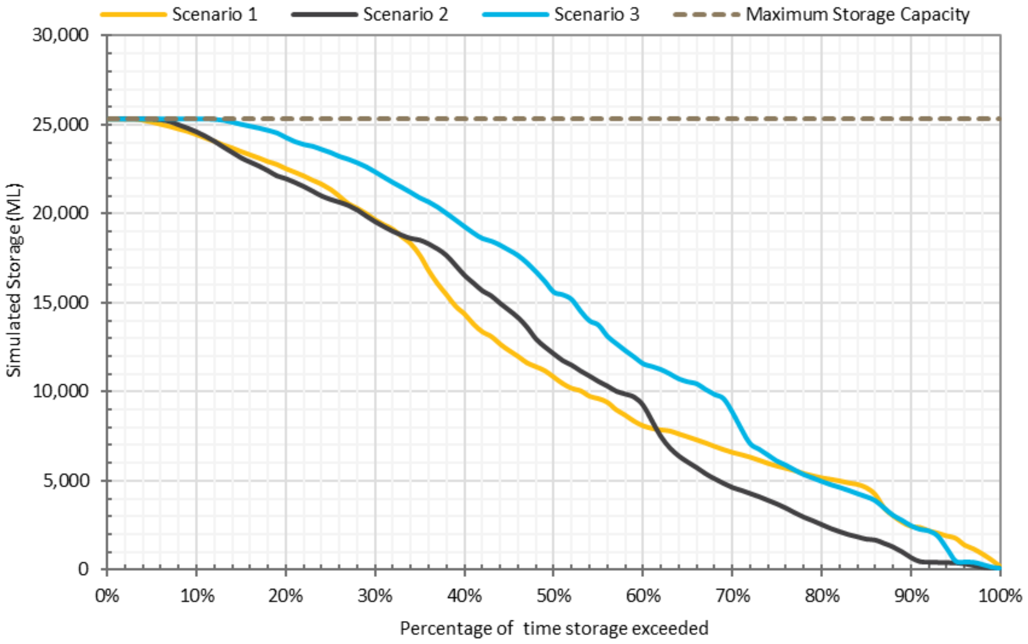


Figure 5.7 Storage duration curve comparison, Scenario 1, 2 and 3 (Realisation No. 13)

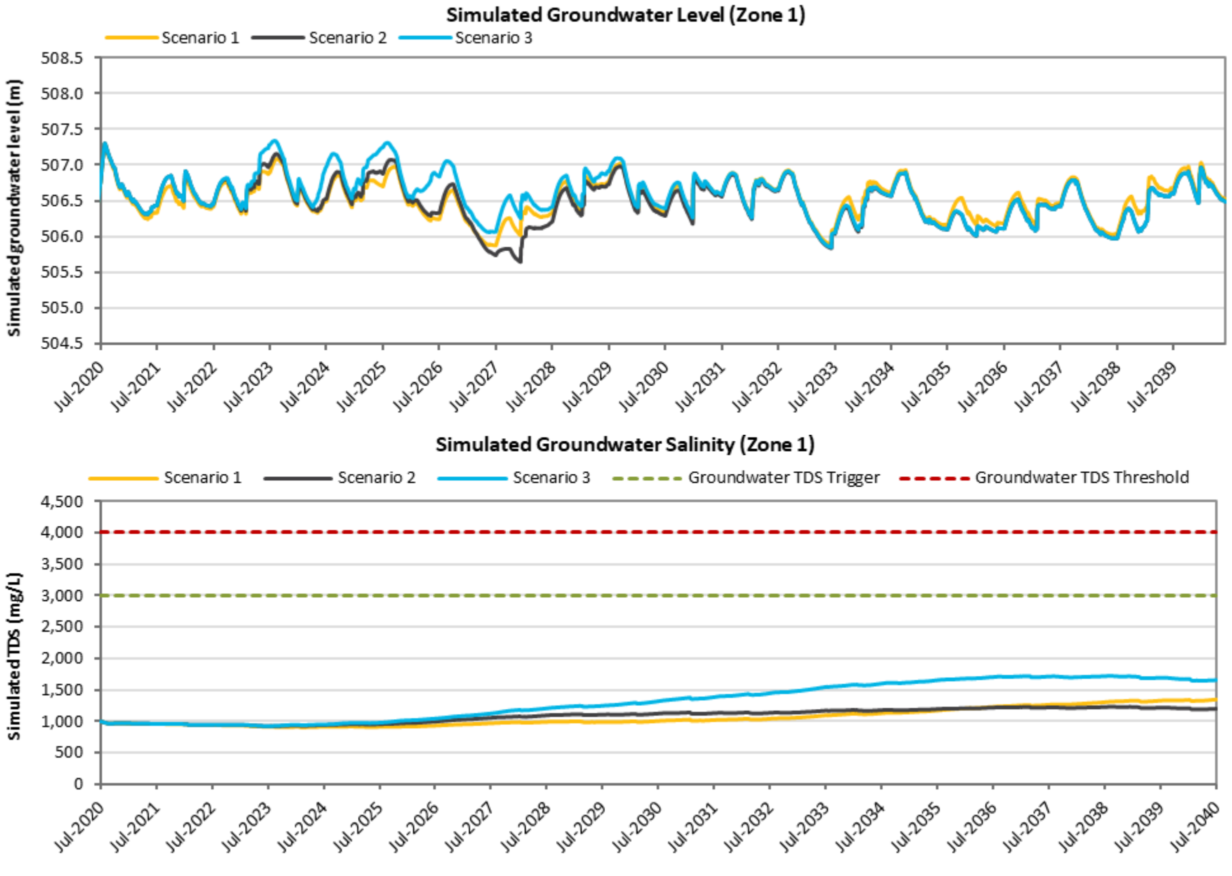


Figure 5.8 Simulated model zone 1 groundwater level and salinity, Scenario 1, 2 and 3 (Realisation 13)

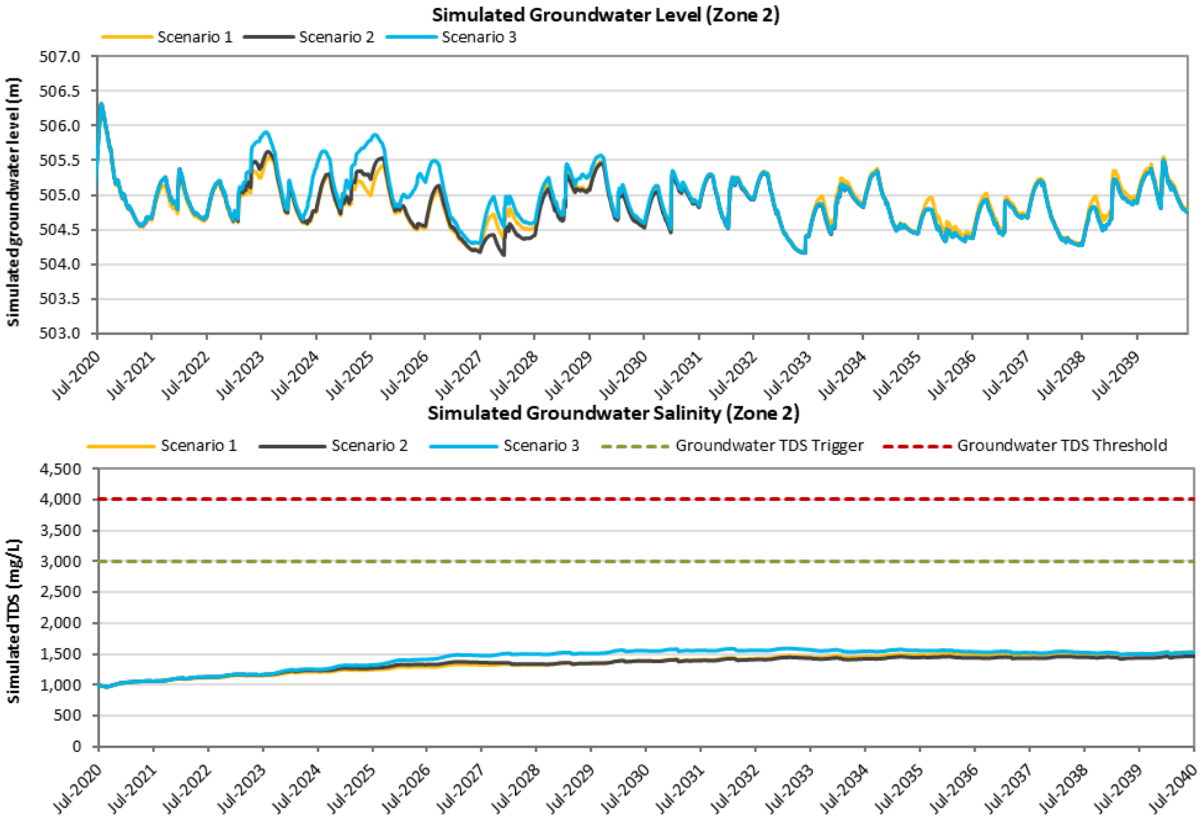


Figure 5.9 Simulated model zone 2 groundwater level and salinity, Scenario 1, 2 and 3 (Realisation 13)

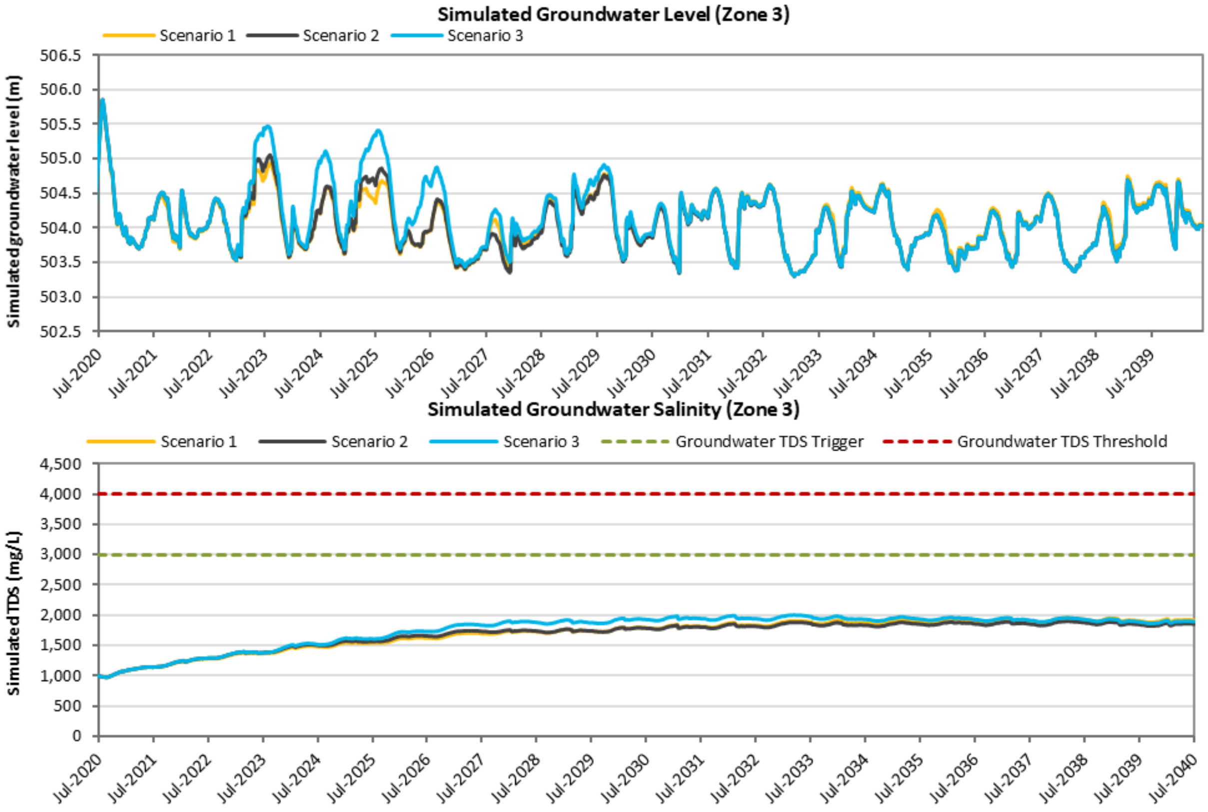


Figure 5.10 Simulated model zone 3 groundwater level and salinity, Scenario 1, 2 and 3 (Realisation 13)

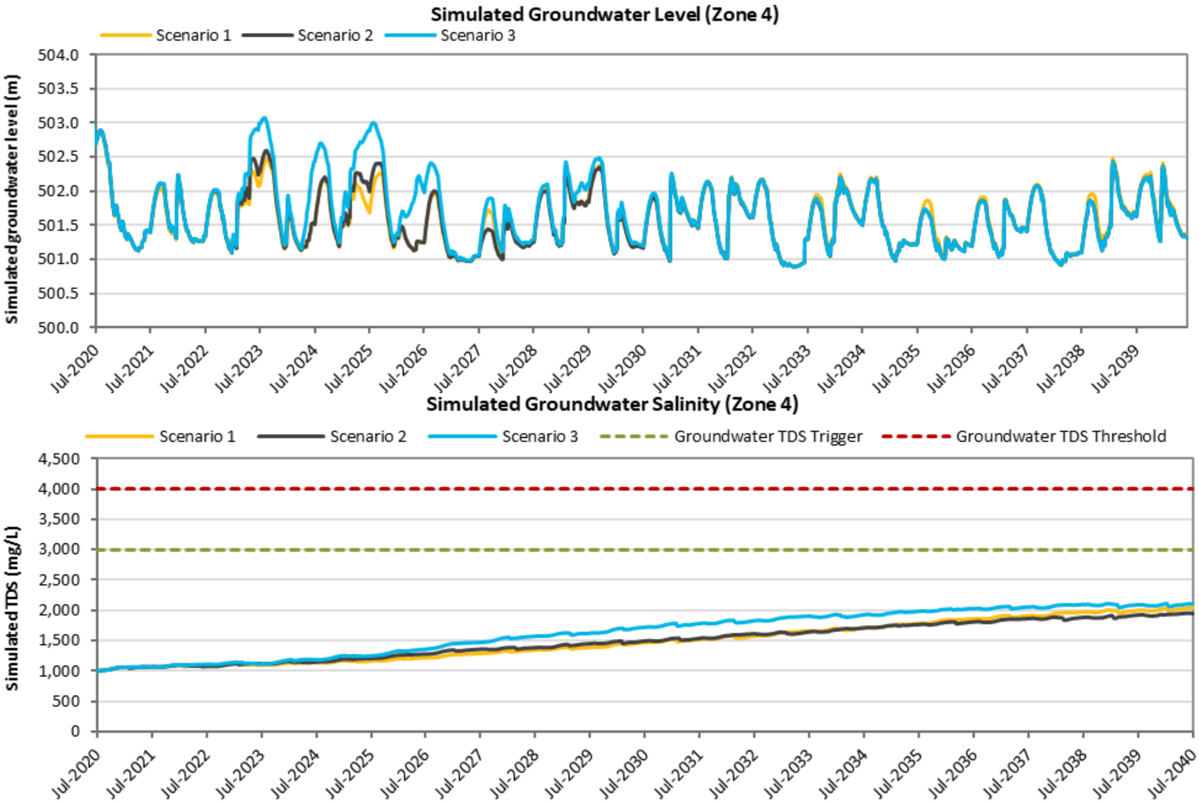


Figure 5.11 Simulated model zone 4 groundwater level and salinity, Scenario 1, 2 and 3 (Realisation 13)

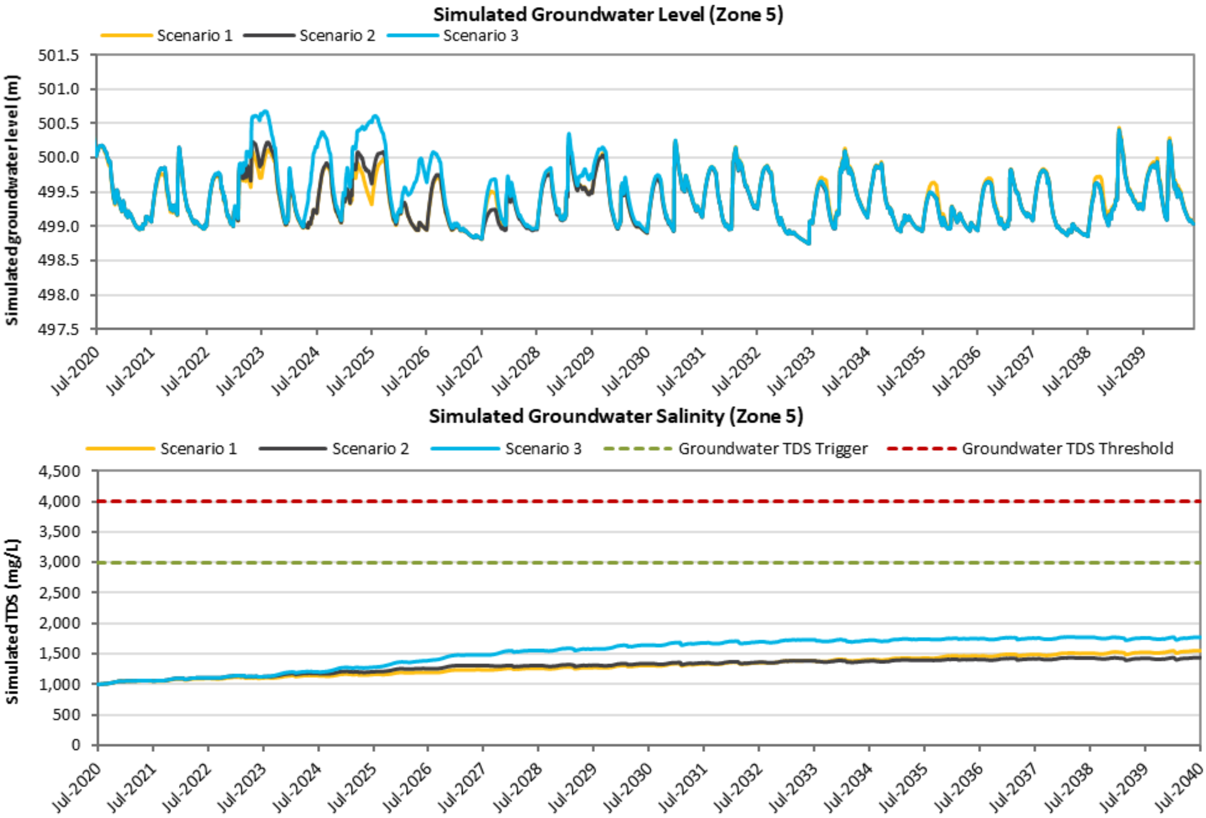
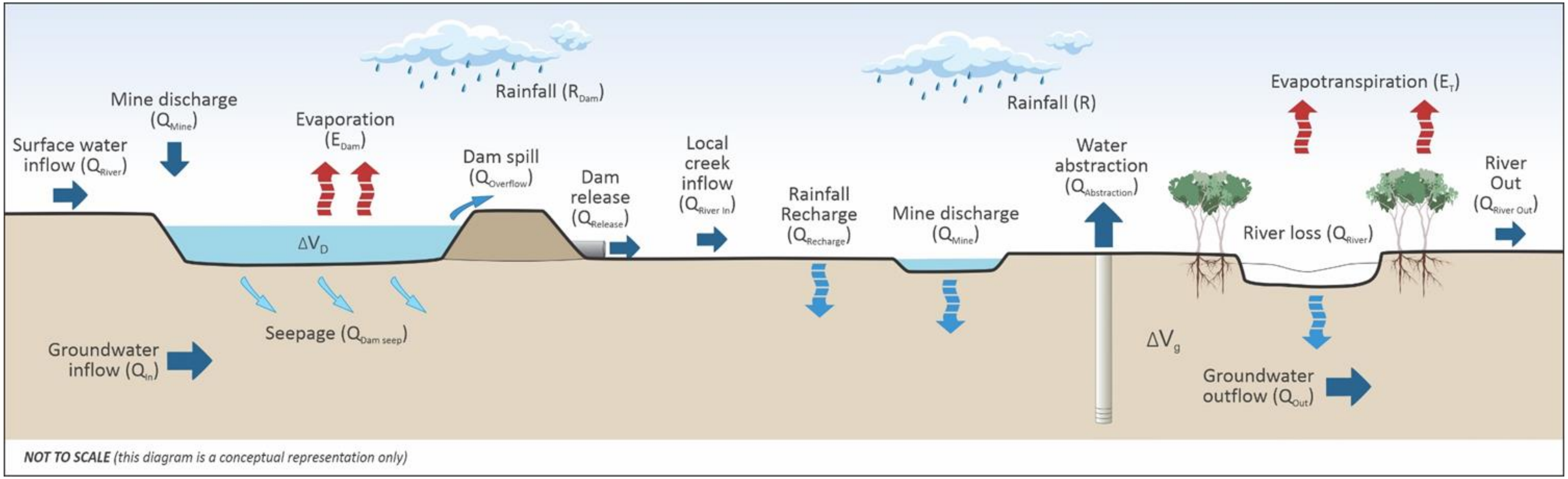


Figure 5.12 Simulated model zone 5 groundwater level and salinity, Scenario 1, 2 and 3 (Realisation 13)

Table 5.5 Annual water balance summary for Scenario 1, 2 and 3 surplus mine water discharge, Dry Year (2018-19)

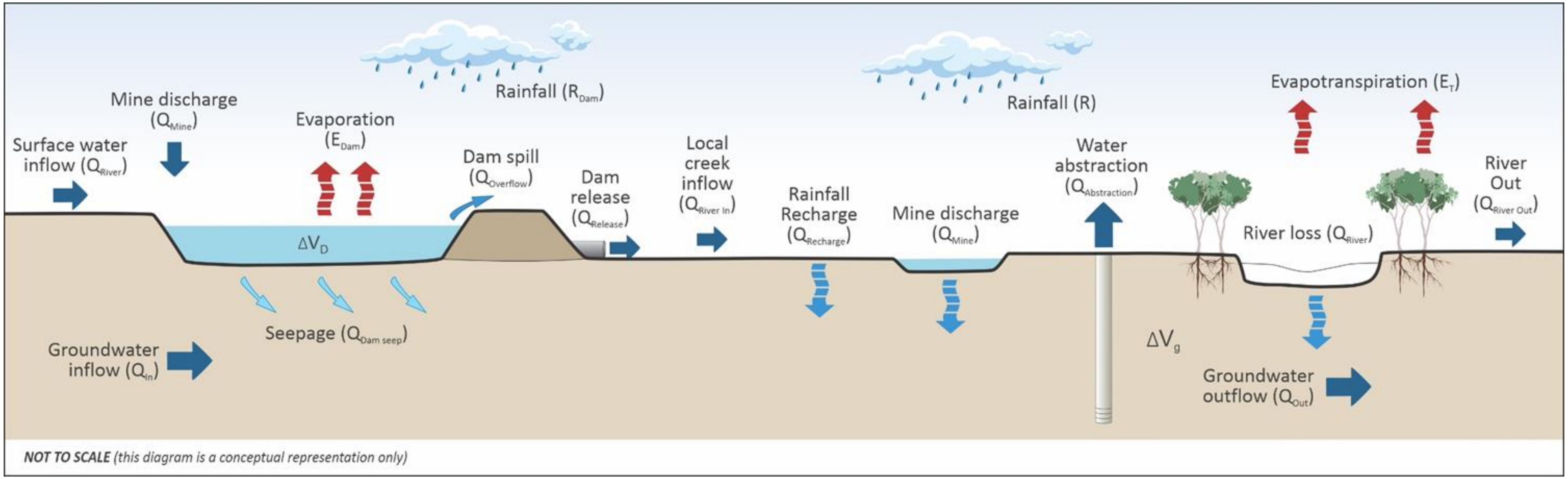


NOT TO SCALE (this diagram is a conceptual representation only)

	Dam Inflows (ML/d)			Dam Outflows (ML/d)				Change in Storage (ML)	Local Creek Inflow (ML/d)	Groundwater Inflows (ML/d)					Groundwater Outflows (ML/d)			Change in storage (ML)	River Outflow (ML/d)
Scenario	Q_{River}	Q_{Mine}	R_{Dam}	E_{Dam}	$Q_{Dam\ Seep}$	$Q_{Overflow}$	$Q_{Release}$	ΔV_D	$Q_{River\ In}$	Q_{In}	$Q_{Recharge}$	$Q_{Dam\ Seep}$	Q_{River}	Q_{Mine}	Q_{Abs}	ET	Q_{Out}	ΔV_G	$Q_{River\ Out}$
S1	0.1	50.0	1.2	23.9	26.3	0.0	23.9	-8,288	0.0	1.5	0.1	26.3	9.8	11.9	13.0	37.1	2.4	-1,027	14.1
S2	0.1	82.4	2.6	47.9	31.6	0.0	29.7	-8,686	0.0	1.5	0.1	31.6	10.5	11.9	13.0	42.6	2.4	-893	19.2
S3	0.1	142.4	4.2	71.8	36.9	5.4	32.9	0	0.0	1.5	0.1	36.9	13.4	11.9	13.0	54.1	2.4	-2,116	25.0

Notes:
1. Inflow and outflows presented as daily averages for the year
2. Change in storage (Ophthalmia Dam and groundwater system) presented as total change over the year

Table 5.6 Annual water balance summary for Scenario 1, 2 and 3 surplus mine water discharge, Wet Year (2000-01)



NOT TO SCALE (this diagram is a conceptual representation only)

Scenario	Dam Inflows (ML/d)				Dam Outflows (ML/d)			Change in Storage (ML)	Local Creek Inflow (ML/d)	Groundwater Inflows (ML/d)					Groundwater Outflows (ML/d)			Change in storage (ML)	River Outflow (ML/d)
	Q_{River}	Q_{Mine}	R_{Dam}	E_{Dam}	$Q_{Dam\ Seep}$	$Q_{Overflow}$	$Q_{Release}$	ΔV_D	$Q_{River\ In}$	Q_{In}	$Q_{Recharge}$	$Q_{Dam\ Seep}$	Q_{River}	Q_{Mine}	Q_{Abs}	ET	Q_{Out}	ΔVG	$Q_{River\ Out}$
S1	239.7	50.0	14.2	51.6	33.6	181.3	28.7	3,276	47.2	1.5	1.6	33.6	18.4	11.9	13.0	48.8	2.4	1,041	238.9
S2	239.2	82.4	16.7	62.7	35.9	205.9	31.4	1,002	47.1	1.5	1.6	35.9	20.1	11.9	13.0	52.3	2.4	1,203	264.3
S3	239.3	142.4	18.9	71.6	37.6	258.9	32.9	0	47.2	1.5	1.6	37.6	27.3	11.9	13.0	63.5	2.5	351	311.6

Notes:
1. Inflow and outflows presented as daily averages for the year
2. Change in storage (Ophthalmia Dam and groundwater system) presented as total change over the year

6 Conclusions

This report details the review and update of the East Pilbara Hub water balance model undertaken to support the BHP's Eastern Pilbara Surplus Water Strategy and provide an improved understanding of the capacity of Ophthalmia Dam with respect to accepting future mine water surplus discharge. Specific modelling analyses and assessments have been undertaken to provide an improved estimate of the sustainable water management capacity of Ophthalmia Dam to support both the design capacity requirements for future surplus schemes and environmental approvals.

The following points provide a summary of the key outcomes and conclusions from the model review and assessment of updated surplus water management scenarios:

- The Goldsim East Pilbara Hub water balance model has been shown to produce simulated dam water balance results that closely match observed Ophthalmia Dam water levels and quality (TDS concentrations) leading to a high level of confidence in the Ophthalmia Dam water balance predictions.

- The groundwater component of the model can replicate observed water level and salinity data and trends reasonably well and is considered fit-for-purpose. However, owing to the spatial and temporal variability in groundwater levels and quality, and the model assumptions and numerical algorithms used to approximate the Ethel Gorge groundwater system, predictions should be used to identify trends and magnitude of change, rather than be considered accurate predictions of future groundwater conditions at a specific location.

- The model predictions of groundwater level and salinity remain within (i.e. below) the criteria specified within the EPWRMP (BHP, 2018) throughout the simulated 20-year model period and under varying hydrological scenarios.

- The 'dry' model runs predict that the potential maximum capacity of the dam to manage surplus water via infiltration, evaporation and controlled discharge, without overtopping of the Dam during the dry season, is approximately 115 ML/d (42 GL/a) without any controlled discharge from the C wall valve, and potentially up to 135 ML/d (49 GL/a) with a 3-month annual controlled discharge.

- To maximise the potential surplus water capacity of the dam (ie at ~135 ML/d), a 3-month, dry season release of water from the C wall valve would be required each year. The operation of the controlled release from the dam has been shown to provide an increase in the potential surplus water management capacity of the dam and therefore reduced the occurrence of artificial (i.e. not rainfall-induced) overtopping of the Dam spillway.

- During the modelled 3-month dry season release of water from the C wall valve, up to 10.1 GL of water is predicted to be released in total, based on an estimated average controlled discharge rate of 113 ML/d over the 90 days. This compares to the 9.4 GL of water that was released during the 3-month release trial conducted by BHP in 2017.

7 References

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Appendix A

Ophthalmia Dam and groundwater system water balance - performance review outputs

A.1 Ophthalmia Dam- historic simulation vs observed storage volume

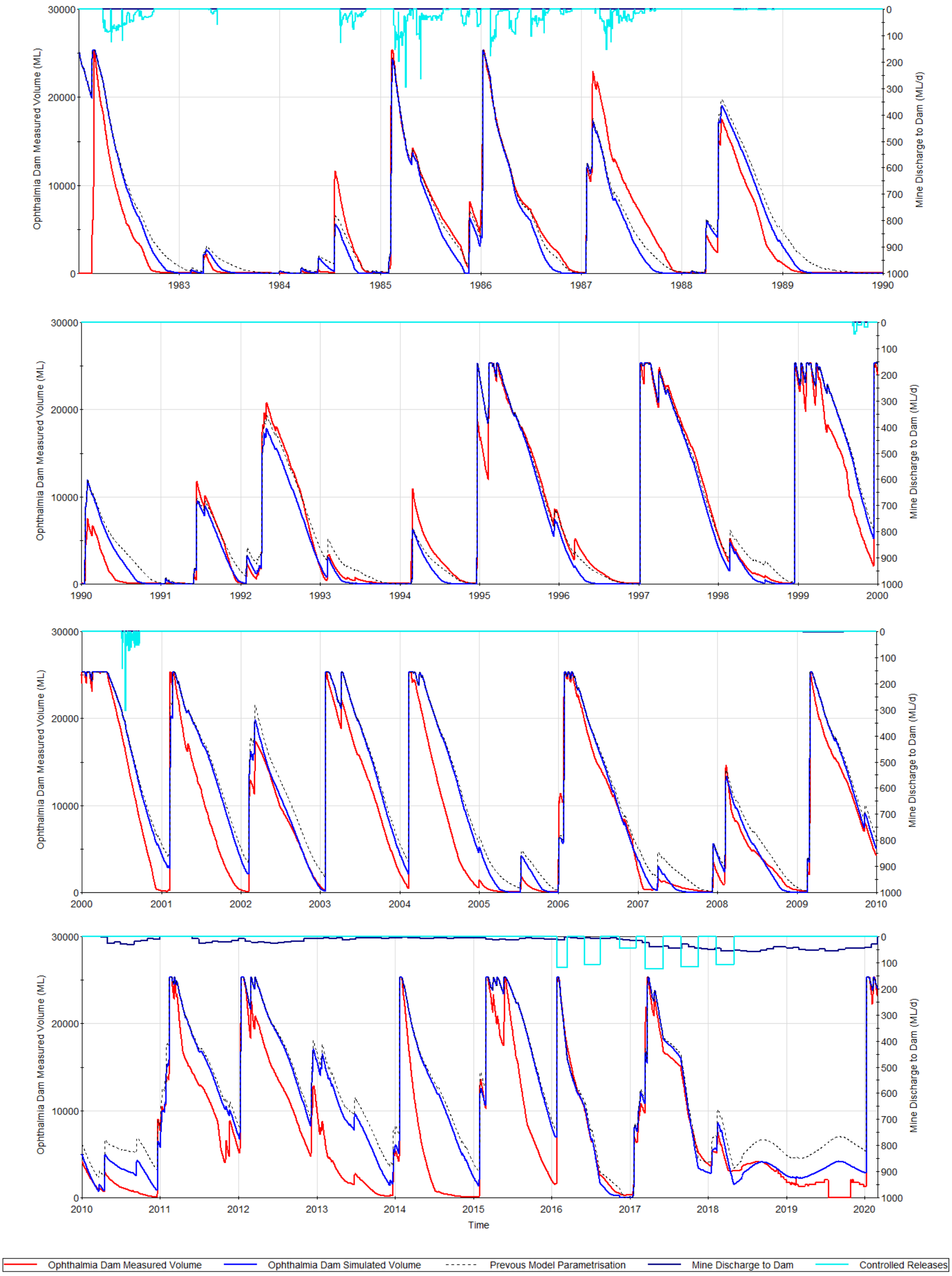

Figure A.1 Ophthalmia Dam water balance – Observed, simulated and Golder (2019) model parameter simulated water storage

A.2 Groundwater system- historic simulation vs observed water elevations

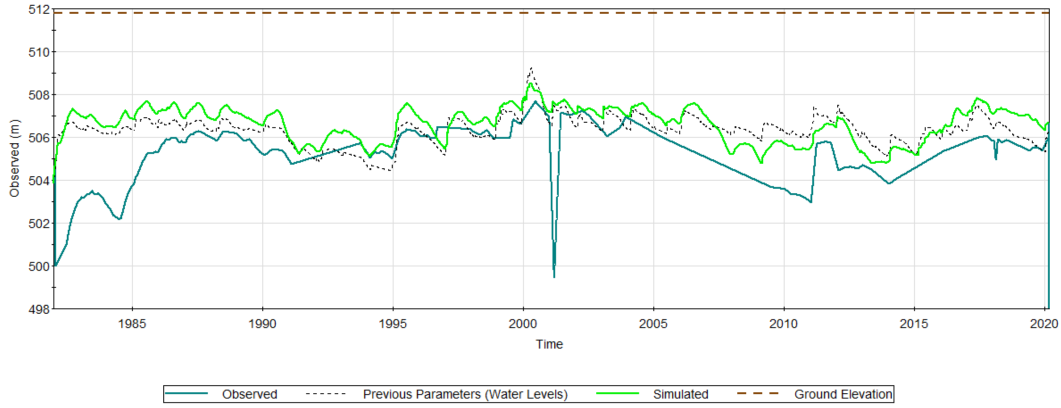

Figure A.2 Zone 1, EEX0931M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

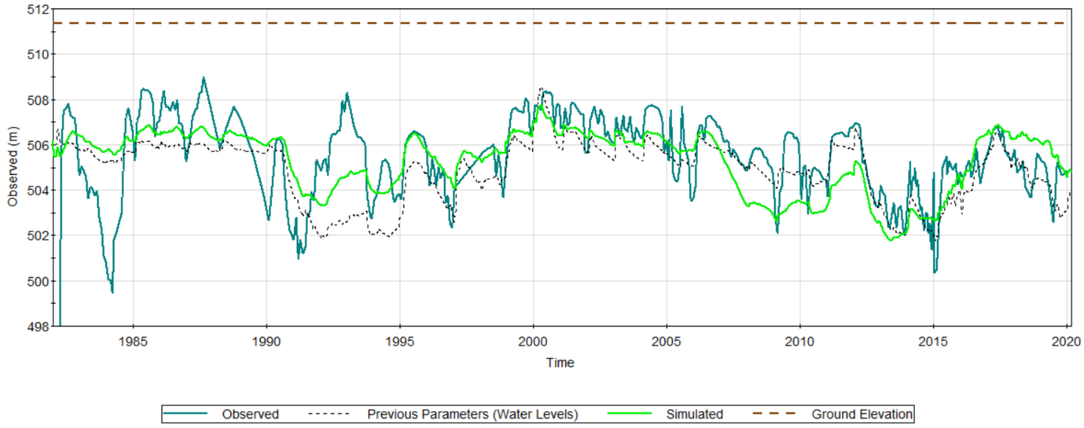

Figure A.3 Zone 1, HEOP0798M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

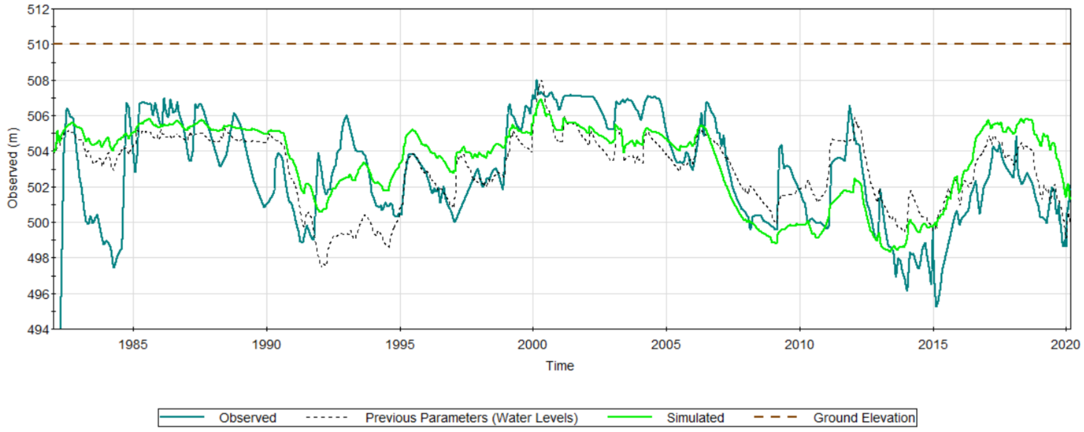

Figure A.4 Zone 2, HEOP0387M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

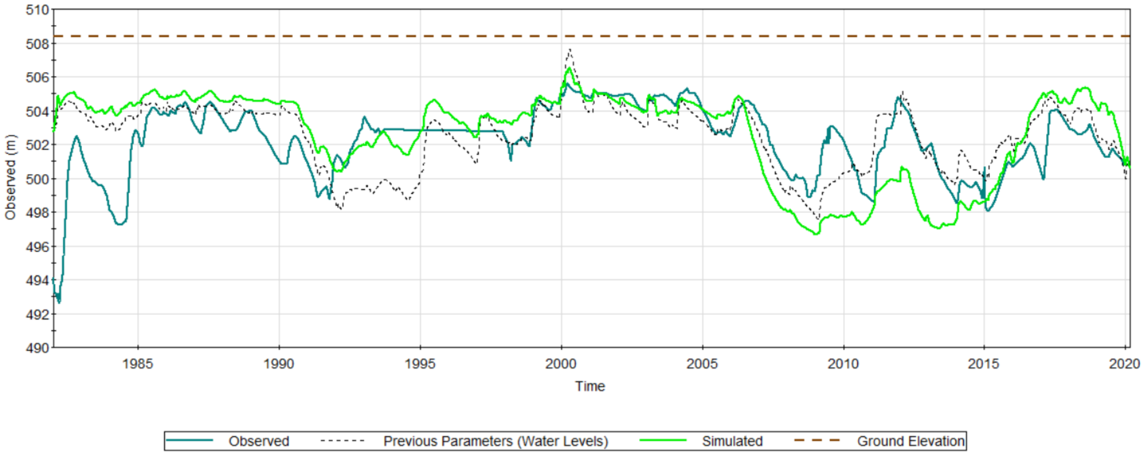

Figure A.5 Zone 2, HEOP0415M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

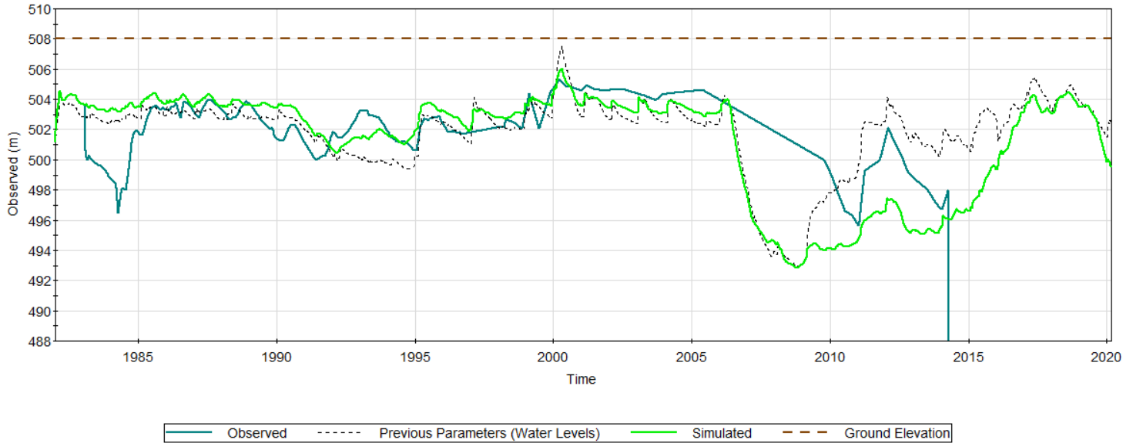

Figure A.6 Zone 3, HRZ0048M1 – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

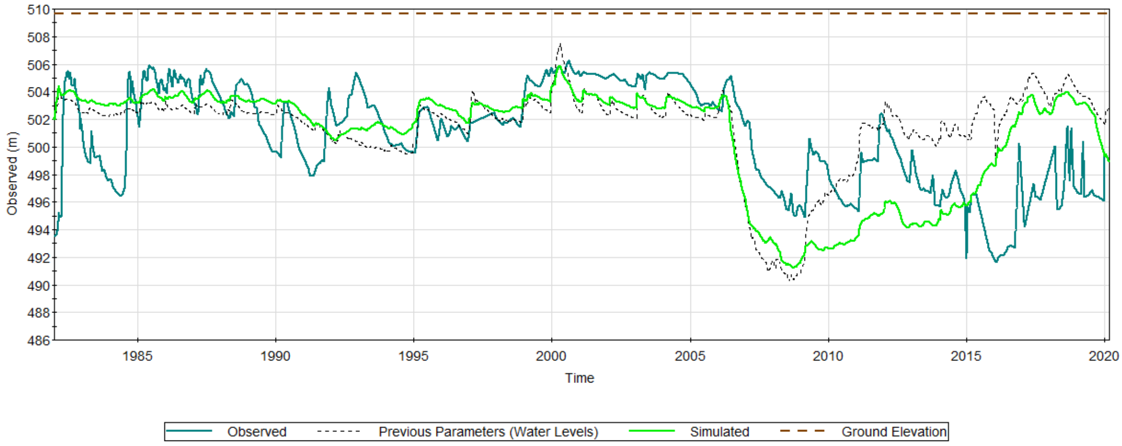

Figure A.7 Zone 3, HEOP0548M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

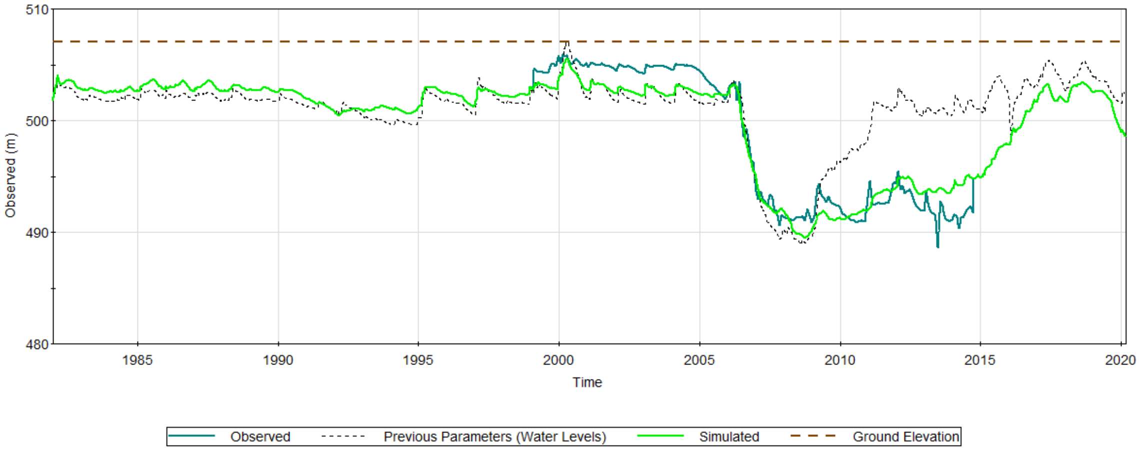

Figure A.8 Zone 3, HEA0119M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

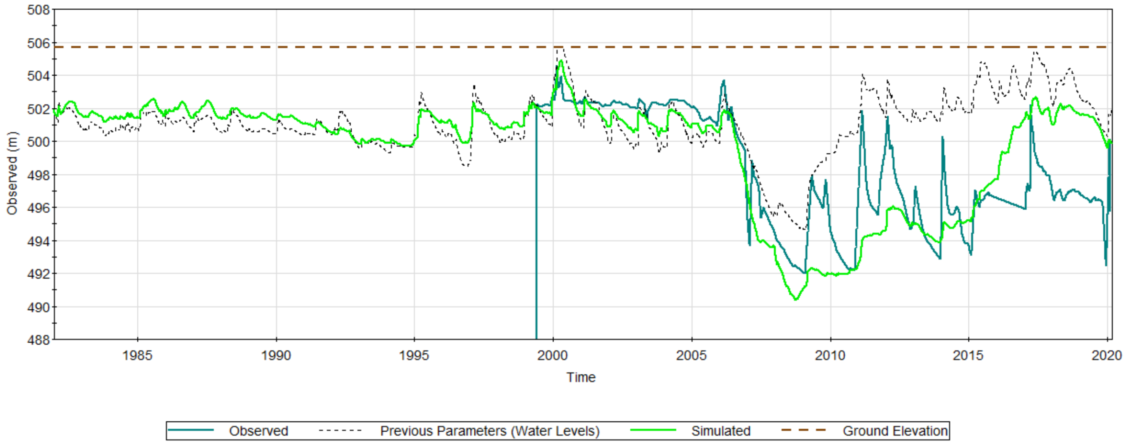

Figure A.9 Zone 4, HEA0139M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

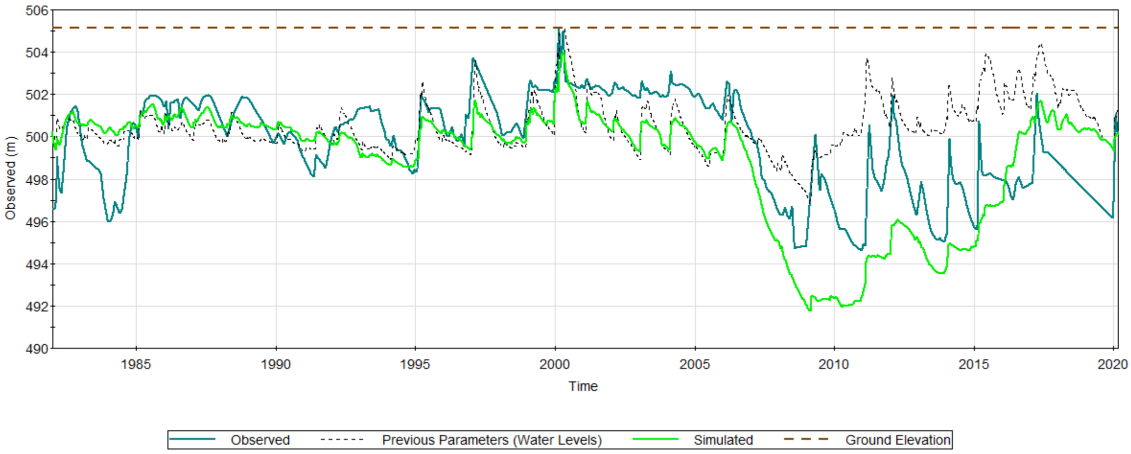

Figure A.10 Zone 4, HEOP0574M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations

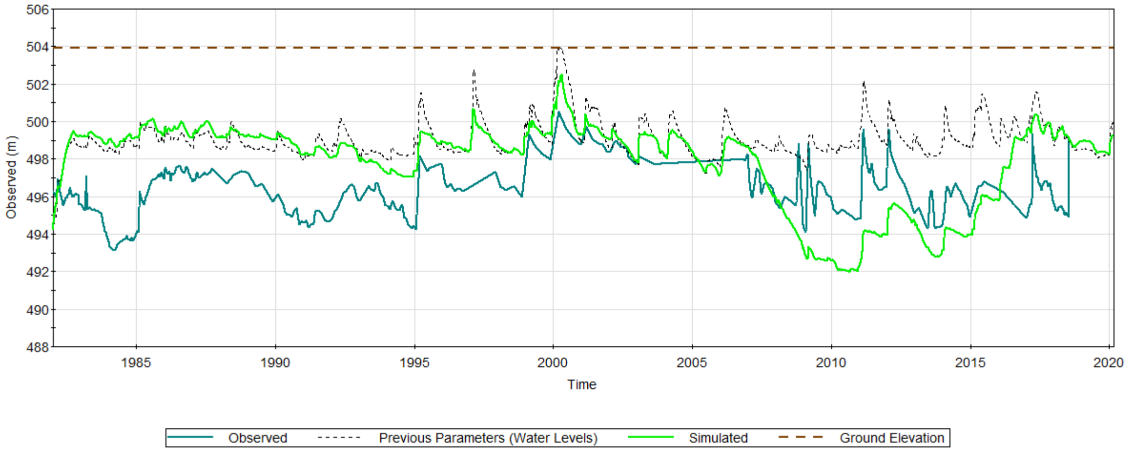

Figure A.11 Zone 5, T0401M – Observed, simulated and Golder (2019) model parameter simulated groundwater elevations www.emmconsulting.com.au