# GHD Pty Ltd

## Z SYSTEM GROUNDWATER INTERACTION

**PSM3200 MARCH 2017**

CONTENTS



FIGURES

# 1 INTRODUCTION

A groundwater modelling study was conducted to characterise the Muja Mine Z System (Z System) mined void storage volumes and water quality as a consequence of diverted stream flow. Z System refers to the mined void and associated pit-lake environment.

The project components include:

- Diverting approximately 13 GL/annum of saline flows from the Collie River East Branch at Buckingham,
- Storage of the diverted flows in Z System,
- Desalination of water stored in Z System, and
- Delivery of approximately 20 GL/annum of raw potable water sourced from Z System to Harris Dam.

The diverting of stream flow into Z System will alter its water balance, changing pit-lake elevations, pit-lake water quality and interactions with the local groundwater environment. Groundwater modelling was undertaken to identify the issues, constraints and sensitivities regarding storage of saline river water in Z System in context to the viability of the wider project. Specific objectives include:

- Quantification of losses (or gains) of water stored in Z System to the surrounding formation, and
- Quantification of the changes in the stored water quality as a consequence of interaction of the stored water with the groundwater environment.

# 2 Z SYSTEM CHARACTERISATION

## 2.1 Aquifer Systems

Z System occurs within the Premier Sub-area, within the Premier Sub-basin, of the Collie Groundwater Area. The Premier subareas contain eight separate aquifers (as shown in Table 1 (DoW 2009).

Z System occurs in the southern lobe of the Muja Mine. A plan view of the mine setting in context to then Collie Group stratigraphy is shown in Figure 2.1. The figure shows the Muja Mine was developed in the Muja Coal Measures. The Muja Coal Measures are bounded to the west by crystalline bedrocks of the Stockton Ridge and to the east by the Eastern Fault and Premier Coal Measures. The Eastern Fault was exposed in the eastern pit walls and generally considered to be of low-transmissivity (Groundwater Resource Consultants 1989). Beneath the mined profile there is Premier Coal Measures.

The low-transmissivity of the Eastern Fault compartmentalises the Muja Coal Measures and the Z System setting. In effect the fault is interpreted to form a barrier to groundwater flow, allowing only minor flows to laterally and vertically traverse the fault zone. This circumstance tends to predominantly isolate the Z System from other groundwater stresses in the Premier Sub-basin.

**TABLE 1**
**AQUIFER SYSTEMS OF PREMIER SUB-AREAS**

| AQUIFER | AQUIFER SYSTEM – RESOURCE GROUP |
|---|---|
| Superficial Sediments | Nakina |
| Nakina Formation | |
| Muja Coal Measures | Muja |
| Premier Coal Measures | Lower Collie |
| Allanson Sandstone | |
| Ewington Coal Measures | |
| Westralia Sandstone | |
| Moorhead | Stockton |
| Shotts | |

Within the Premier Sub-area (hence Z System) all of the Muja Coal Measures have been mined and the mined areas predominantly backfilled by undifferentiated interburden strata from run-of-mine operations. Schematic north - south and east - west cross-sections of Z System are shown on Figure 2.2 and Figure 2.3, respectively. These figures show the Muja Coal Measures took the form of a double-plunging synclinal fold (egg-carton shape); Figure 2.2 shows the presence of a structural-high in the fold-form on the north-south alignment. The structural high peaks at 110 m AHD. This is a strata-bound feature, not necessarily a hydraulic barrier.

The geometry of Z System is important in terms of simulating the pit-lake water balance. The geometry of Z System was characterised based on 1 m topographic contours provided by GHD (dated 31 July 2014). These contours are available to an elevation of 80 m AHD; presumably the pit lake water level at the time the DTM was captured. Below 80 m AHD the Z System geometry is based on the Muja Premier Final Landform design (dated 18 September 2015). Figure 2.4 illustrates the geometry of the void.

The hydrology of Z System is potentially influenced by nearby mining activities in addition to climatic factors. In the void setting, there is also a large amplitude of residual drawdown and potential for future change linked to nearby active mining in Pit 3 and Pit 1 Deeps, Premier Mine. The pit lake elevation has been monitored on an *ad hoc* basis since October 2008 as shown in Figure 2.5 and has shown a steady increase over that time from 74.09 m AHD to the current (23 January 2017) elevation of 109.1 m AHD. These data provide opportunity to characterise the water balance of Z System.

In the periphery of Z System the groundwater environment will show recovery trends compatible to the rise in the pit-lake elevation. The backfill and formations adjacent to the void are hydraulically connected to the pit-lake, part of a continuum, and will behave in concert with the pit-lake elevation. Contextually, the pit-lake is a sink, being recharged by groundwater inflow. The groundwater flow will be towards the pit-lake under the hydraulics gradients that prevail in the backfill and juxtaposed formations.

## 2.2 Water Quality

The groundwater in the Collie Basin is naturally acidic, commonly with pH less than 5 and usually between 3 and 4 in mined voids. The acidity is attributed to the presence of sulphide-bearing sediments within and limited buffering capacity of the coal measures successions. Where oxidation occurs, such as in mining exposures and where the water table has been lowered, the sulphide minerals tend to become increasingly acid forming, giving rise to the lower pH environments associated with in-pit sumps, underground coal mine working and final voids. The acidic environment provides propensity for dissolution and mobilisation of metals stored in the coal seams and argillaceous sediments of the coal measures. Commonly in the mined voids, the metals aluminium, iron, nickel and zinc exceed ANZECC & ARMCANZ (2000) guidelines for freshwater ecosystems.

Figures 2.6 through Figure 2.8 inclusive illustrate the evolution of water chemistry over the same period. These data indicate the pit lake water is brackish and acidic. Acidity is linked to oxidation of pyrite from strata that lack buffering capacity. Metals aluminium, iron and zinc are accumulated to concentrations that exceed the ANZECC & ARMCANZ (2000) freshwater guidelines. Measured aluminium and zinc concentrations range up to 16 and 2.4 mg/L, respectively. Also, the concentrations of aluminium and zinc show a broad range of transient fluctuations. The measured concentrations are expected to:

- Reflect near-shore shallow sampling that may not be entirely representative, and
- Be predominantly linked to desorption from the backfill Muja Coal Measures under acidic conditions rather than evapo-concentration.

The lake is also expected to be stratified, but with thermal gradients promoting transient mixing and overturning of the stored waters. A comparison between the Z System metals concentrations and those measured in the Chicken Creek mined voids during 2004 (Centre of Excellence for Sustainable Mine Lakes 2007) is provide is provided in Table 2.

**TABLE 2**
**COMPARATIVE VOID WATER QUALITIES**

| PARAMETER | CONCENTRATION (mg/L) | |
|---|---|---|
| | Z SYSTEM (2015) | CHICKEN CREEK VOID |
| Aluminium | 15 | 15 - 16 |
| Nickel | - | 0.3 |
| Iron | 3.5 | 0.2 - 3.3 |
| Zinc | 2.2 | 0.8 – 1.2 |

It is difficult to know if the measured metals concentrations in Z System will stabilise or increase over time.

The available data show wide variations over time and this may be attributed to several factors. Based on experience in the Collie Basin there is expectation that the pit-lake water qualities in context to acidity and metals concentrations will depend on:

- Loadings received from rainfall runoff,
- Diverted stream flow interactions with the void sidewalls and backfill materials, and
- Residence times.

These cumulative aspects provide uncertainty regarding actual transient pit-lake acidity and metals concentrations.

Experience shows that short-term residence times (several months or less) usually is sufficient to result in increased acidity and resultant pH less than 4.0. In this respect, it is also anticipated that the temporary wetting of the backfill profile with season divertible stream flow will provide opportunity and sufficient residence time for reaction with oxidising sulphates and resultant increased acidity. Presumably, the backfill hosts a large bank of sulphide minerals, though they may have differential concentrations/loadings and random oxidisation and mobilisation potentials. Similarly for metals hosted by the Muja Coal Measures. It is assumed there is a large bank of potential loading in storage, but the release mechanisms and concentrations may vary widely over time.

These aspects make the prediction of transient pH and metals concentrations difficult. This perspective is reinforced by consideration of the measured transient TDS (Figure 2.6) and metals (aluminium, zinc, iron and manganese; Figure 2.8) concentrations. These data typically show fluctuation across a range up to an order of magnitude, but perhaps noting that lowermost concentrations (generally prior to 2003 when Z System was an operating sup in an active mine) have not been replicated. From a practical perspective, the causes of the observed concentration fluctuations are likely to be a result of cumulative influences that are difficult to discretise and quantify.

## 3 STREAM FLOW DIVERSION

It is proposed that approximately 13 GL/annum of saline stream flow will be diverted from the Collie River East Branch at Buckingham and stored in Z System. The divertible flow volume and water quality were derived from daily data available for the period from 2002 to 2015.

The divertible flow volume is subject to several constraints, including:

- Annual and seasonal variability in stream flow,
- Minimum environmental flow requirements,
- Minimum salinity threshold, and
- Maximum pump capacity.

Historical stream flow and salinity data were obtained for the period from 2002 to 2016 and are shown in Figure 3.1. It is assumed that this 15-year sequence is, on average, representative of future stream flow expected at Buckingham, providing a transient synthetic series for input to the predictive modelling simulations.

The specified minimum environmental flow requirements were:

- 1 ML/day from November to June, and
- 3.5 ML/day from July to October.

Stream flow is only permitted to be diverted to Z System if salinity exceeds the minimum threshold of 1,750 mg/L. The maximum pump capacity was assumed to be 400 ML/day. Constraints on the divertible flow volume are also illustrated in Figure 3.1.

The above-mentioned constraints were implemented in a spreadsheet to determine the divertible stream flow volume as shown in Figure 3.2. This sequence was used as an input to the forward modelling of Z System.

## 4 LUMP PARAMETER WATER BALANCE MODEL

A transient water and salt balance was developed for Z System based on the available transient pit-lake elevation and quality data. The lumped parameter model used a daily time step and covered the period from 2008 to 2014 for which there were observations of both pit lake water level and salinity. Under existing conditions the water and salt balance comprises the following fluxes (as shown schematically in Figure 4.1):

- Rainfall,
- Runoff,
- Evaporation, and
- Groundwater Exchange.

The water balance fluxes were determined through a process of calibrating observed and modelled pit lake elevations for the period from 2008 to 2014. The surface water catchment was referenced from estimates provided by The Griffin Coal Mining Company Pty Ltd (2016) for Muja Void closure studies. The lumped parameter model only uses the physical attributes of the void and storage algorithm. As such it does not discretely consider the backfill profile nor the hydraulics that support groundwater inflow.

## 4.1 Direct Rainfall and Evaporation

Direct rainfall and evaporation are functions of climate and the pit lake surface area. Both fluxes are relatively well constrained by observed climate data and the known relationship between pit lake elevation and surface area.

The contribution of runoff and groundwater inflow/outflow to changes in pit lake storage are less well constrained. These fluxes were determined iteratively through the calibration process.

## 4.2 Runoff

Daily runoff is estimated based on Equation 1:

1. Daily Runoff = Runoff Coefficient x Surface Water Catchment Area x Daily Rainfall.

   Where Surface Water Catchment Area = 3.255 km$^2$.

For the first iteration, the groundwater contribution to the rise in pit-lake elevation was assumed to be negligible. Under this assumption, a surface water runoff coefficient of approximately 70 per cent was required to achieve a reasonable calibration. Runoff coefficients of 25 to 40 per cent (average about 32 per cent) were developed based on 10 years (1980 to 1989) of rainfall and pumping data from the Muja Mine (Groundwater Resource Consultants 1989). The application of a 32 per cent runoff coefficient indicates that surface water inflow alone is not likely to be responsible for the observed transient rise in pit-lake elevation and that groundwater inflow is likely to be a significant contributor. That is the pit-lake acts as a groundwater sink, being the fate of all groundwater flow in the coal measures succession compartmentalised by the Eastern Fault. A runoff coefficient of 32 per cent was adopted to reflect the relatively high runoff rates expected in the catchment.

## 4.3 Recharge from Rainfall

The major source of groundwater recharge is from rainfall. Across the majority of the Collie Basin estimates of recharge range from 9 to 14 per cent of mean annual rainfall, with an average of 10 per cent.

To close the water balance the groundwater contribution must be determined. For this assessment, a simplistic approach towards determining the groundwater inflow was adopted as shown in Equation 2:

2. Groundwater Inflow = Recharge Coefficient x Groundwater Catchment Area x Daily Rainfall.

Recharge was assumed to be 10 per cent of annual rainfall based on the previous Muja Mine groundwater (Groundwater Resource Consultants 1989) and groundwater flow modelling (SKM 2010) studies. The groundwater catchment area was adjusted until a reasonable fit was achieved between observed and modelled water levels.

## 4.4 Modelled Water Balance

A comparison of observed and modelled lumped parameter water levels for Z System is shown in Figure 4.2. The comparisons reflect a reasonable model calibration. In this respect, however, it is import that the calibration only relates to pit-lake elevations up to about 110 m AHD.

The conceptual hydrogeological model and water balance frames Z System as a groundwater sink; that is net groundwater flow is from the aquifer to the mined void. The groundwater recharge catchment area was determined to be approximately 11 km$^2$. This correlated with the surface area bound between the Eastern Fault and the Stockton Ridge (11.3 km$^2$). There is evidence (Groundwater Resource Consultants 1989 and SKLM 2010) that indicates the Eastern Fault is a low-transmissivity barrier to groundwater flow. These two lines of evidence indicate that the ultimate groundwater catchment for Z System is constrained to the area located between the Eastern Fault and the Stockton Ridge as shown in Figure 2.1.

For the lumped parameter modelling purposes, it is assumed that complete instantaneous mixing of the diverted stream flow occurs in Z System. Source concentrations for groundwater and runoff salinity were estimated by calibration against observed TDS values for the lake. A comparison of observed and modelled salinity is shown in Figure 4.2. Assumed salinities for groundwater and surface runoff are 1,000 and 700 mg/L respectively. Confidence in the calibration of the salt balance is relatively low owing to several sources of uncertainty including a limited number of observations and chemical stratification of the pit lake. Further, there is recognition that saline groundwater was discharged into Z System from the nearby Buckingham 3 Pit from 2005 to 2008 and this may contribute to the higher than expected salt loadings.

In summary, the key attributes of the developed water balance includes:

- Direct rainfall to the pit-lake surface area,
- Rainfall recharge – 10 per cent of rainfall on 11.3 km$^2$ catchment area,
- Rainfall runoff – 32 per cent of rainfall on 3.255 km$^2$ catchment area, and
- Eastern Fault forming a barrier to groundwater flow, essentially forming a closed system with negligible interactions with the Premier Sub-basin groundwater environments north of the fault.

## 4.5 Forward Modelling

The water balance model was used to simulate the pit lake water balance under the proposed operational conditions. Note that the lumped parameter model is calibrated to an upper pit-lake elevation of about 100 m AHD and therefore is blind to influences that might alter the eater balance above this elevation.

The water balance for the operational system is shown in Figure 4.3 below. Additional fluxes relative to the existing conditions include inflow from Buckingham and outflow to desalination. Inflow from Buckingham was discussed in Section 3. The volume that can be provided to desalination is one of the outcomes of this study. The disposal volume was determined based on the following rules:

- Initial Disposal Start Level of 120 m AHD,
- Minimum Operating Level of 80 m AHD,
- Maximum Operating Level of 160 m AHD, and
- Maximum Disposal Rate / Desalination Capacity of 40 ML/day.

Fluxes for the average annual water balance are also shown in Figure 4.3. The results highlight that the fluxes due to stream diversion and disposal to desalination are significantly greater than the natural fluxes in the system. The average annual water balance also demonstrates that there is a net outflow resulting in depletion of storage. This suggests that the maximum disposal rate cannot be sustained indefinitely (based on a simple water balance approach).

Figure 4.4 shows the simulated pit lake water level for the 15-year simulation period. Based on the historical climate data the modelling indicates an initial net inflow to the pit. In the latter part of the sequence water is drawn from storage at a greater rate than it is replenished resulting in a decline in pit lake levels. Figure 4.5 illustrates the corresponding draw rates for disposal to desalination. The desalination feed can be sustained at capacity for a period where water is drawn from storage but eventually water levels approach the minimum operating level necessitating a reduction in the disposal rate.

Under base case conditions it is assumed that the pit acts as a sink and therefore groundwater always flows from the aquifer to the pit. The simplistic representation used for the water balance model means groundwater inflow is driven entirely by rainfall as shown in Figure 4.6.

### 4.6 Sensitivity Analysis

The effect of a ± 25 per cent change in key parameters on the pit water level and the subsequent salinity was assessed. Key parameters include:

- Recharge,
- Runoff,
- Evaporation, and
- Stream flow.

Pit water levels and rates of disposal to desalination are shown in Figures 4.7 and 4.8. Sensitivity to direct rainfall is low and not shown on the plots.

The results indicate that the model is not particularly sensitive to uncertainty in the parameters that govern the natural fluxes to the system. The performance of the system is, however, sensitive to the rate at which water can be diverted from Buckingham.

For the base case model groundwater exchange is a function of recharge only. The sensitivity is shown in Figure 4.9.

The sensitivity to salt load source concentrations was also evaluated. Results are shown in Figure 4.10. Z System salinity is most sensitive to stream flow salinity owing to its high concentrations (average 6,600 mg/L) and high flows.

### 4.7 Scenario Analysis – Drought Conditions

The sensitivity of the water balance to drought conditions was assessed by synthetically introducing droughts into the historical climate record and using the subsequent data to drive the water balance.

The historical rainfall record for Collie (BoM Station 009628) shows that the lowest rainfall year on record was 2010 and that low rainfall years generally do not occur for more than 2 years in a row. For this assessment, a drought was defined as two years of rainfall equal to that occurring in 2010.

Drought conditions were synthesised by introducing 2010 rainfall, evaporation and stream flow data at various points in the climatic data sequence to determine the impact of a drought on pit water levels and disposal volumes relative to the base case conditions. The worst-case scenario was determined by selecting the time series with the largest deficit in the volume disposed to desalination relative to the base case.

The worst-case scenario corresponds to a drought occurring in Years 5 and 6 as shown in Figure 4.11 to 4.13. The largest modelled deficit in the volume that can be disposed to desalination is 7.8 GL/a.

### 4.8 Scenario Analysis – Groundwater Level

The conceptual hydrogeological model frames net groundwater inflow from the aquifer to the mined void. This concept is valid, as a minimum, up to about 110 m AHD as supported by the water balance model. There may, however, be a tipping point where, if exceeded by pit water levels, the stored water will infiltrate to the aquifer. The likelihood of a tipping point is unknown and may be dependent on factors that include:

- Changes to hydraulic characteristics of the Eastern Fault in higher elevation settings,
- Changes to flow paths in Premier Coal Measures at higher elevations, and
- Hydraulic gradients to the nearby Premier Mine, Pit 3 active (at least until mid-2022) dewatering and mining operations.

The following tipping points were assessed:

- 100 m AHD (representative of a decline in regional groundwater levels; that is due to future mine dewatering or reduced rainfall), and

- 110 to 160 m AHD (representative of the fact that the precise tipping point is unknown but likely to be greater than the current level of 109 m AHD, and that groundwater levels may begin to recover if mine dewatering is reduced).

Figures 4.14 to 4.15 show the effect of a tipping point on the pit water level and the disposal rate to desalination.

It is also of interest to quantify the losses (or gains) of water with the surrounding environment under alternative groundwater level scenarios. This is shown in Figure 4.16. Owing to the simplistic nature of the water balance modelling this is the only scenario where outflow to the aquifer is permitted in the setup of the water balance. As is to be expected, the results demonstrate that the lower the groundwater level the greater the outflow from the pit.

## 5 FEFLOW GROUNDWATER FLOW MODELLING

A numerical FEFLOW groundwater flow model was developed to address the project objectives in a more physically based manner. The lumped parameter water balance modelling was used to inform the conceptual hydrogeological model of the Z System and to determine the various model inputs and parameterisation.

### 5.1 Model Setup

The PSM Collie Basin FEFLOW model (a derivative of the Department of Water (2010) Collie Basin Model) was adapted to address the project objectives. The adaptations include:

- Limiting the model domain to the area between Stockton Ridge and the Eastern Fault,
- Inclusion of a custom plug-in within the Muja Coal Measures (model slice 1 to 3, inclusive) to represent exchange of groundwater with water supplied by external (stream flow, runoff, rainfall) sources to the pit lake, and
- Optimisation of the finite element mesh.

This approach provides that the Muja Coal Measures in the original Department of Water model (SKM 2010) are replicated, but now represent the mine backfill. This approach enables reasonable representation of the backfill distributions. All inputs were prescribed based on the fluxes described in Section 3 and Section 4, with the following exceptions:

- Groundwater inflow/outflow is calculated by FEFLOW based on the relative water levels between the pit lake and the aquifer, and
- The volume removed from the lake is set equal to the pumping capacity of 40 ML/day once the minimum operating level is reached.

The layer form of the FEFLOW model is described in Table 3, parameterisation is shown in Table 4 and model cross-sections are illustrated in Figure 5.1 and Figure 5.2. Note on Figure 5.1 and Figure 5.2 that the geology patches 2, 3 and 4 now represent backfill profiles. Shown in Figure 5.2 is the structural high in the fold fabric that manifests in Z System. The numerical model was calibrated by matching observed and simulated pit lake water levels. Calibration was guided by the findings of the lumped parameter water balance model and refined by adjusting the hydraulics of the Eastern Fault as the Z System water balance was sensitive to inflows across the fault zone. In the calibrated model, the Eastern Fault was discretised as a barrier to groundwater flow (see Section 2.1, Figure 2.1 and Figure 2.3) and characterised with isotropic hydraulic conductivity of 0.0001 m/day. This approach is similar to that used in the Collie Basin Model (SKM 2010) where the Eastern Fault was parameterised with hydraulic conductivity 0.00086 m/day. The calibrated model hydraulics as a described for the Collie Basin Model (SKM 2010) a described in Table 4. Calibration results are shown in Figure 5.3.

**TABLE 3**
**FEFLOW LAYER FORM (SKM 2010)**

<table>
<tr><th colspan="3">SLICE/LAYER</th><th rowspan="3">AQUIFER SYSTEM</th></tr>
<tr><th rowspan="2">NUMBER</th><th colspan="2">NOMENCLATURE</th></tr>
<tr><th>SKM (2010)</th><th>Z SYSTEM MODEL</th></tr>
<tr><td>1</td><td colspan="2">Nakina Formation</td><td>Nakina</td></tr>
<tr><td>2</td><td>Muja 1<br>Muja 2</td><td rowspan="3">Backfill and Void Plug-in</td><td rowspan="3">Muja</td></tr>
<tr><td>3</td><td>Muja 2</td></tr>
<tr><td>4</td><td>Muja 3</td></tr>
<tr><td>5</td><td colspan="2">Premier Coal Measures</td><td rowspan="4">Lower Collie</td></tr>
<tr><td>6</td><td colspan="2">Allanson Sandstone</td></tr>
<tr><td>7</td><td colspan="2">Ewington Coal Measures</td></tr>
<tr><td>8</td><td colspan="2">Westralia Sandstone</td></tr>
<tr><td>9</td><td colspan="2">Moorhead</td><td rowspan="2">Stockton</td></tr>
<tr><td>10</td><td colspan="2">Shotts</td></tr>
</table>

**TABLE 4**
**Z SYSTEM MODEL HYDRAULICS AND STORAGE**

| SLICE/LAYER | HYDRAULIC CONDUCTIVITY (M/DAY) | | HYDRAULICS ANISOTROPY | SPECIFIC YIELD (-) |
|---|---|---|---|---|
| | LATERAL | VERTICAL | | |
| Nakina Formation | 1.04 | 0.0104 | 100 | 0.1 |
| Backfill | 0.6 | 0.002 | 300 | 0.05 |
| Backfill | 3.5 | 0.01 | 300 | |
| Backfill | 2.6 | 0.005 | 500 | |
| Premier Coal Measures | 0.9 | 0.003 | 300 | |
| Allanson Sandstone | 1.7 | 0.006 | 300 | |
| Ewington Coal Measures | 0.2 | 0.0007 | 300 | |
| Westralia Sandstone | 0.09 | 0.0009 | 100 | |
| Stockton | 0.07 | 0.0007 | 100 | |
| Basement | 0.005 | 0.0005 | 10 | |

Notes: The void plug-in has specific yield 1.0 (-).

The hydraulics and storage characteristics of the backfill are unknown. Both aspects are anticipated to be widely variable and anisotropic, but perhaps when considered in their entirety not significantly different from the *in situ* Muja Coal Measures. In this respect, it was considered that the hydraulics in the original Collie Basin model (SKM 2010) represent conservatively high transmissivities, so these parameters were replicated. Similarly for the specific yield, though recognising that 0.05 (-) may be an underestimation of the backfill properties. Sensitivity analyses were used to explore higher transmissivity and higher specific yield backfill influences. The parameterisation of sensitivity simulations that increase the transmissivity and storage of the backfill profile are shown in Table 5.

**TABLE 5**
**Z SYSTEM MODEL BACKFILL SENSITIVITY PARAMETERISATION**

| SLICE/LAYER | HYDRAULIC CONDUCTIVITY (M/DAY) | | HYDRAULICS ANISOTROPY | SPECIFIC YIELD (-) |
|---|---|---|---|---|
| | LATERAL | VERTICAL | | |
| Backfill | 3.0 | 0.10 | 300 | 0.10 |
| Backfill | 21 | 0.05 | 300 | |
| Backfill | 13 | 0.025 | 500 | |

## 5.2 Forward Modelling

The groundwater flow model was used to simulate the pit lake water balance under the synthetic stream flow series and operational conditions described in Section 3 and Section 4, respectively. The model was run for a period of 30 years by repeating the 15-year historical climate sequence.

The initial head distribution for the model was developed by running the calibrated model forward to the current time.

The model simulates flow only. Water quality is derived through post-processing of the results based on assumed source concentrations and simulated fluxes. This approach assumes complete instantaneous mixing of the various sources.

## 5.3 Results

Figure 5.4 shows the simulated Z System water levels over the 30-year simulation period. The results indicate that the pit lake levels fall below the minimum operating water level at times during the simulation. Note that the FEFLOW predictions show sensitivity to the synthetic stream flow series, with lower-bound predicted storage level and Z System salinity at the end of the 15-year synthetic series cycle. These attributes would seem to be artefacts of the model.

Figure 5.5 shows the simulated pit lake salinity. Results from the FEFLOW modelling are similar to those estimated by the water balance approach.

Figure 5.6 shows the exchange between groundwater and Z System. At times the predictions show a net loss of groundwater from Z System to the aquifer. This is likely associated with surging of the Z System water level with water from river diversion. As the Z System water level is drawn down by abstraction and evaporation, groundwater flow towards Z System is the dominant flow direction. This implies that solutes cannot infiltrate far from Z System.

Figure 5.7 shows the various components of the simulated water balance. To preserve the scale inflow from Collie River East Branch and disposal to desalination are not shown on the plots. Inflow is as described in Section 4. Outflow was maintained at a constant rate of 40 ML/day once the minimum operating level was reached.

## 5.4 Sensitivity Analysis

Figures 5.4 and 5.5 also illustrate the sensitivity of the modelled water levels and lake salinity, respectively, to hydraulic conductivity, specific yield and evaporation.

Figure 5.8 shows the sensitivity to the source concentration terms.

The sensitivity analysis demonstrates that the dominant component of the Z System water balance is the diverted stream flow. This is true in terms of both water levels and quality in Z System.

# 6 DISCUSSION

Water balance assessments based on transient measurements of pit-lake elevations support interpretations that Z System is a groundwater sink. Measured pit-lake elevations demonstrate contributions from a groundwater environment recovering after sustained groundwater abstraction to support mining. The historical water balance, with pit-lake elevations rising to 109.1 m AHD by January 2017 show typical water balance contributions that include:

- Groundwater inflow – 0.78 GL/annum,
- Runoff (runoff coefficient of 0.32) – 0.68 GL/annum,
- Direct rainfall – 0.17 GL/annum, and
- Discharge by evaporation - 0.34 GL/annum.

The Eastern Fault on the northeast perimeter of Z System is interpreted to form a barrier to groundwater flow, essentially compartmentalising the local water balance and limiting influences for the wider Premier Sub-basin. Note that the water balance is calibrated to pit-lake elevations up to about 110 m AHD. Above this elevation the water balance and pit-lake responses to divertible stream flow are not calibrated and consequently incorporate uncertainty.

The performance of the Z System, in terms of both water level and salinity, is most sensitive to diversion of flows from the Collie River East Branch. This owes to the fact that the flow rates and salinities from the diverted stream flow are significantly greater than for any of the natural fluxes to Z System.

The modelling indicates that under the assumed baseline conditions there is a risk that the desalination capacity cannot be met in some years. This risk is exacerbated by the possibility of a gradually drying climate, drought and declining groundwater levels due to mine dewatering. The largest shortfall in the volume that can be supplied to desalination was modelled as 7.8 GL/annum. The FEFLOW modelling, however, showed that when water is drawn from Z System at the maximum pumping capacity of 40 ML/day, water levels only fall below the minimum operating level for a short period.

Given the sensitive nature of the Z System to the stream flow diversion, a stochastic approach could be used, with consideration of climate and land use changes, to generate longer/ multiple realisations of rainfall data as inputs to the calibrated rainfall-runoff model (for example Lucicat). Resulting rainfall and stream flow realisations would be used to test the Z System performance.

The FEFLOW model was used to calculate the flow rates between the aquifer and Z System. The results indicate that there are times where the net flow direction can be either from the aquifer to the pit lake or vice versa. The net flow direction over the duration of the simulation however is from the aquifer towards the pit. This implies that the risk of contamination of the aquifer with saline stream flow is somewhat mitigated.

It is difficult to know if the measured acidity and metals concentrations in Z System will stabilise or increase over time and the influences of the divertible stream flow in this regard. There is uncertainty whether the samples collected form the edge of the pit-lake are reasonably representative. The available data consistently show pH < 4.0 and wide variations over time in context to TDS and selected metals concentrations. The consistent acidity is interpreted to show that short-term residence times are sufficient to consume any acid-buffering attributes of the influx waters and lower the pH. For The TDS and metals, there are different potential sources related to:

- Loadings received from rainfall runoff,
- Diverted stream flow interactions with the void sidewalls and backfill materials, and
- Residence times in acidic waters.

These cumulative aspects provide uncertainty regarding actual transient pit-lake acidity and metals concentrations.

Presumably, the backfill of Muja Coal Measures sediments hosts a large bank of sulphide minerals and metals, though they may have differential concentrations/loadings and random oxidisation and mobilisation potentials. It is recognised there is likely a large bank of potential loadings in storage, but the release mechanisms and concentrations may vary widely over time. The measured transient pit-lake quality data typically show fluctuation across a wide range. From a practical perspective, the causes of the observed concentration fluctuations are likely to be a result of cumulative influences that are difficult to discretise and quantify.

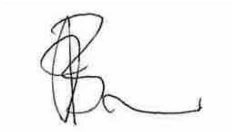
## 7 RECOMMENDATIONS

The assessments of Z System reflect the available data, recognising that there has not been systematic monitoring. The understanding of the Z System transient water balance functions and connections to the wider Premier Sub-basin groundwater stresses can be improved through further monitoring. In this regard it is recommended to:

- Upgrade the access to the pit-lake,
- Install automatic data loggers to measure the pit-lake elevation, Electrical Conductivity (EC) and temperature on a daily basis. Data could be collected on the bank of the pit-lake and in vertical profiles near the centre of the water body,
- Source daily rainfall records (probably from Muja Power station and Premier Mine),
- Sample the pit-lake water column to gather a snapshot of water quality (acidity, TDS, EC, temperature, turbidity, metals, nutrients and other sensitive parameters). This will gauge variability and stratification within the pit-lake and the representation provided by the earlier quality data,
- Sample rainfall runoff during different rainfall events,

- Sample pit-lake quality after a significant rainfall event. This may guide the rate of acidification provided runoff volumes are sufficiently large, and
- Given the pit-lake is a gaining system, then storage characteristics are likely to be influenced by an infrequent rainfall event. The sensitivity to a 20-year ARI event will likely add robustness to the available storage. Similarly, the likelihood of repetitive drought years will influence divertible stream flow volumes and will provide risk to the available storage. Both aspects probably will influence residence times for water in Z System and quality.

For and on behalf of
PELLS SULLIVAN MEYNINK



IAN BRUNNER
Principal

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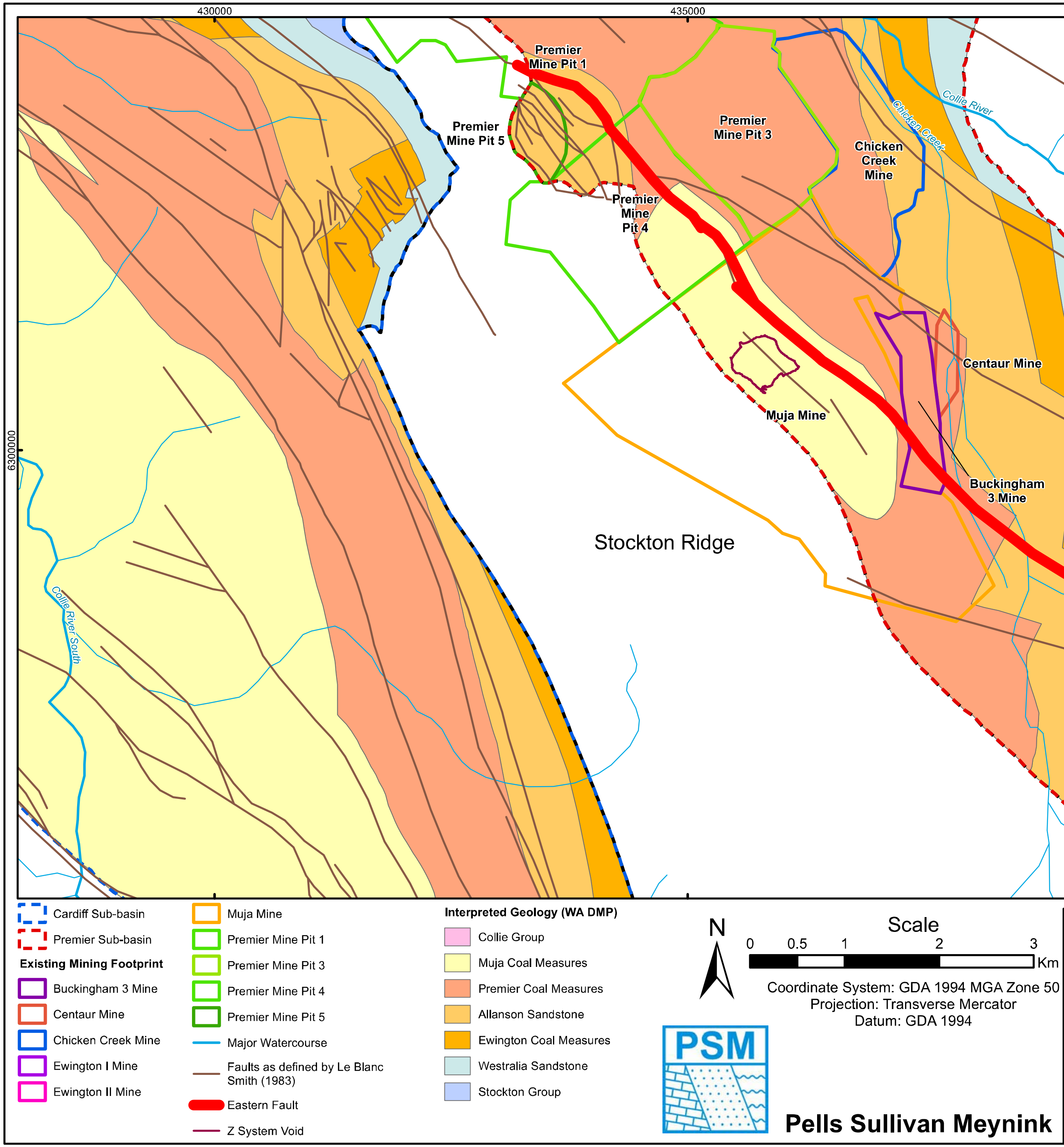
1. Centre of Excellence for Sustainable Mine Lakes (2008): Final Report to State Government January 2002 to March 2007.
2. Groundwater Resource Consultants (1989): Hydrogeological Assessment of the Muja Open Cut Final Void. Report prepared for The Griffin Cola Mining Company Pty Ltd.
3. SKM (2010): Collie Basin Groundwater Modelling. Report prepared for Department of Water – Western Australia.
4. The Griffin Coal Mining Company Pty. Ltd. (2016): Estimated Surface Water Collection – Muja Void. Final V DoW.xls

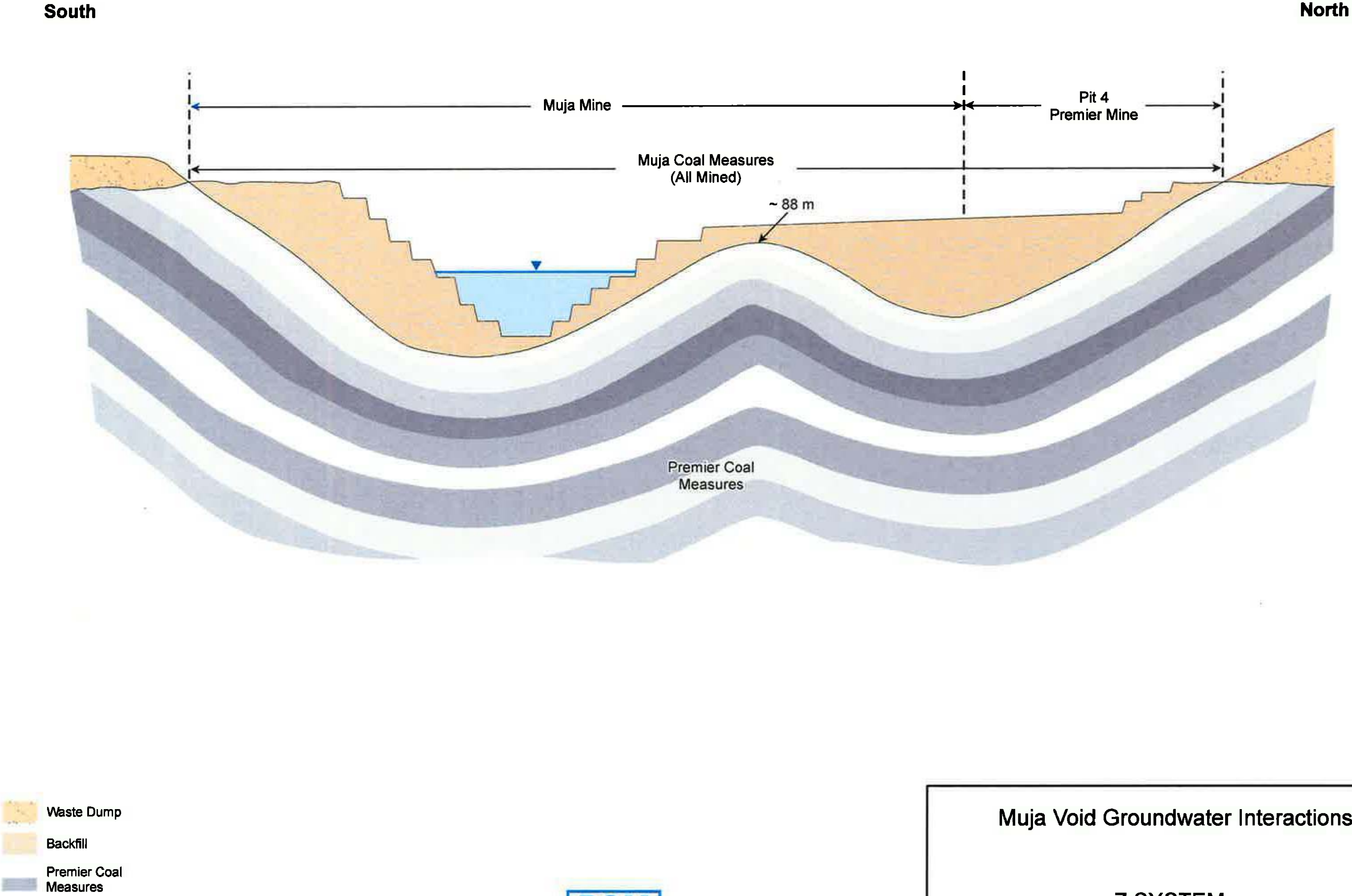



Muja Void Groundwater Interactions

REGIONAL SETTING

PSM3200-002R

Figure 2-1

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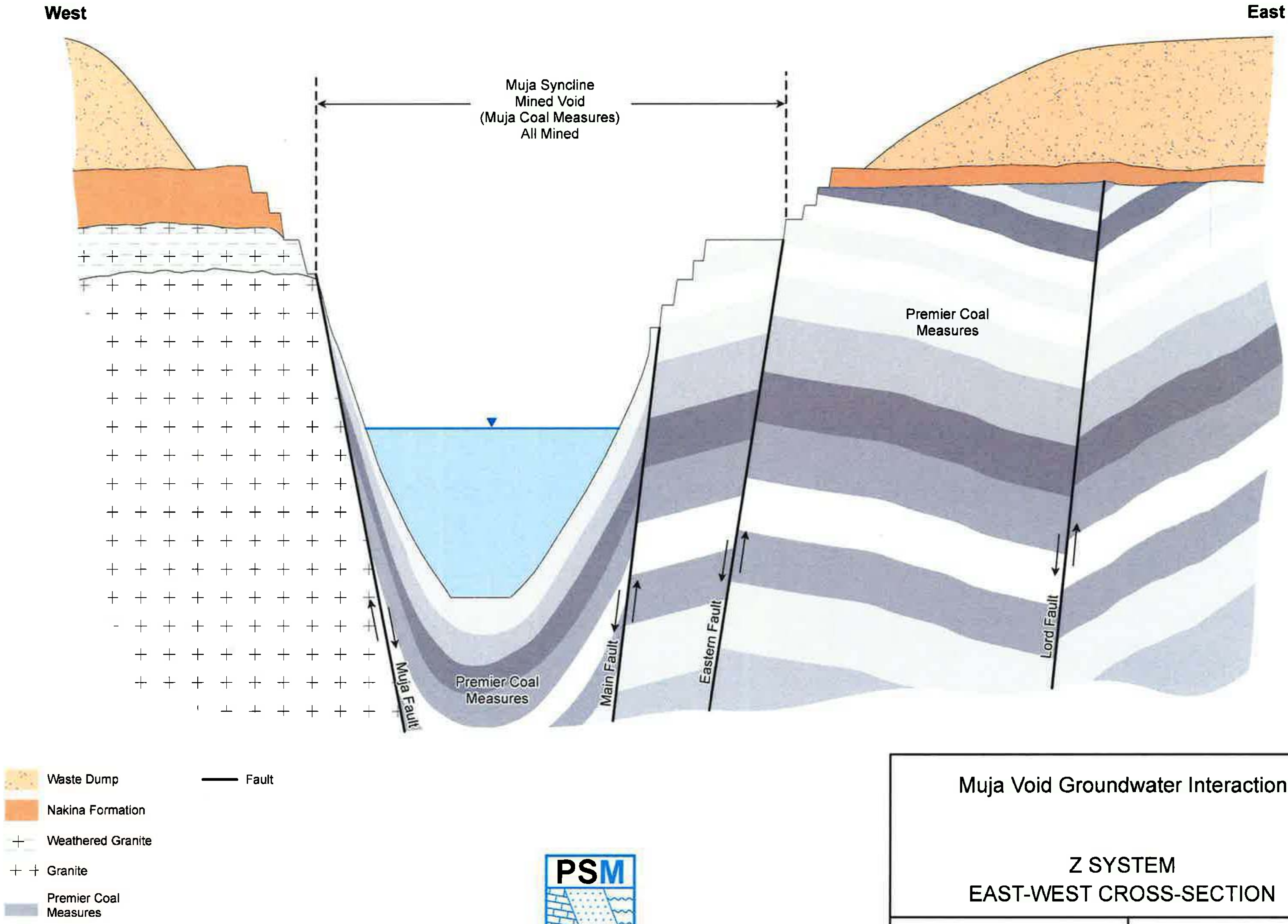
Muja Void Groundwater Interactions

Z SYSTEM
NORTH-SOUTH CROSS-SECTION

PSM3200-002R

Figure 2.2




Muja Void Groundwater Interactions

Z SYSTEM
EAST-WEST CROSS-SECTION

PSM

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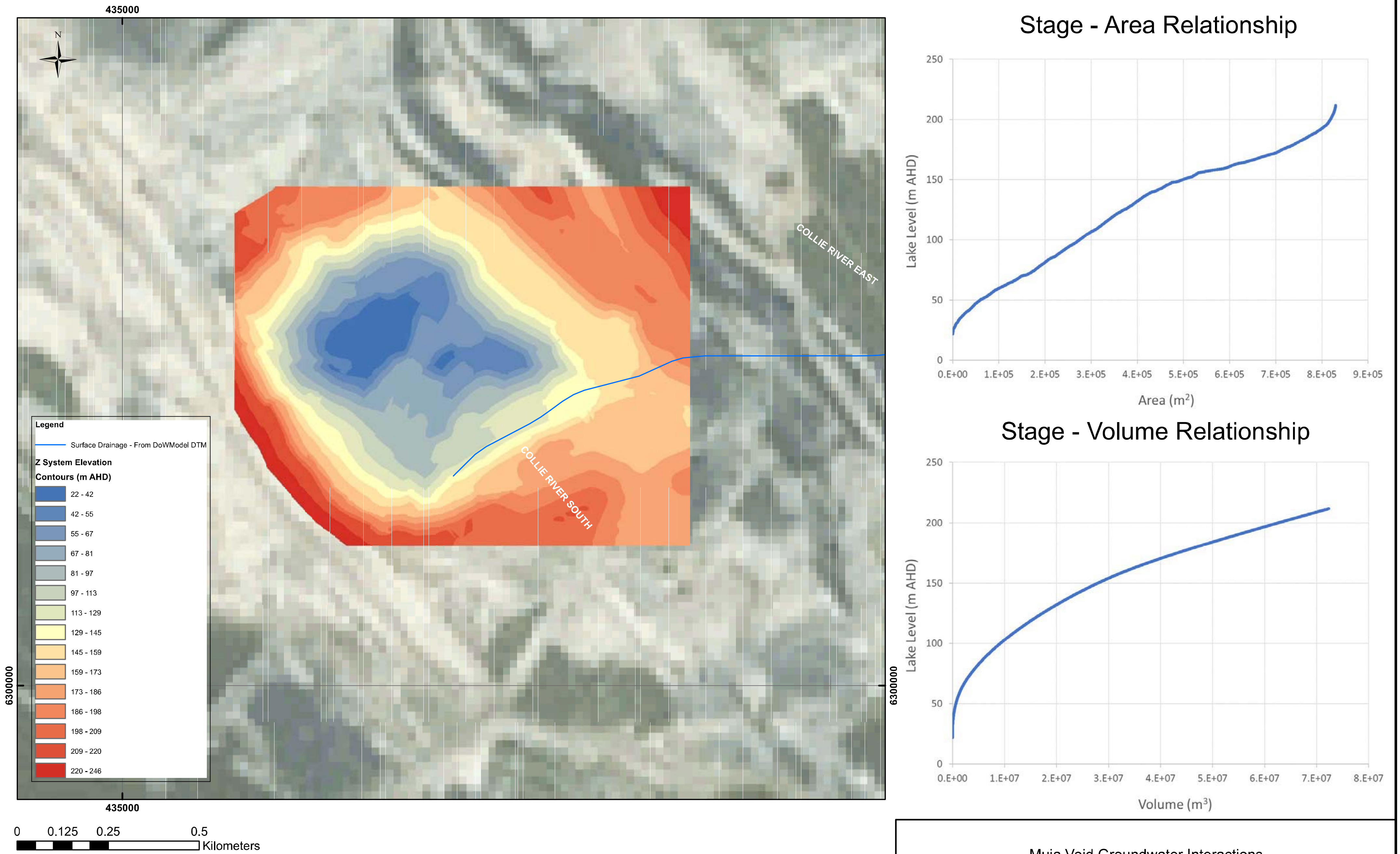
|---|---|
| PSM3200-002R | Figure 2.3 |




Projection grid: MGA Zone 50 (GDA1994)

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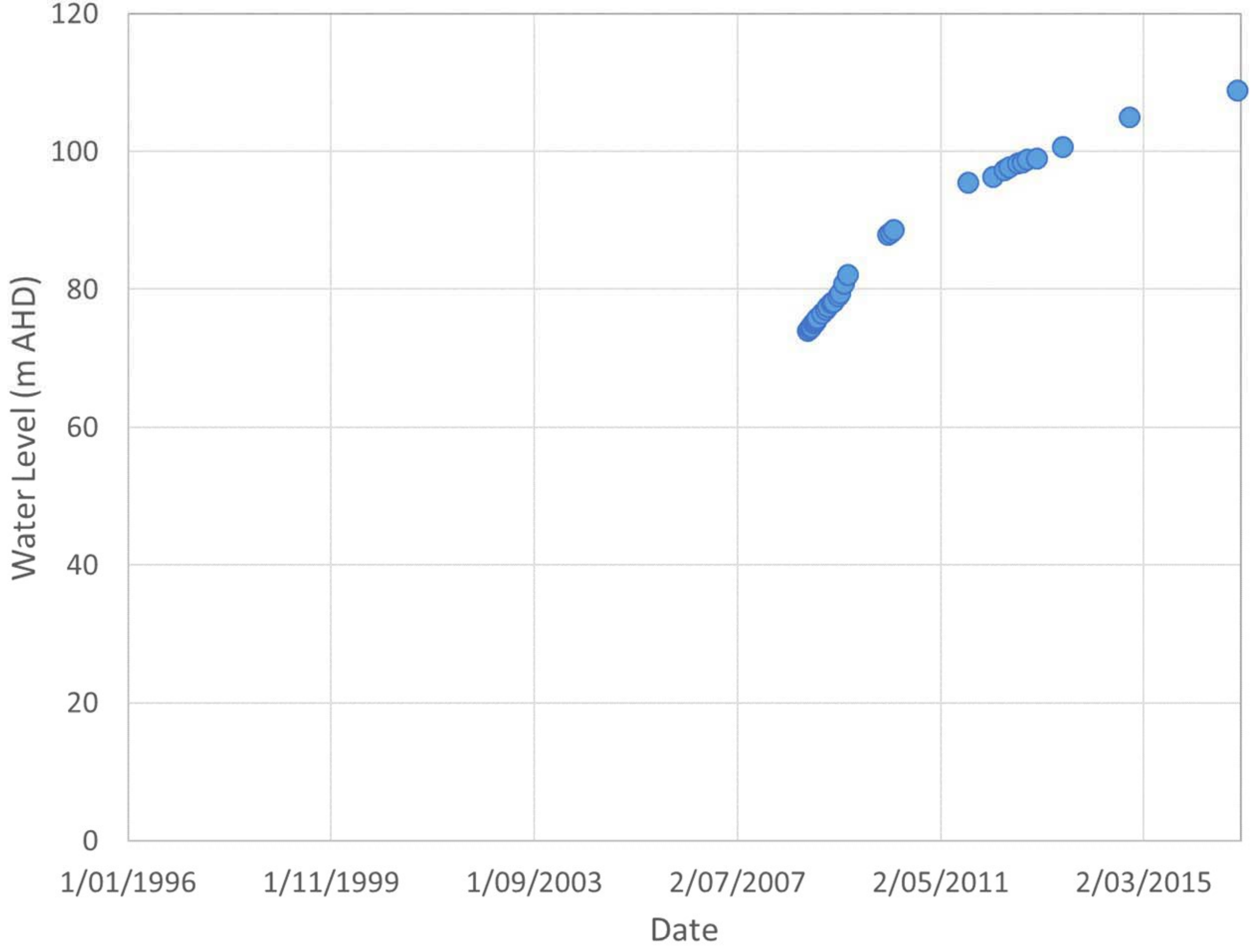
| Muja Void Groundwater Interactions<br>Z SYSTEM VOID GEOMETRY | |
|---|---|
| PSM3200-002R | Figure 2-4 |

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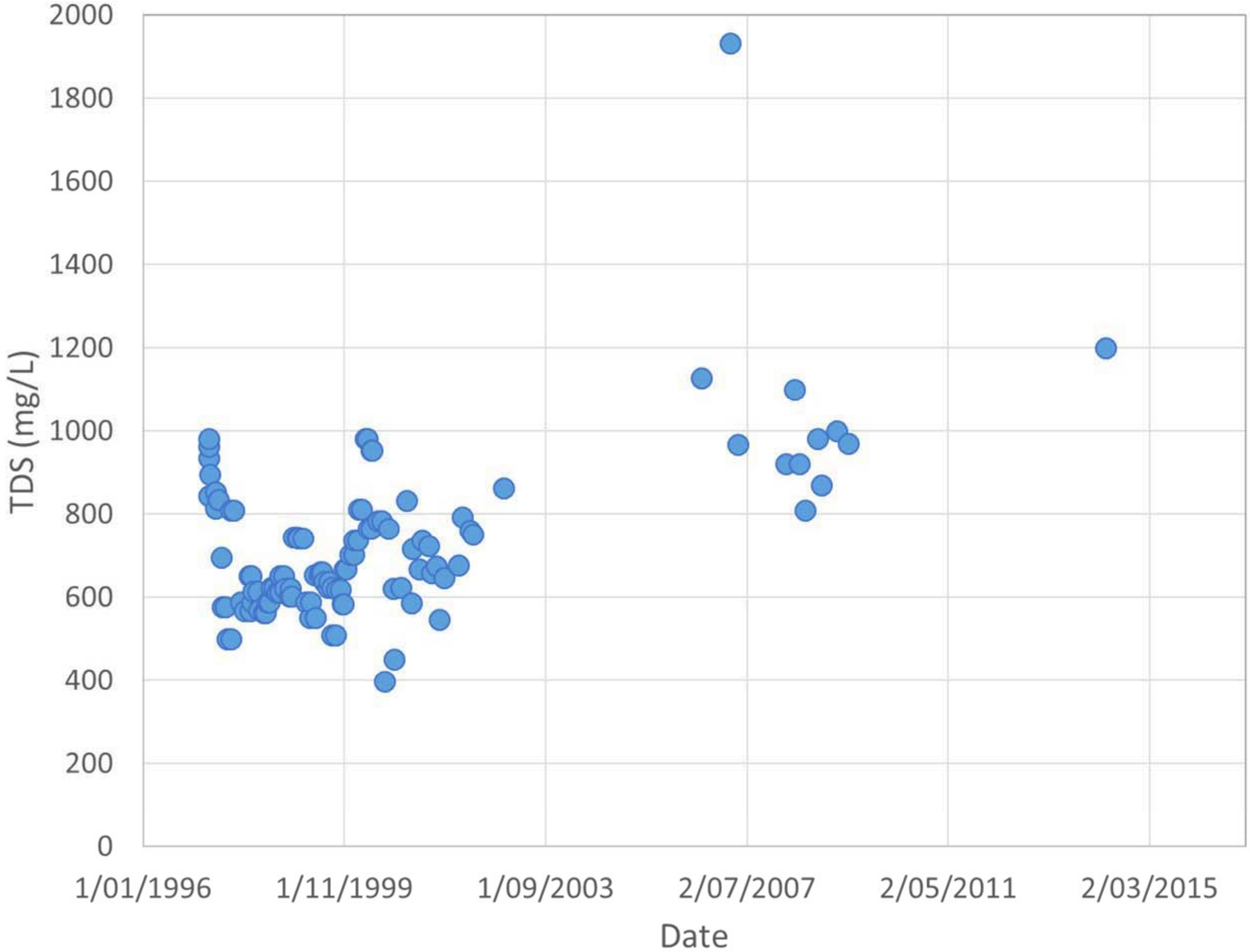
Muja Void Groundwater Interactions

Z SYSTEM
PIT LAKE WATER LEVELS

PSM3200-002R

Figure 2-5

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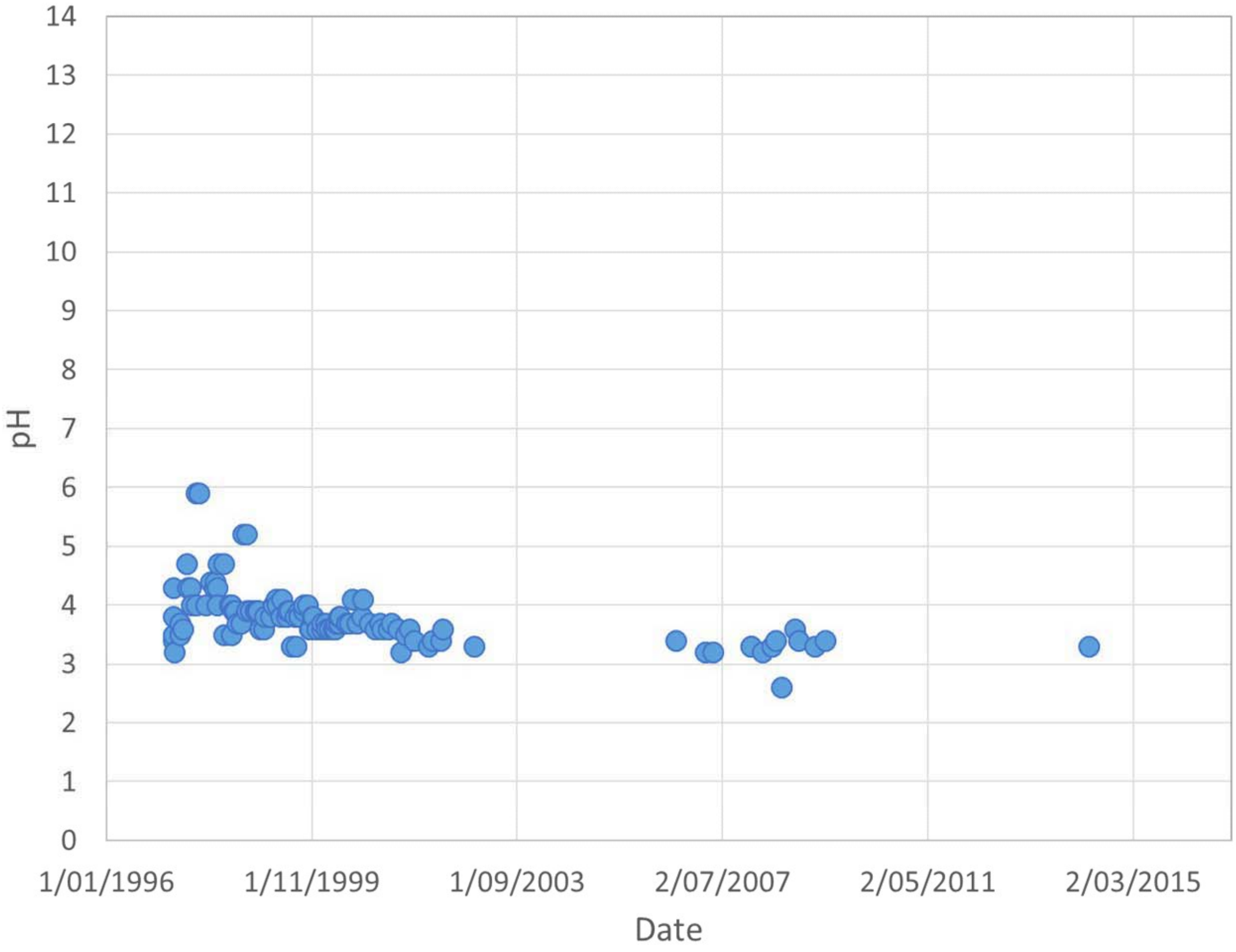
| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>TOTAL DISSOLVED SOLIDS | |
| PSM3200-002R | Figure 2-6 |

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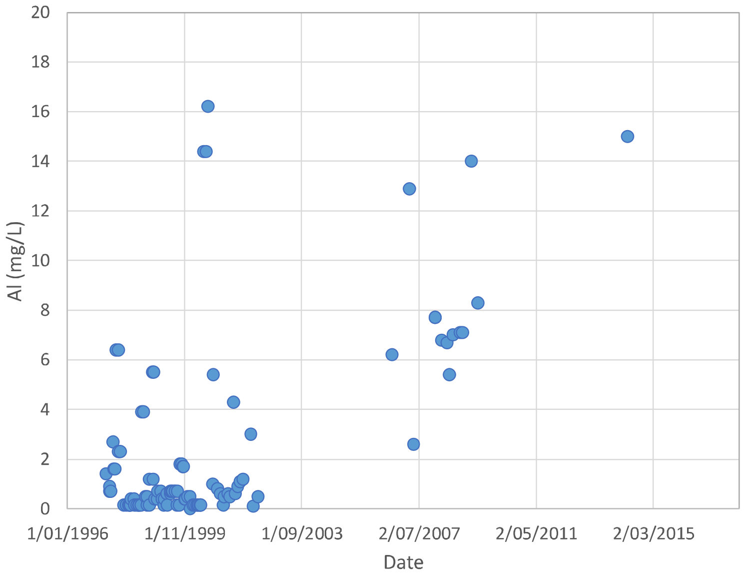
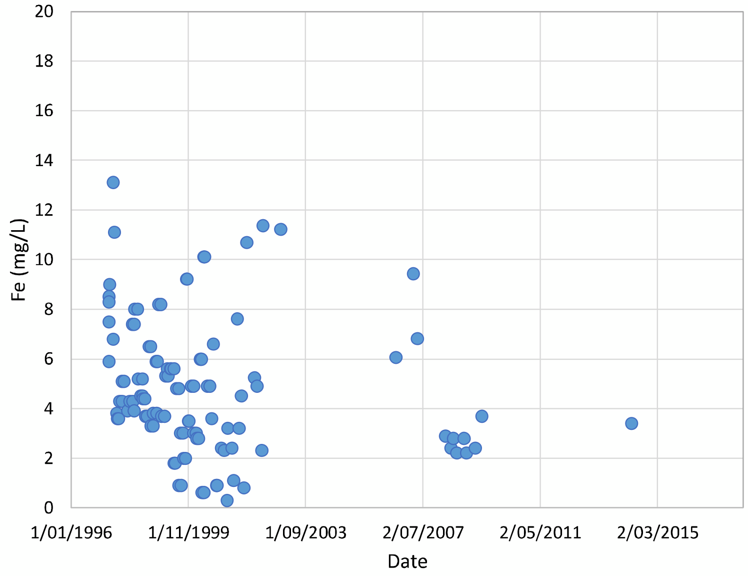
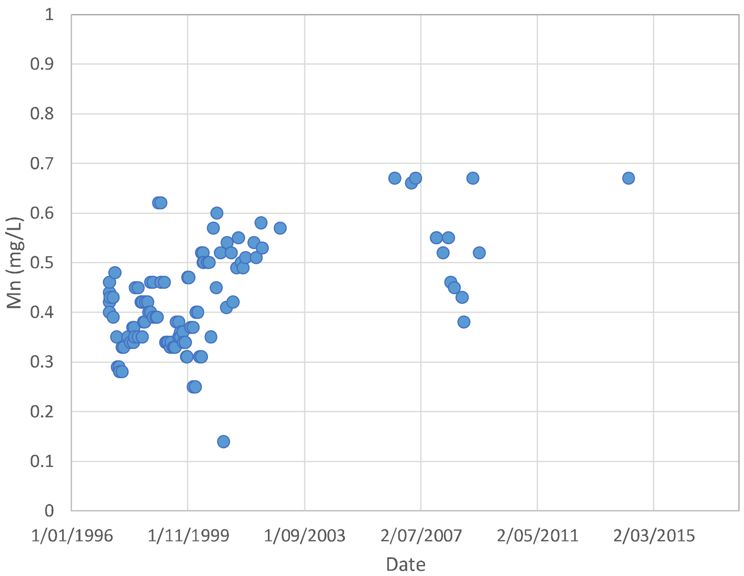
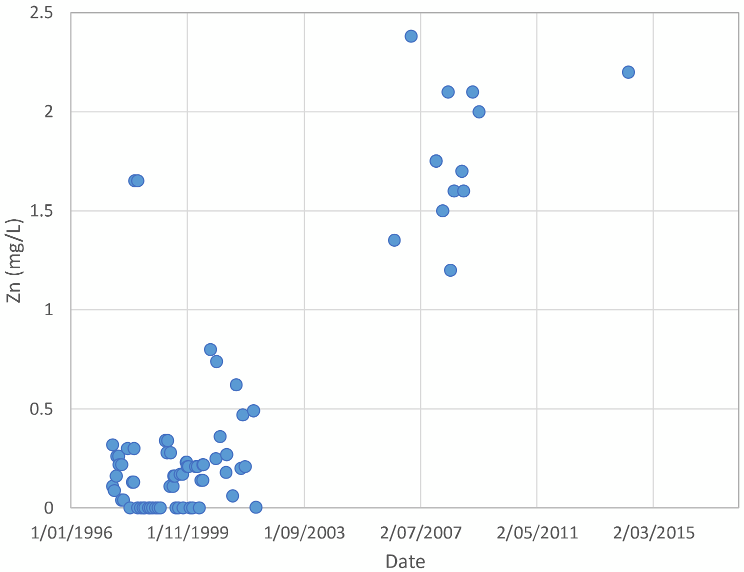
| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>pH | |
| PSM3200-002R | Figure 2-7 |

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Muja Void Groundwater Interactions

Z SYSTEM
SELECTED METALS

| PSM3200-002R | Figure 2-8 |
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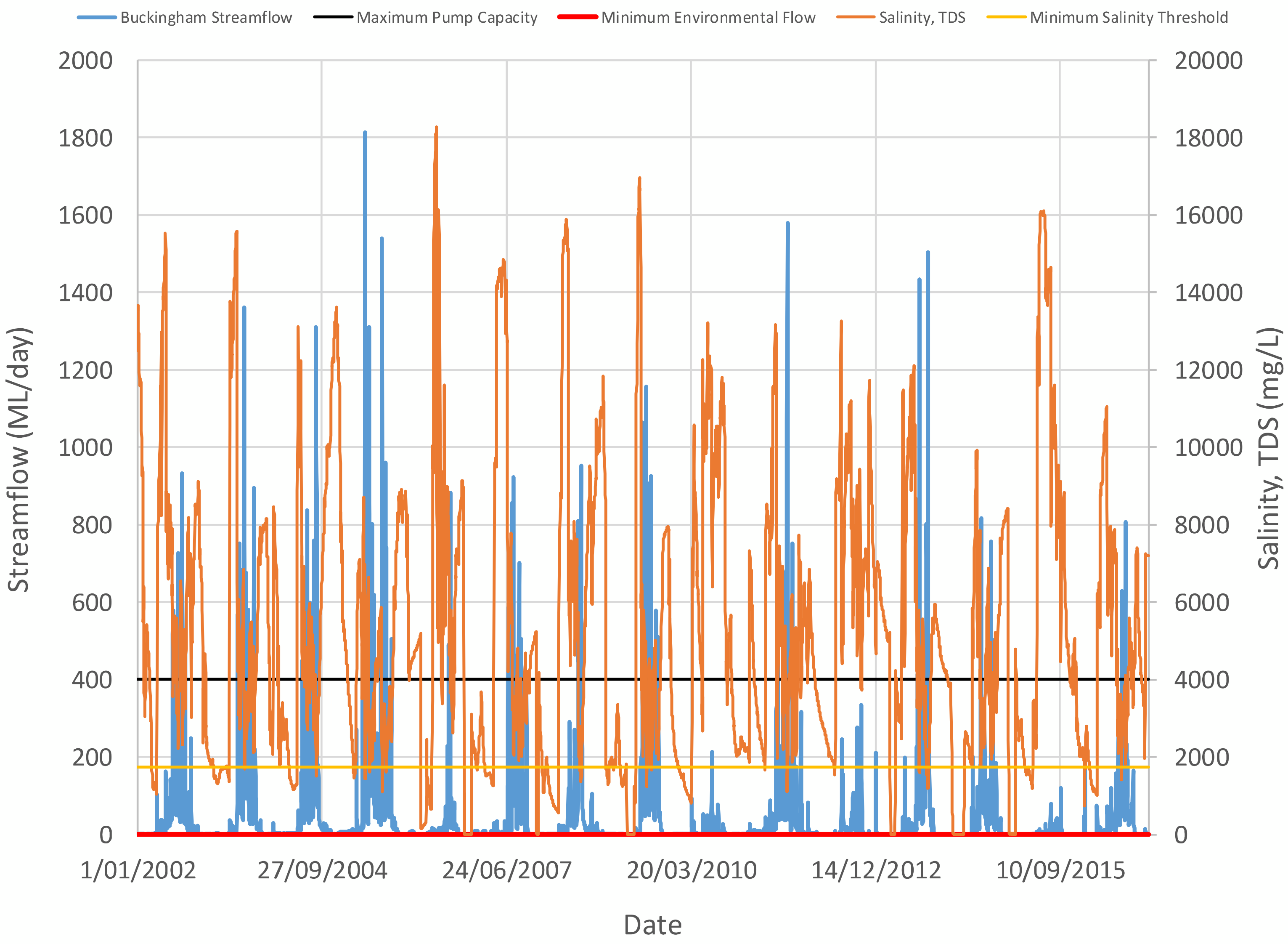


**Pells Sullivan Meynink**

Muja Void Groundwater Interactions

COLLIE RIVER EAST BRANCH
STREAMFLOW, SALINITY AND CONSTRAINTS
ON THE DIVERTIBLE VOLUME

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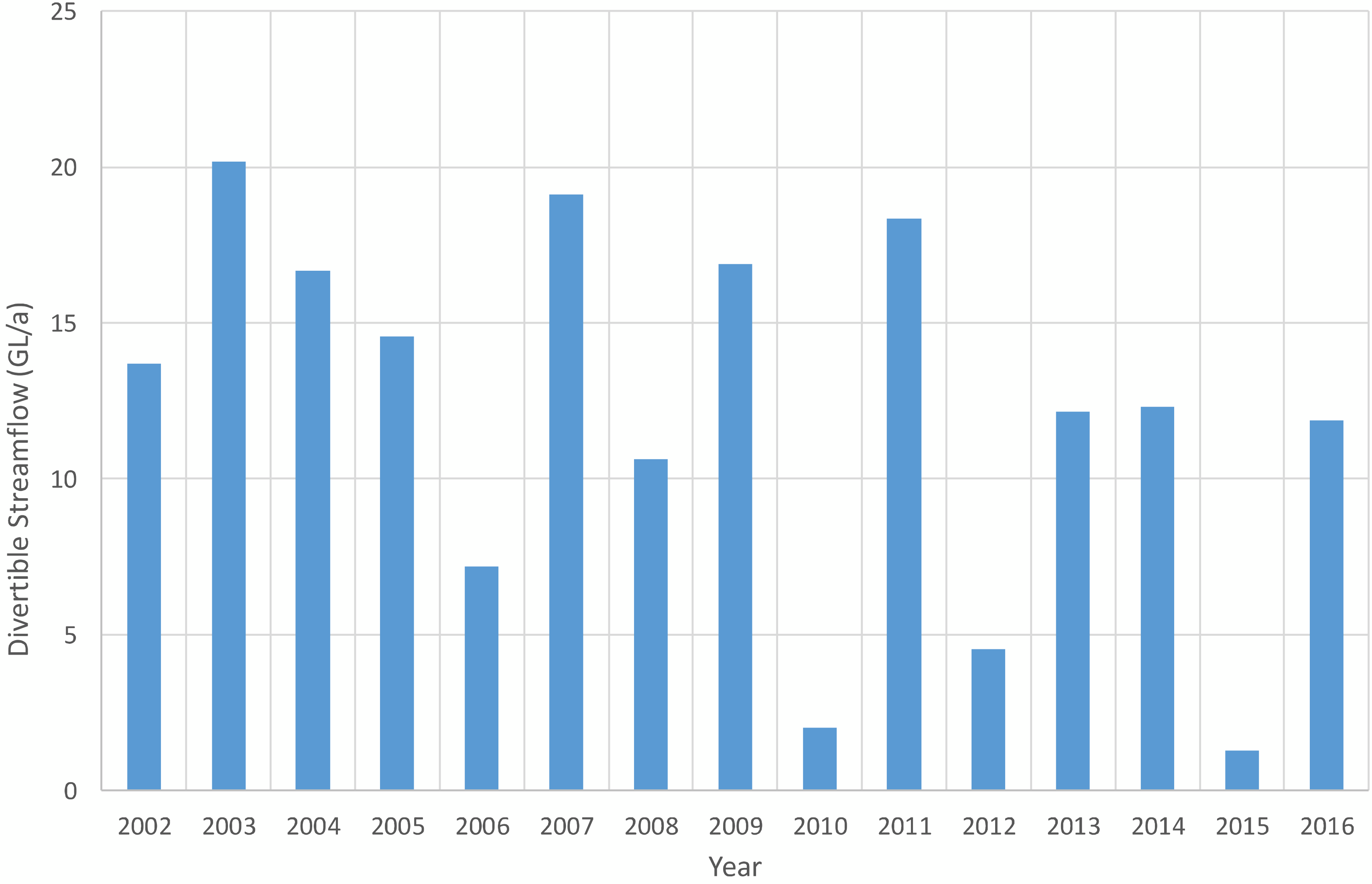
|---|---|
| PSM3200-002R | Figure 3-1 |

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Muja Void Groundwater Interactions

COLLIE RIVER EAST BRANCH
DIVERTIBLE STREAMFLOW

| | |
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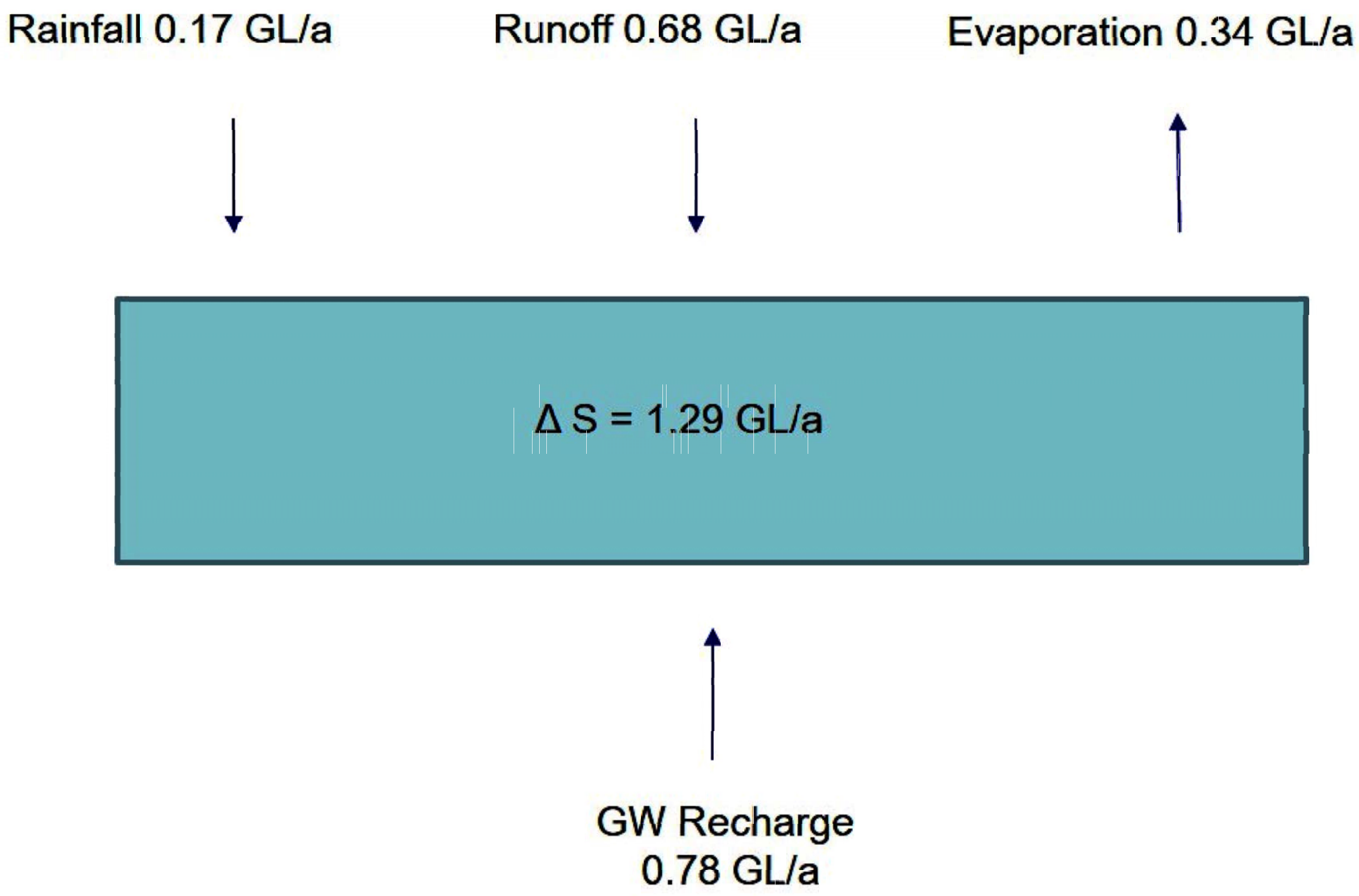
| PSM3200-002R | Figure 3-2 |

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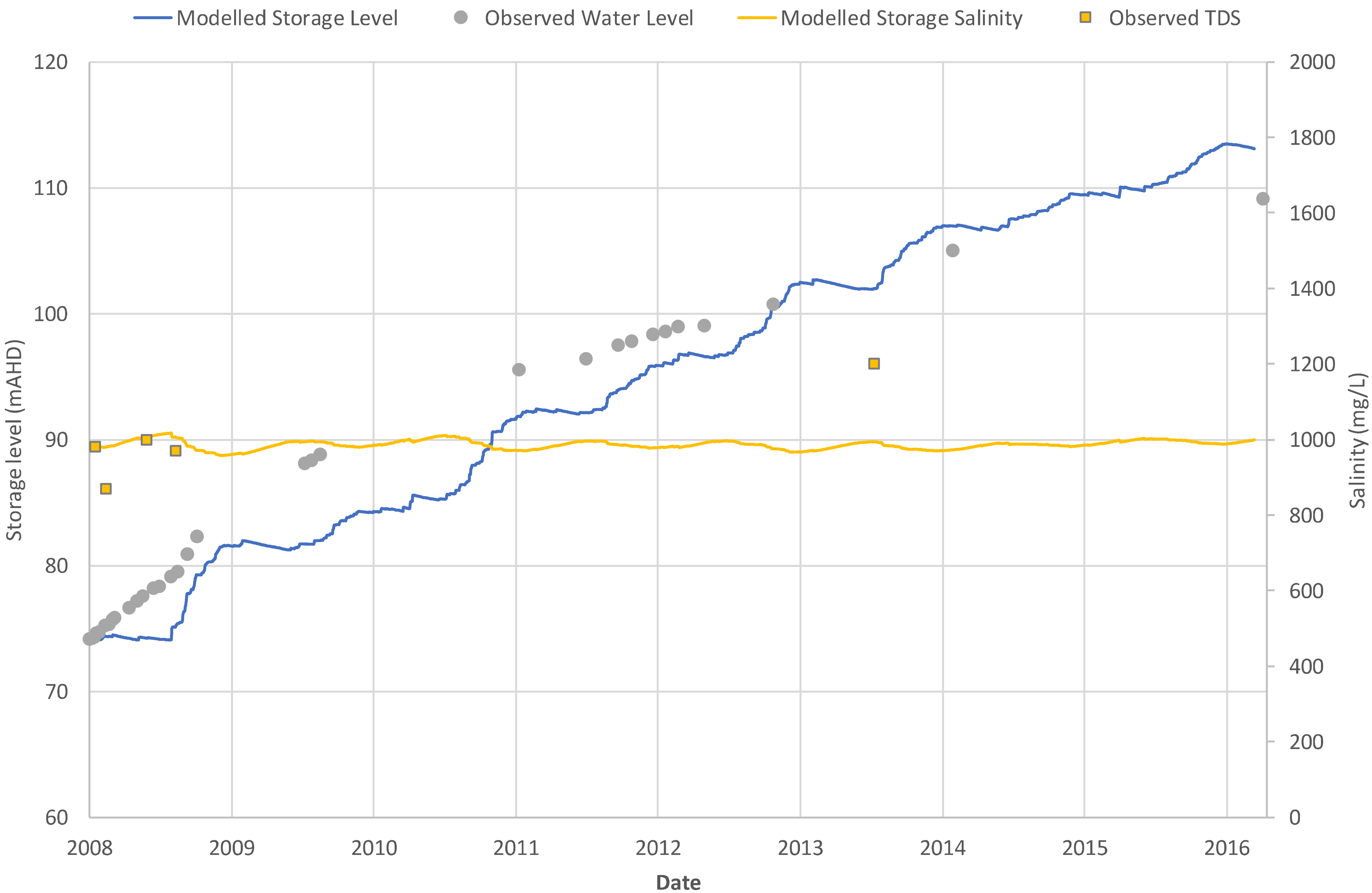
| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>HISTORICAL WATER BALANCE | |
| PSM3200-002R | Figure 4-1 |

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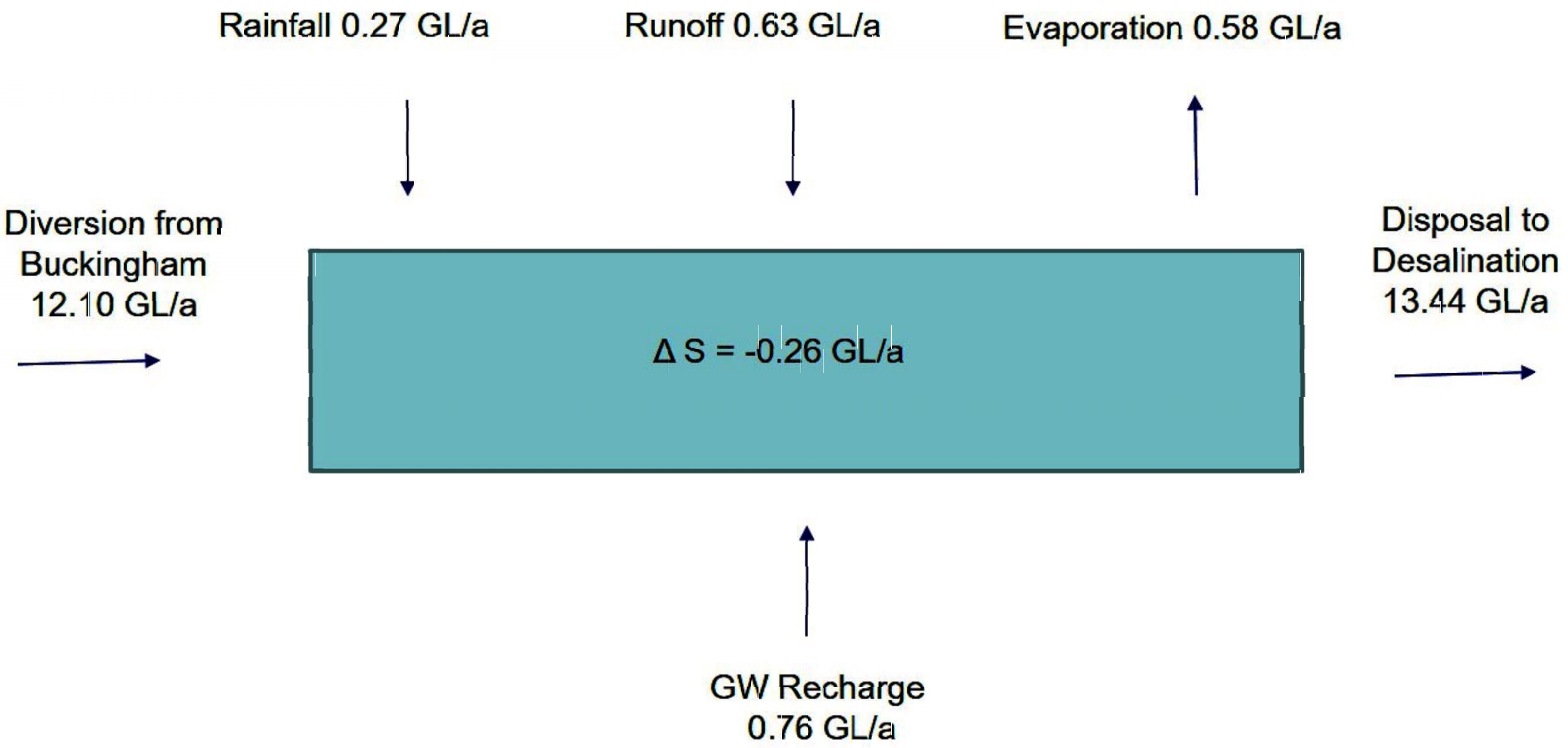
| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>MODELLED VS OBSERVED<br>PIT WATER LEVEL AND SALINITY | |
| PSM3200-002R | Figure 4-2 |

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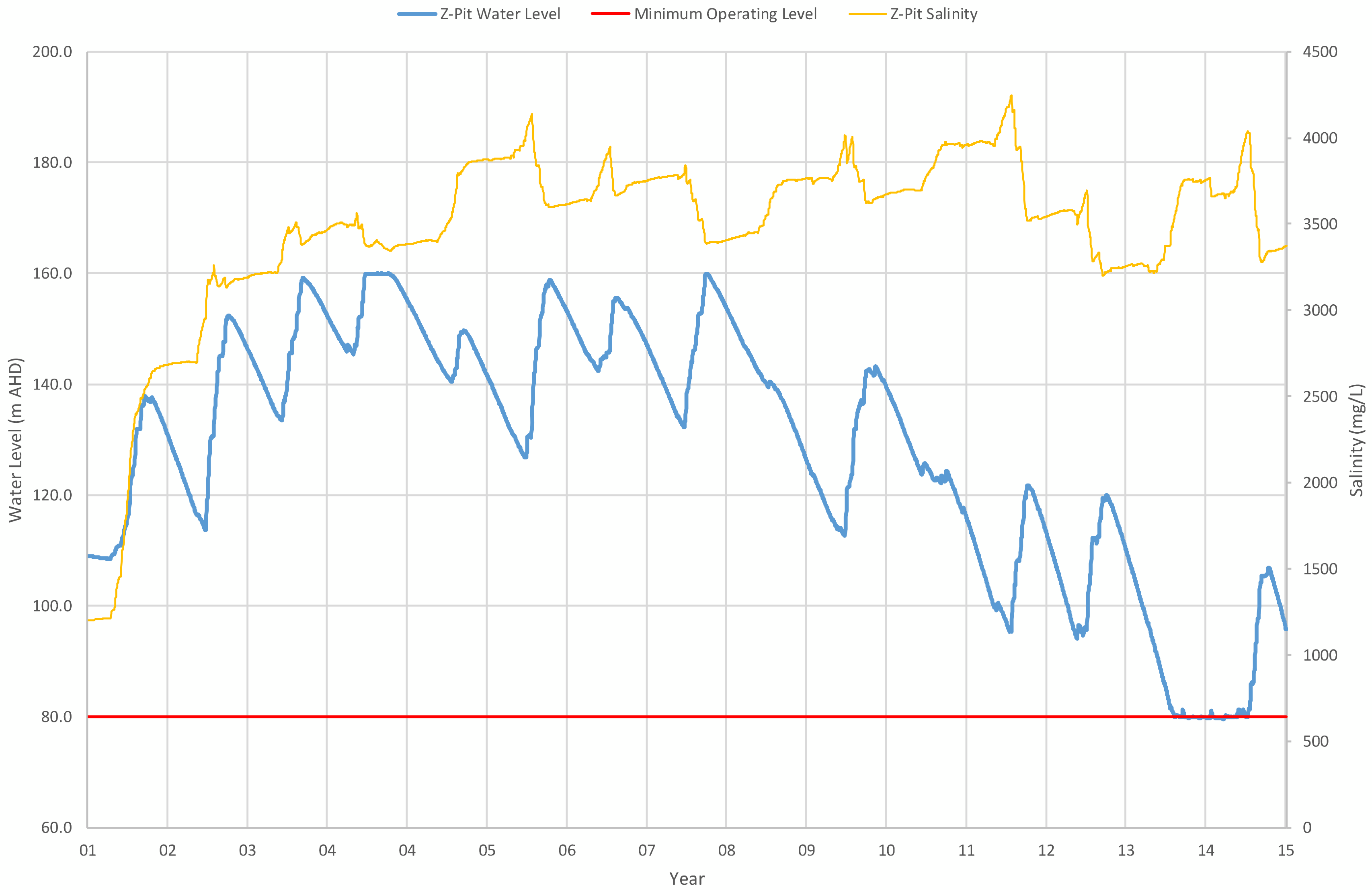
Muja Void Groundwater Interactions

Z SYSTEM
OPERATIONAL WATER BALANCE

PSM3200-002R

Figure 4-3

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| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>MODELLED PIT LAKE LEVEL AND SALINITY | |
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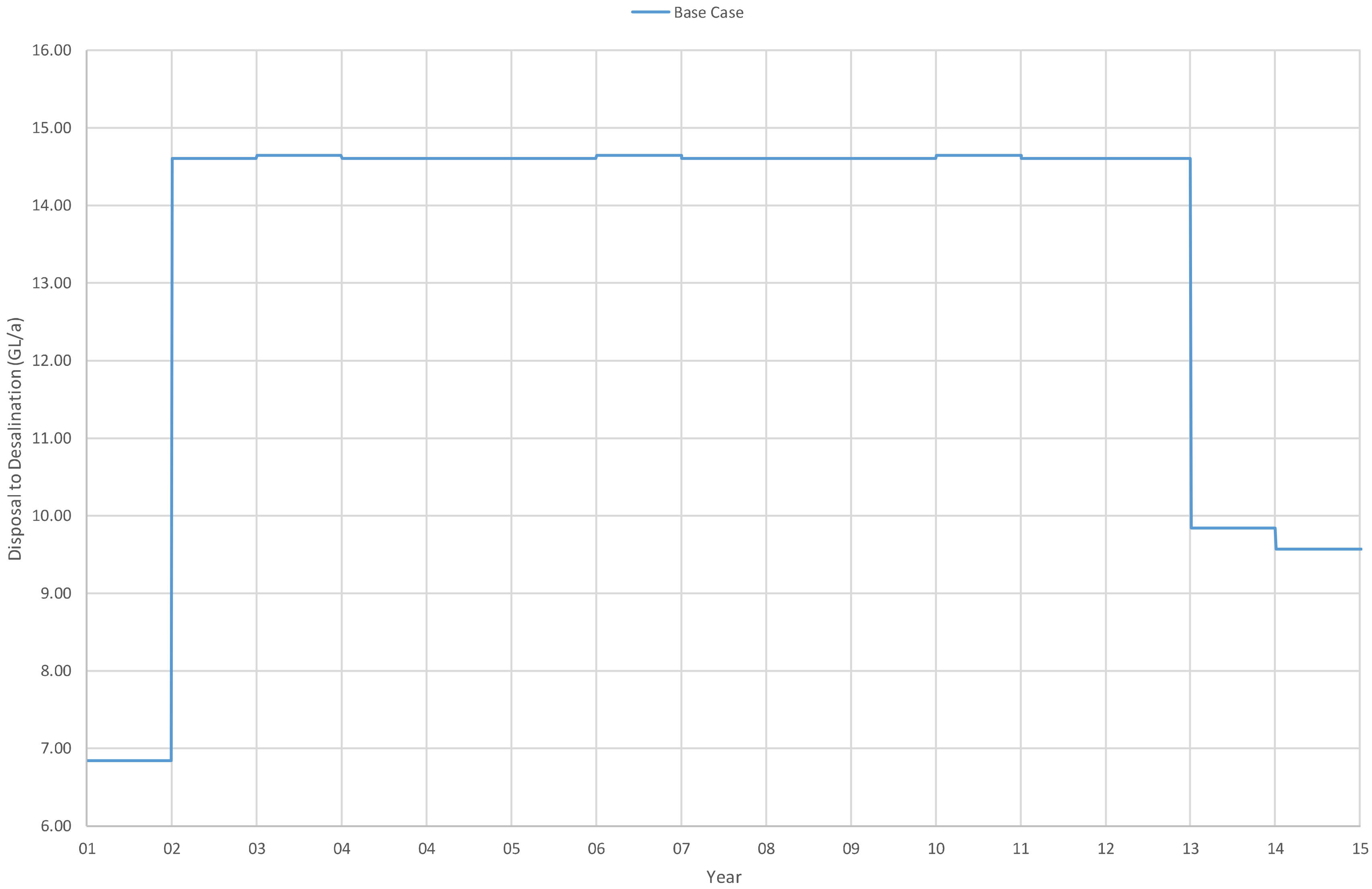
| PSM3200-002R | Figure 4-4 |

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Muja Void Groundwater Interactions

Z SYSTEM
MODELLED DRAW RATE
(SUPPLY TO DESALINATION)

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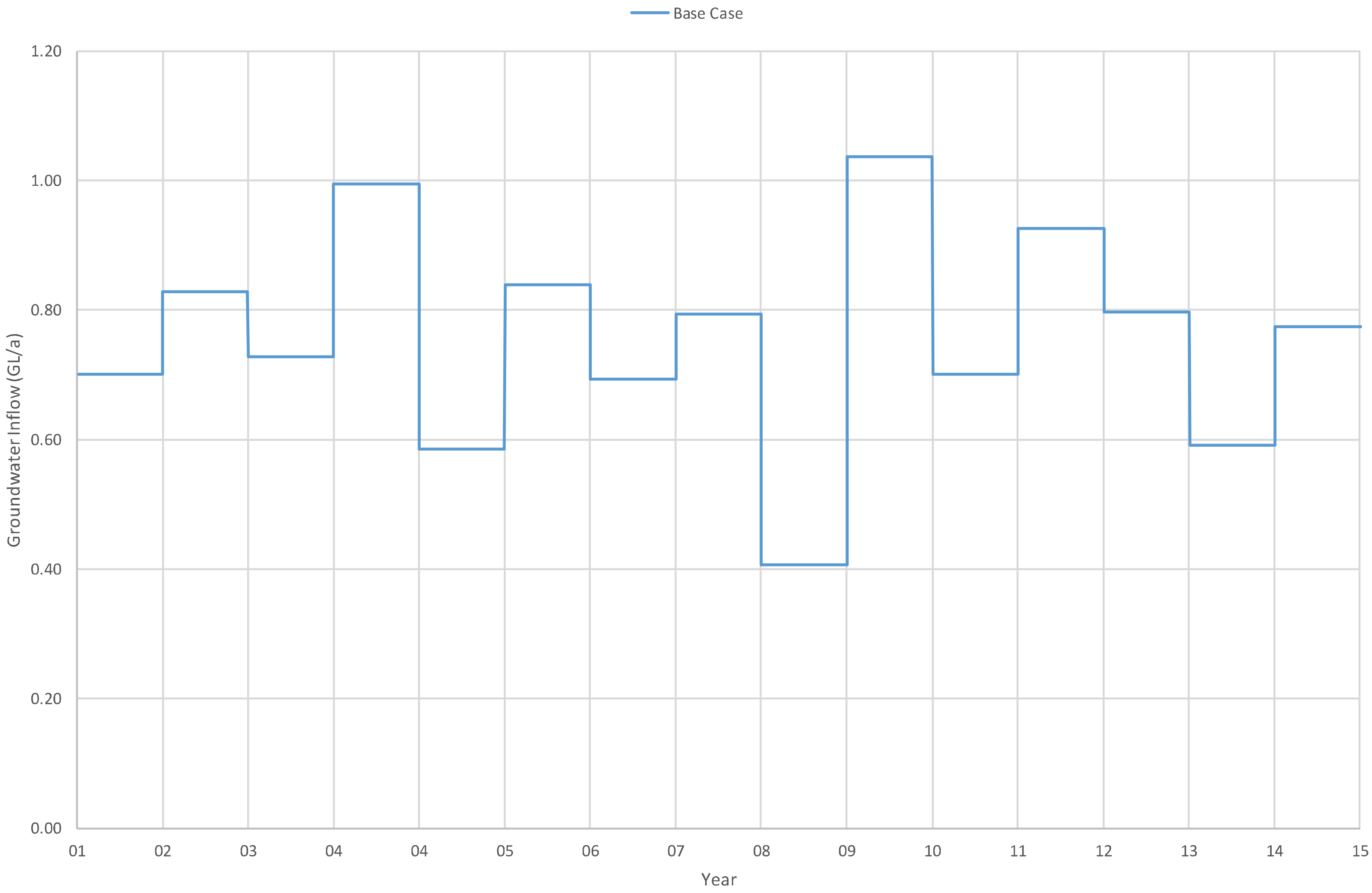
| PSM3200-002R | Figure 4-5 |

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Muja Void Groundwater Interactions

Z SYSTEM
MODELLED GROUNDWATER INFLOW

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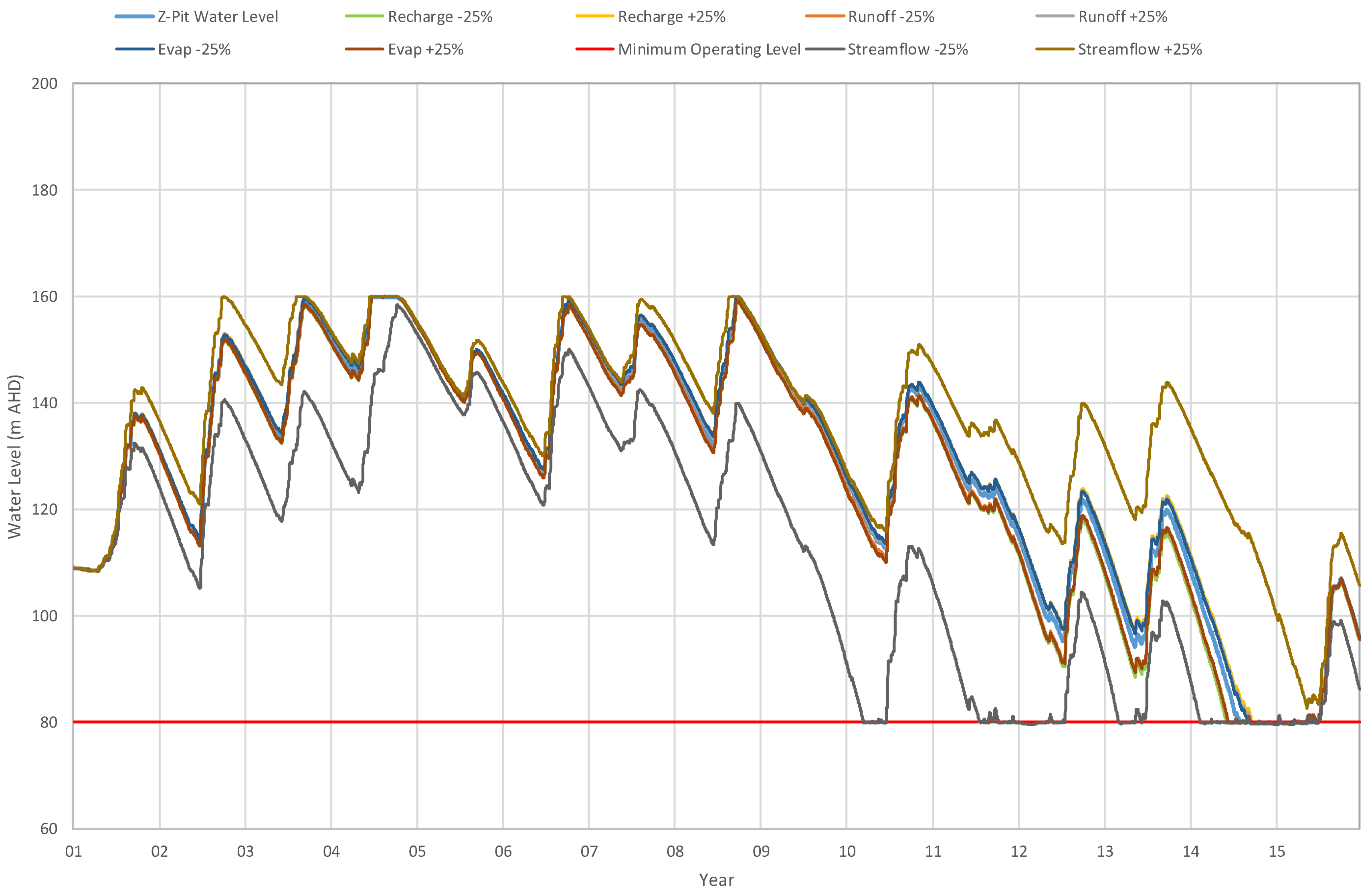
| PSM3200-002R | Figure 4-6 |

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Muja Void Groundwater Interactions

Z SYSTEM
MODELLED PIT WATER LEVEL
SENSITIVITY ANALYSIS

| PSM3200-002R | Figure 4-7 |
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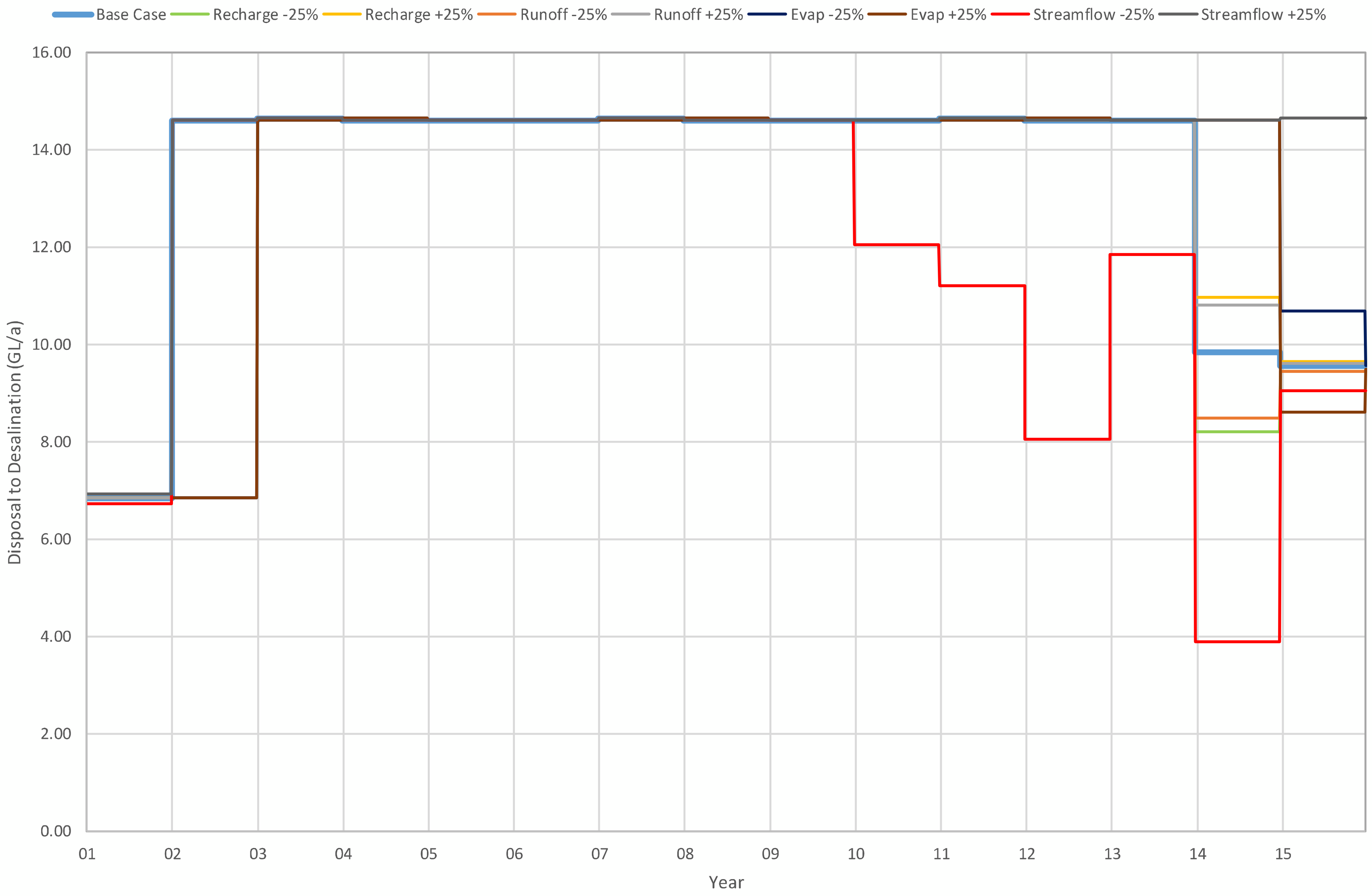


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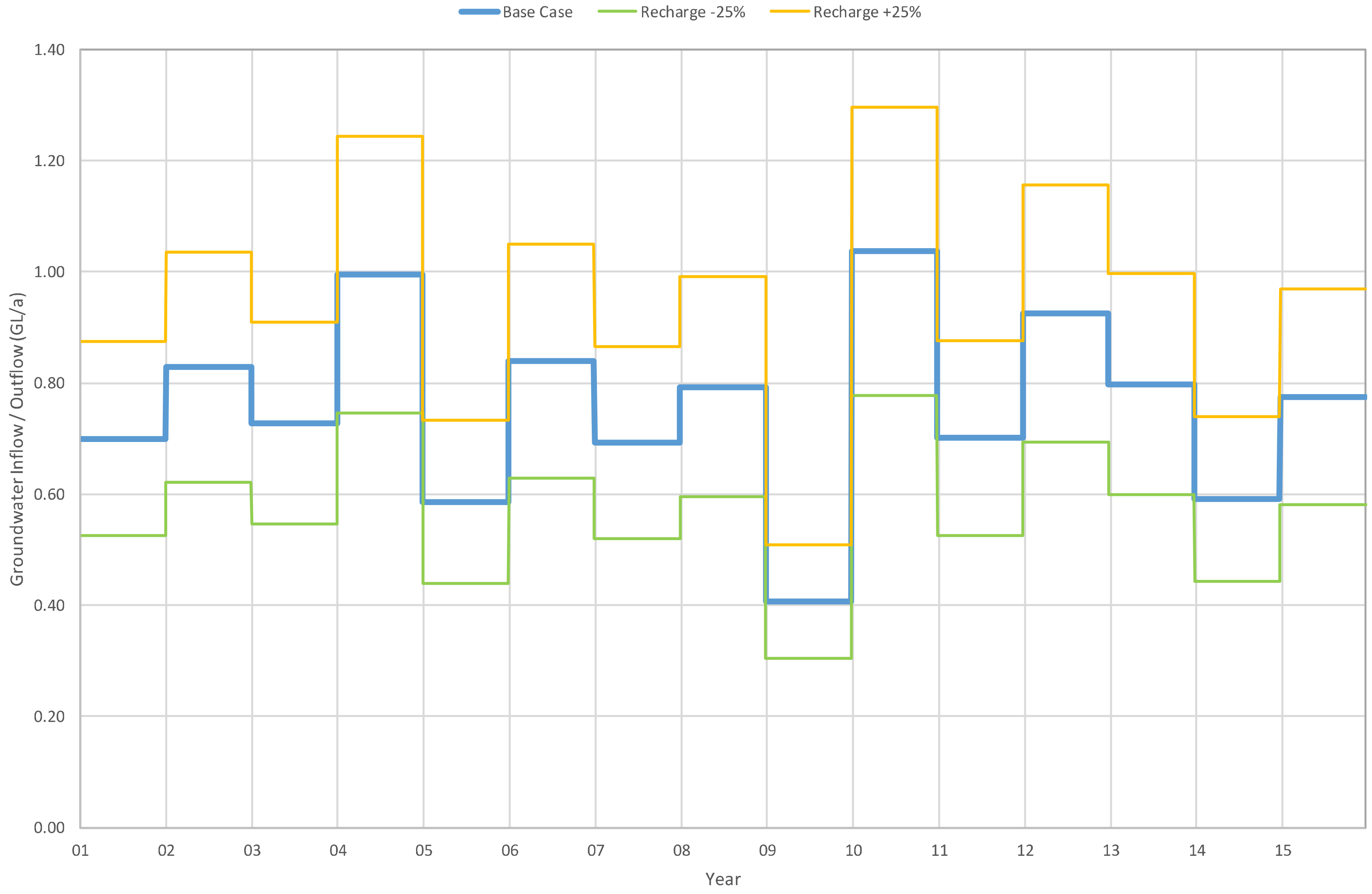
| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>MODELLED DRAW RATE<br>SENSITIVITY ANALYSIS | |
|---|---|
| PSM3200-002R | Figure 4-8 |

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| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>MODELLED GROUNDWATER INFLOW<br>SENSITIVITY ANALYSIS | |
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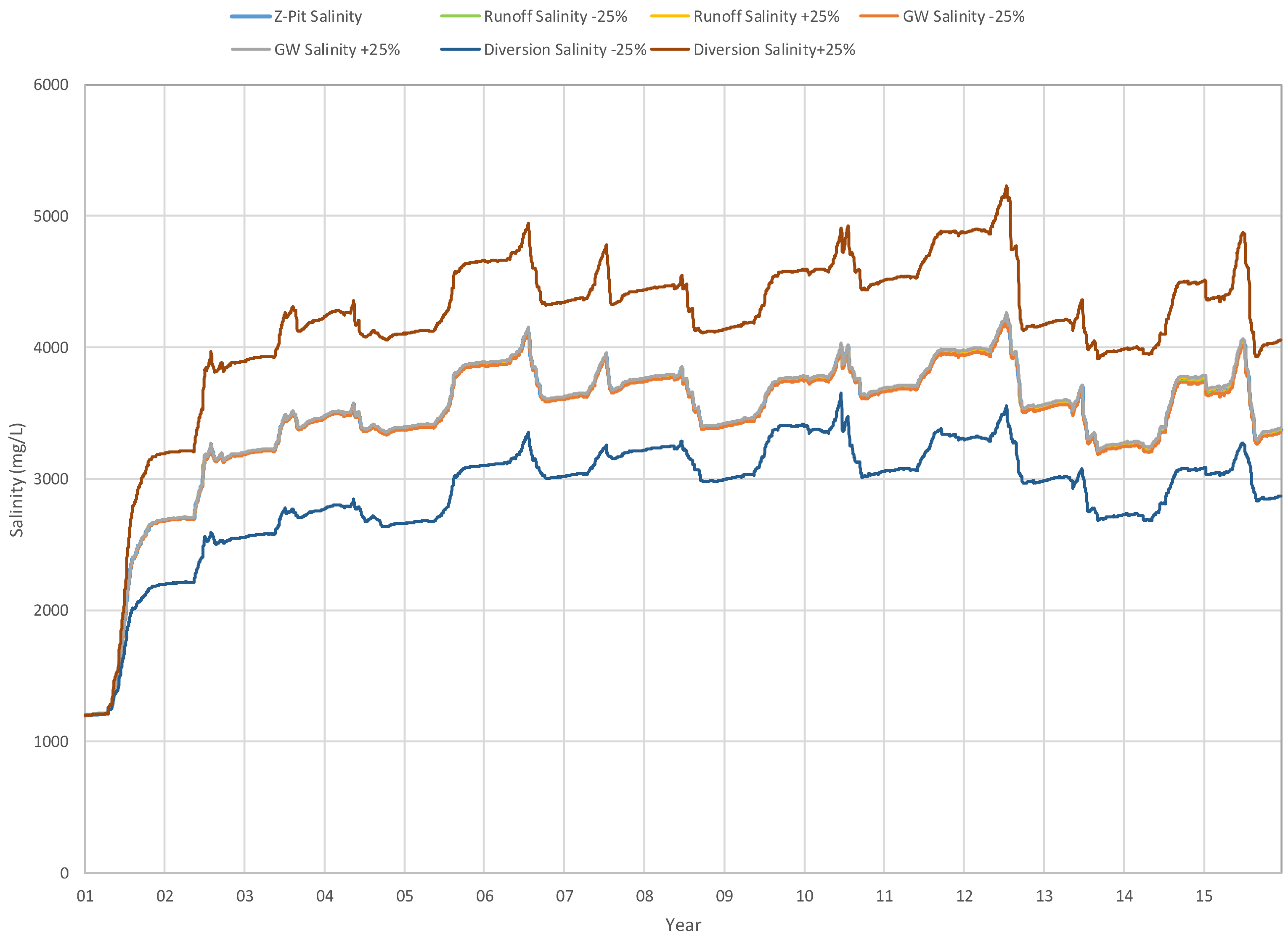
| PSM3200-002R | Figure 4-9 |

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| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>MODELLED PIT LAKE SALINITY<br>SENSITIVITY ANALYSIS | |
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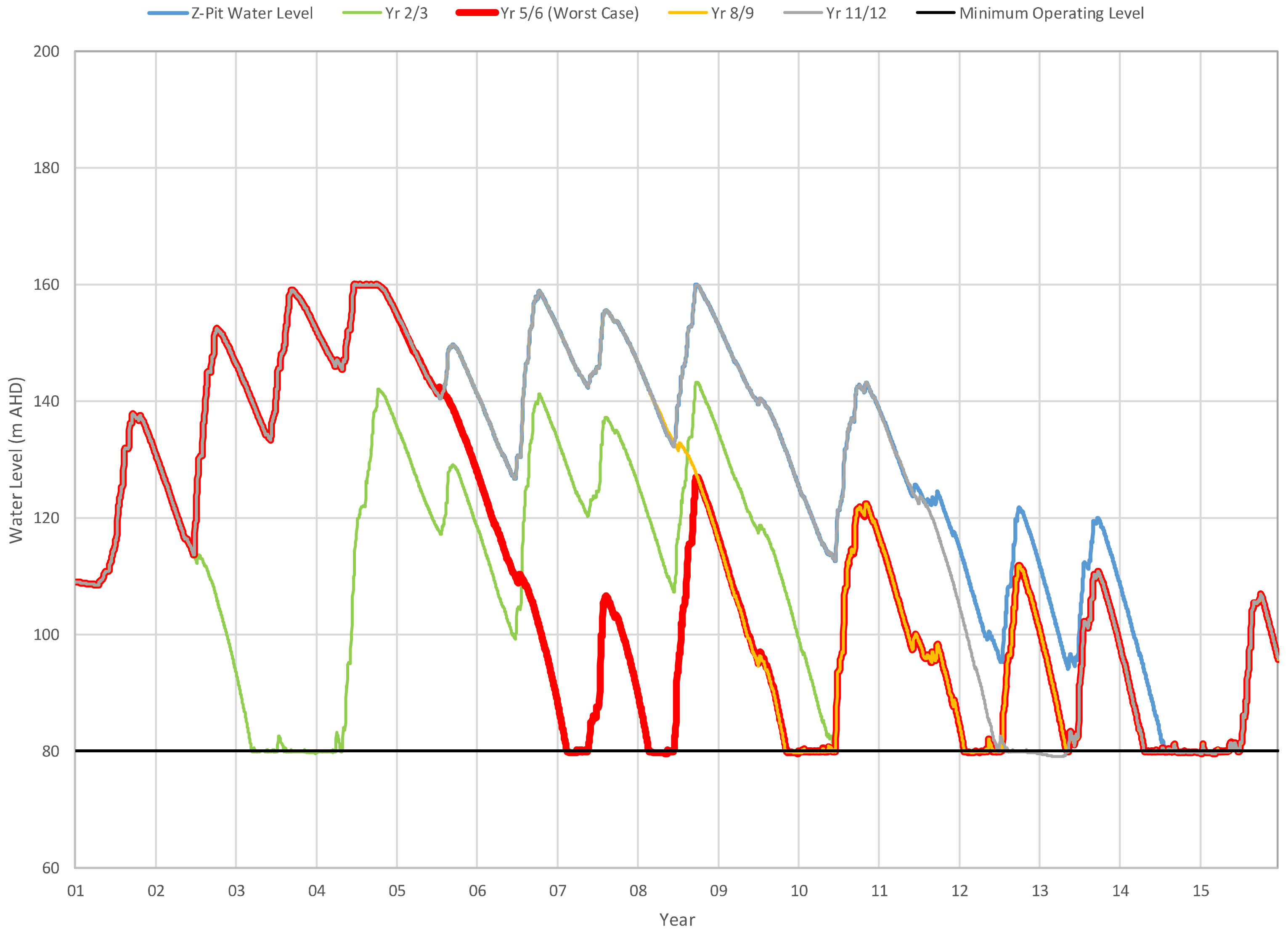
| PSM3200-002R | Figure 4-10 |




Muja Void Groundwater Interactions

Z SYSTEM
MODELLED PIT LAKE WATER LEVEL
DROUGHT SCENARIOS

Pells Sullivan Meynink

| PSM3200-002R | Figure 4-11 |
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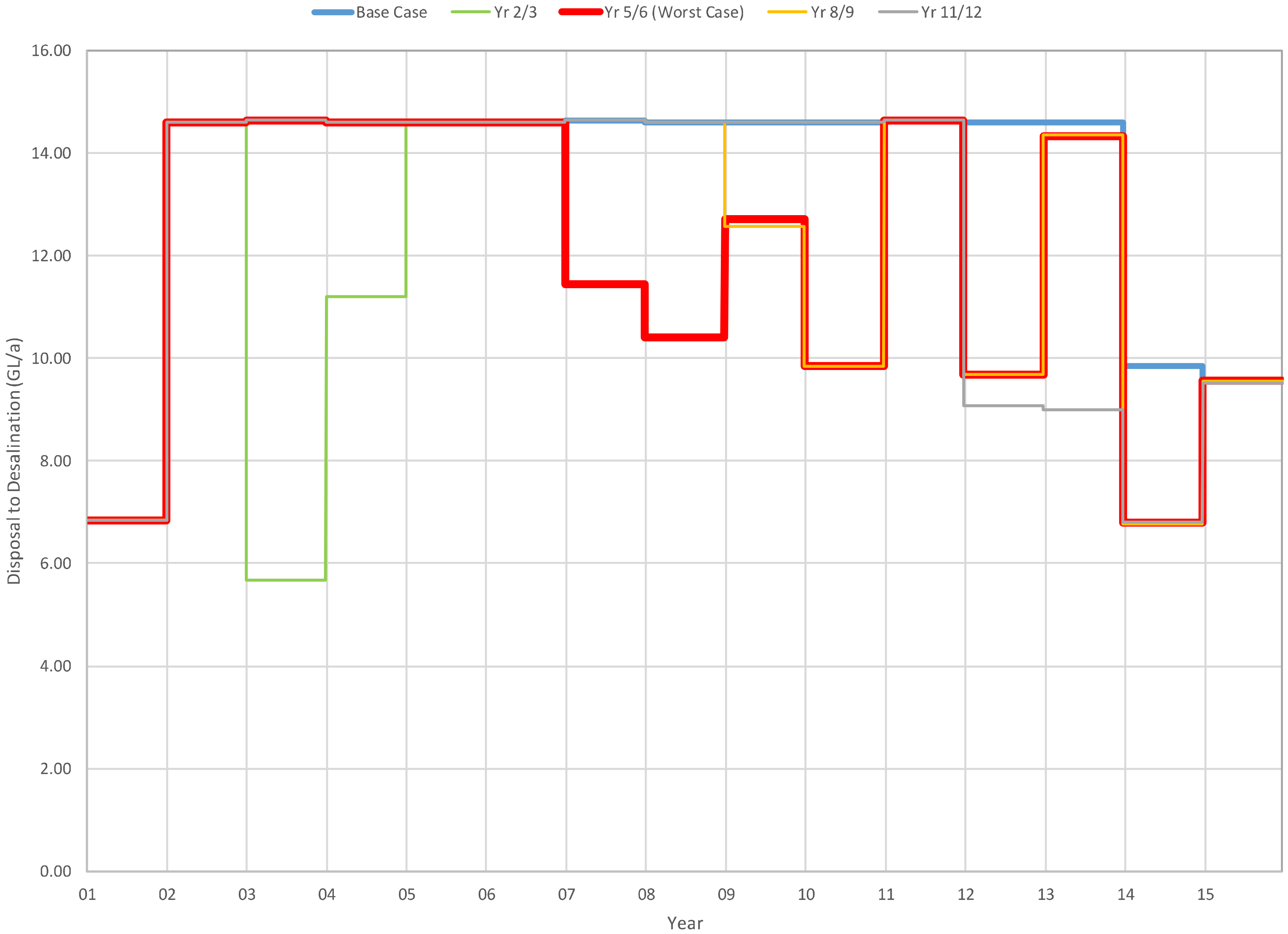


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Muja Void Groundwater Interactions

Z SYSTEM
MODELLED DRAW RATE
DROUGHT SCENARIOS

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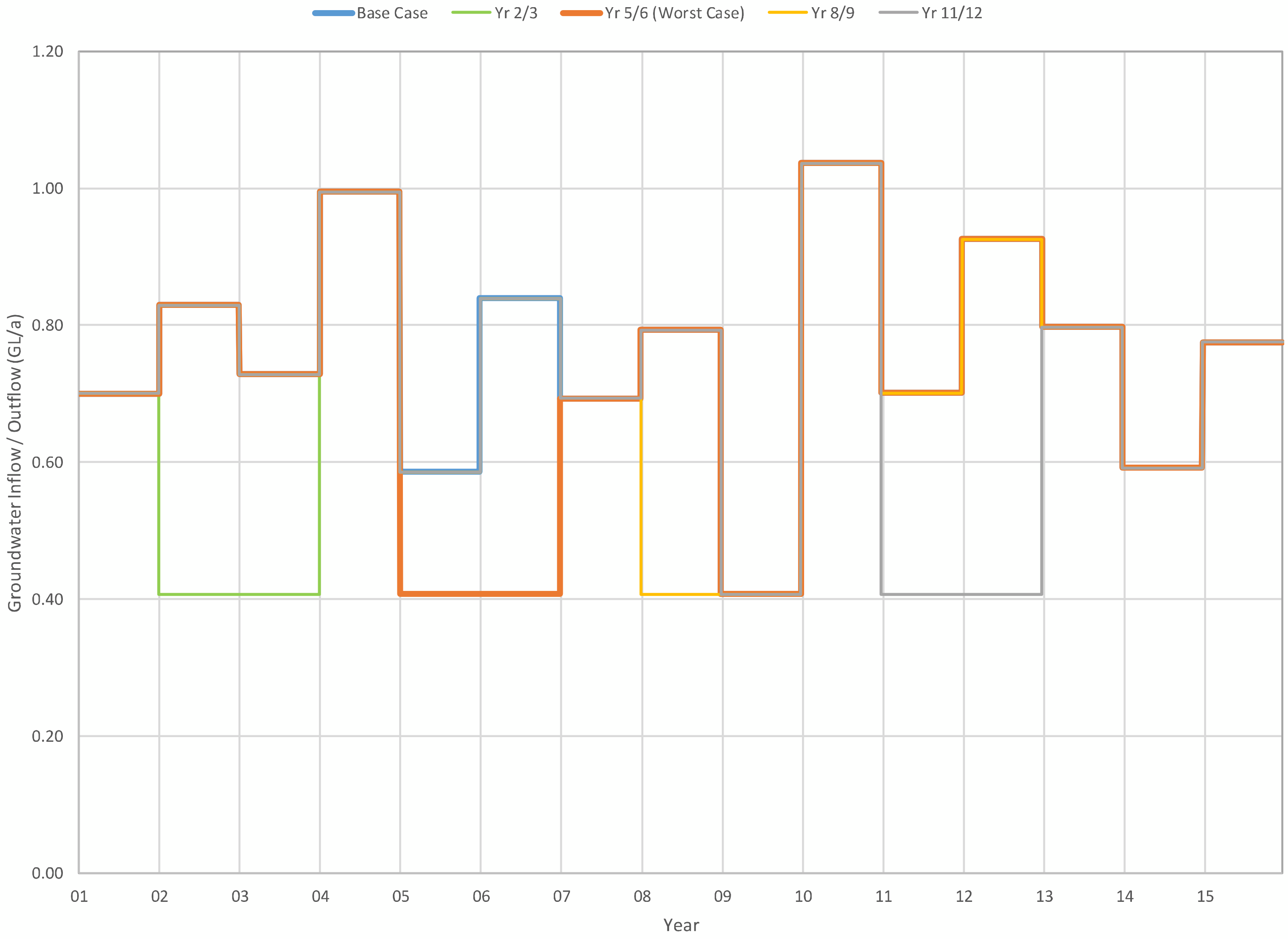
| PSM3200-002R | Figure 4-12 |

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| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>MODELLED GROUNDWATER INFLOW<br>DROUGHT SCENARIOS | |
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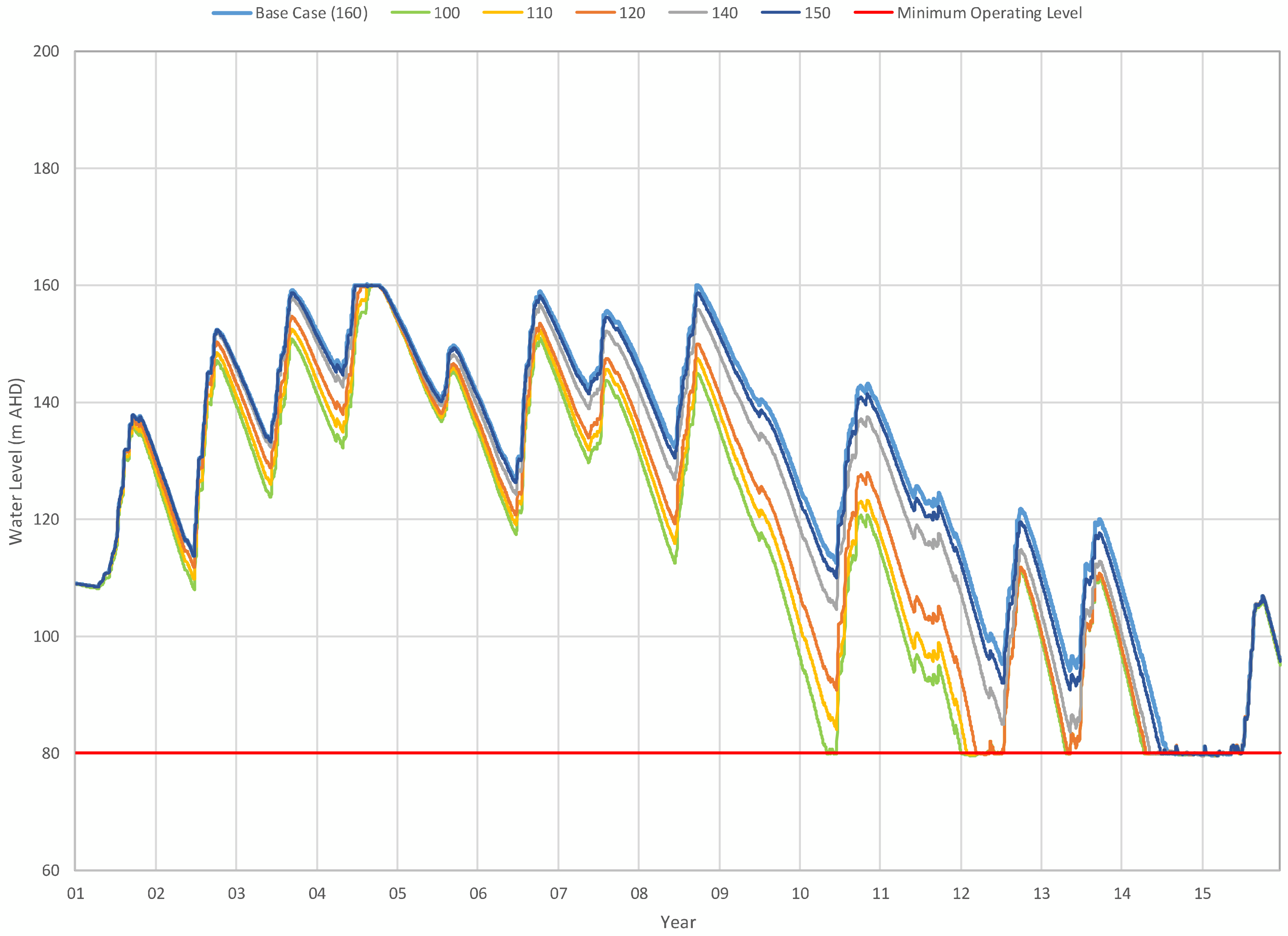
| PSM3200-002R | Figure 4-13 |




Muja Void Groundwater Interactions

Z SYSTEM
MODELLED PIT LAKE WATER LEVEL
ALTERNATIVE GROUNDWATER LEVEL SCENARIOS

| PSM3200-002R | Figure 4-14 |
|---|---|

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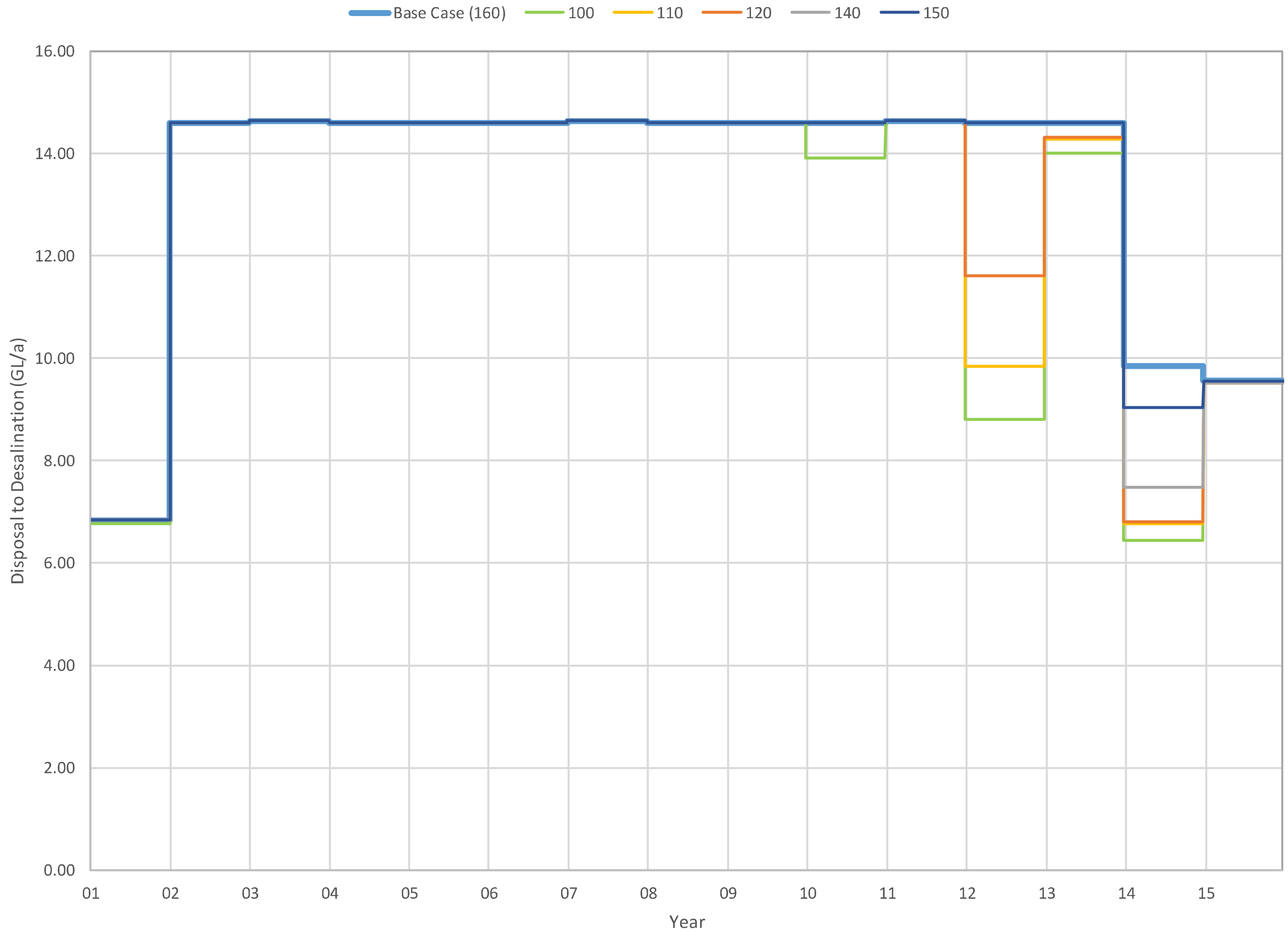


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| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>MODELLED DRAW RATE<br>ALTERNATIVE GROUNDWATER LEVEL SCENARIOS | |
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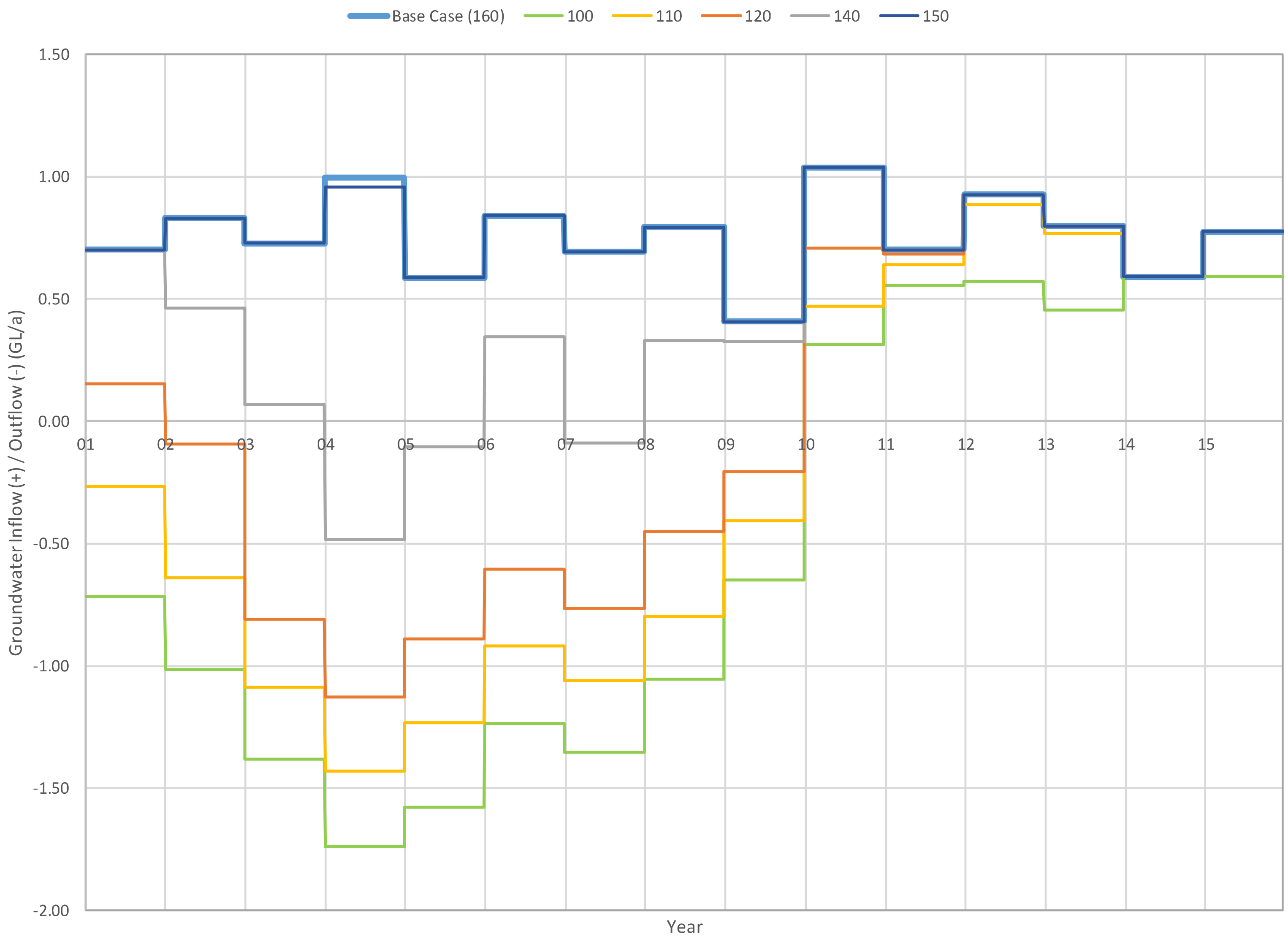
| PSM3200-002R | Figure 4-15 |




Muja Void Groundwater Interactions

Z SYSTEM
MODELLED GROUNDWATER EXCHANGE
ALTERNATIVE GROUNDWATER LEVEL SCENARIOS

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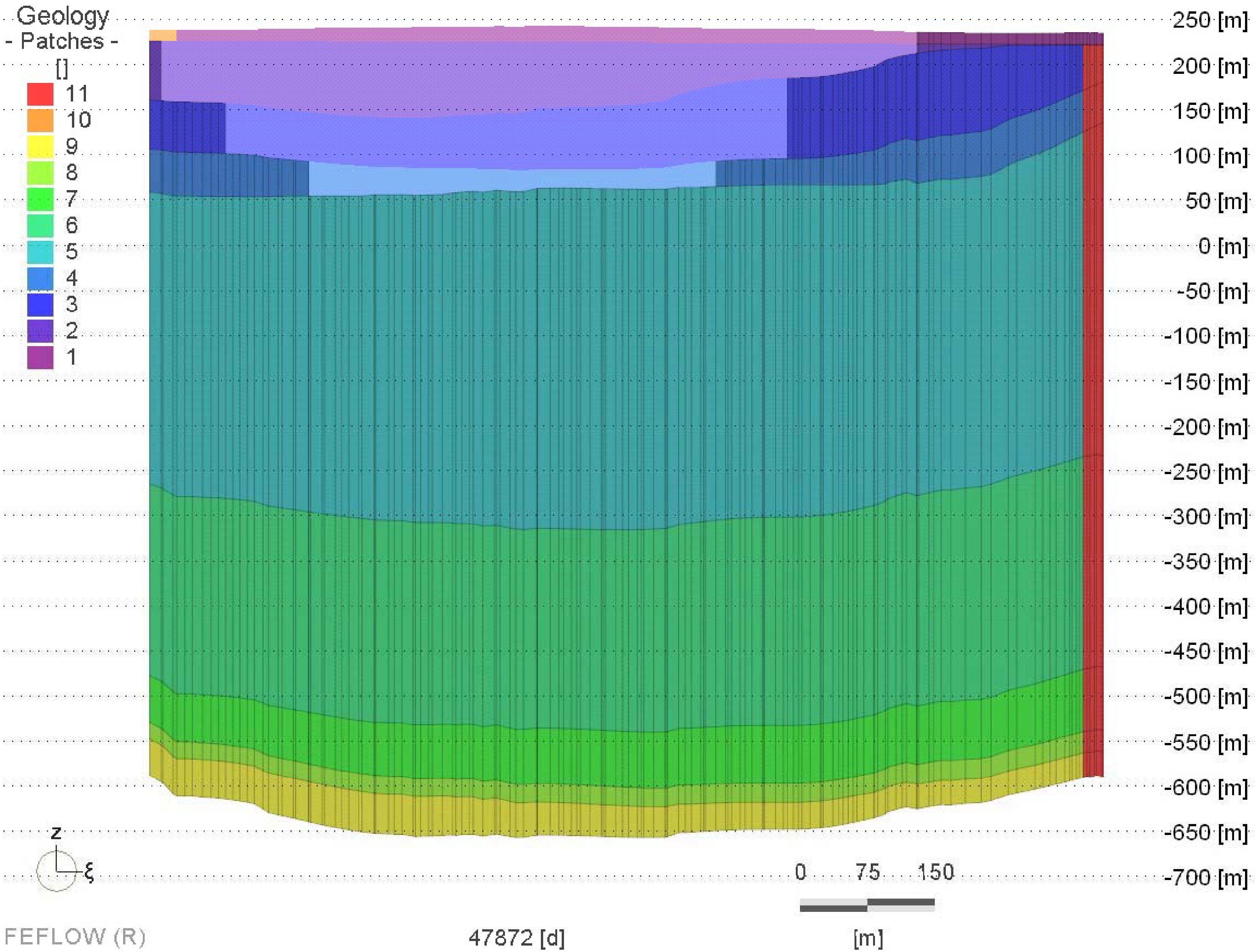
PSM3200-002R

Figure 4-16




| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>FEFLOW MODEL<br>SW-NE CROSS SECTION | |
|---|---|
| PSM3200-002R | Figure 5-1 |

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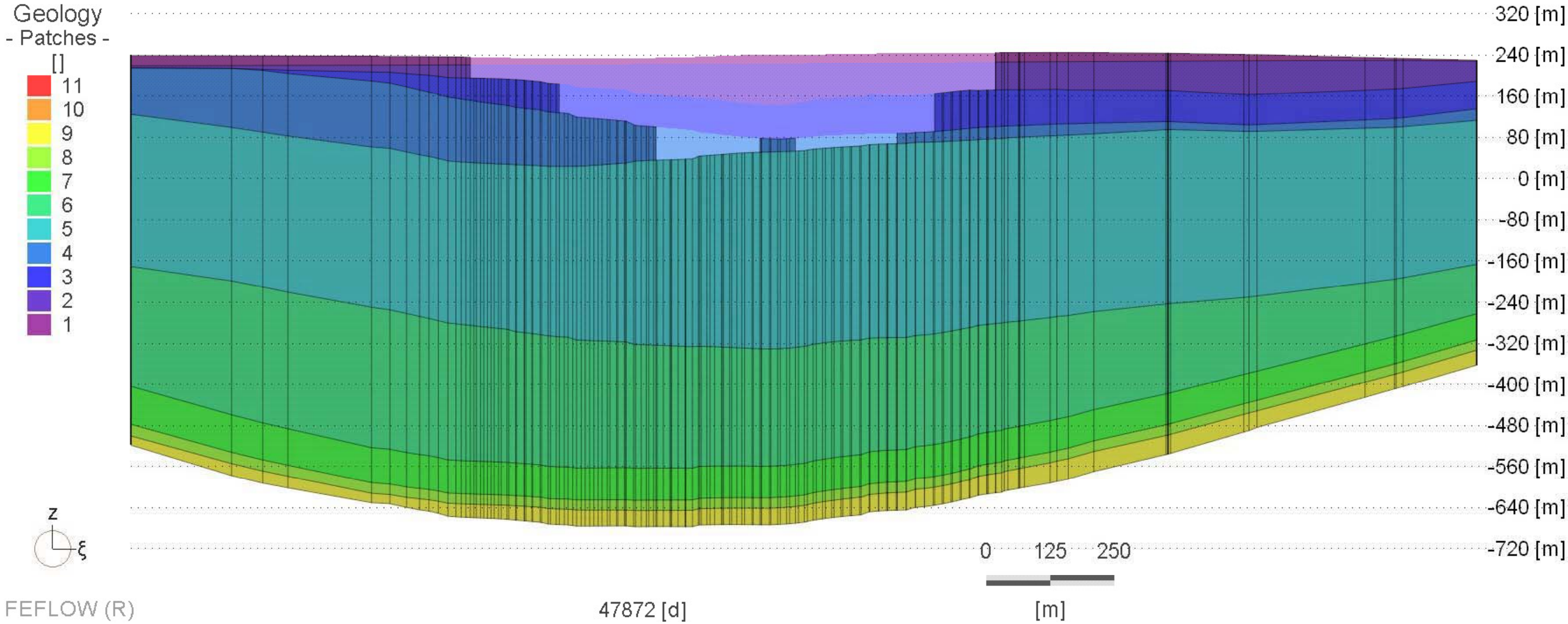


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Muja Void Groundwater Interactions

Z SYSTEM
FEFLOW MODEL
SE-NW CROSS SECTION

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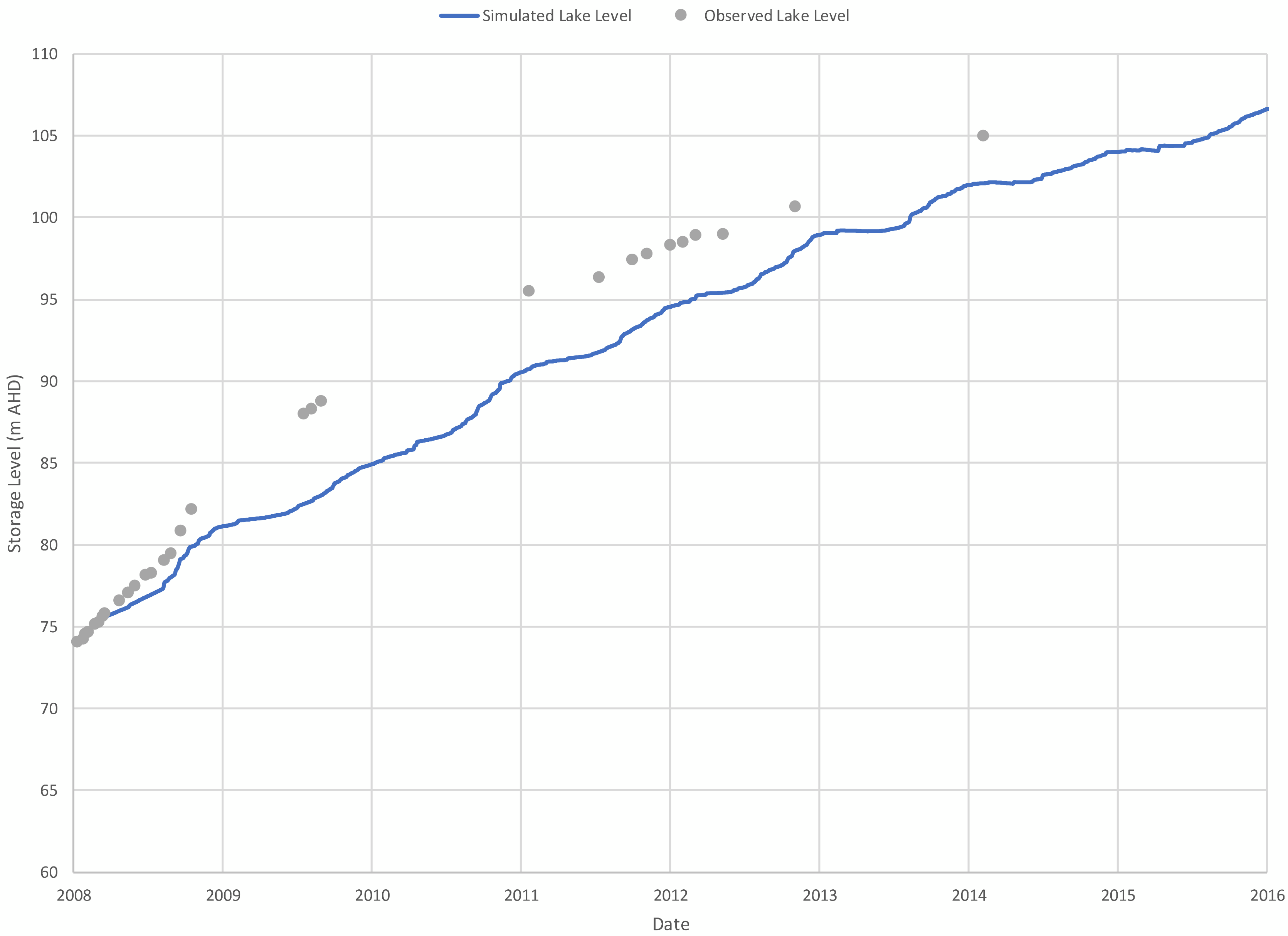
| PSM3200-002R | Figure 5-2 |

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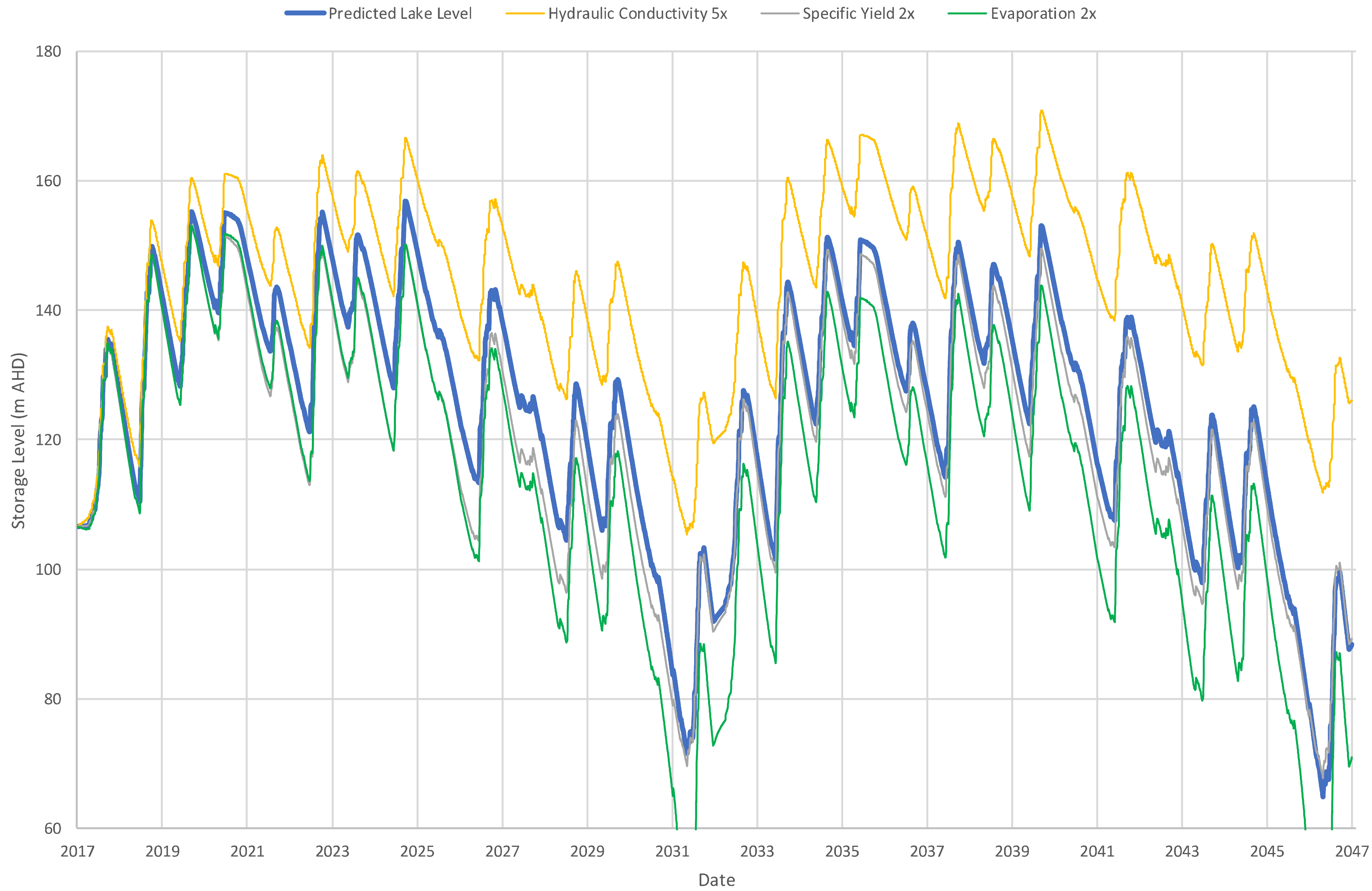
Muja Void Groundwater Interactions

Z SYSTEM
FEFLOW MODEL CALIBRATION
MODELLED LAKE WATER LEVELS

PSM3200-002R

Figure 5-3

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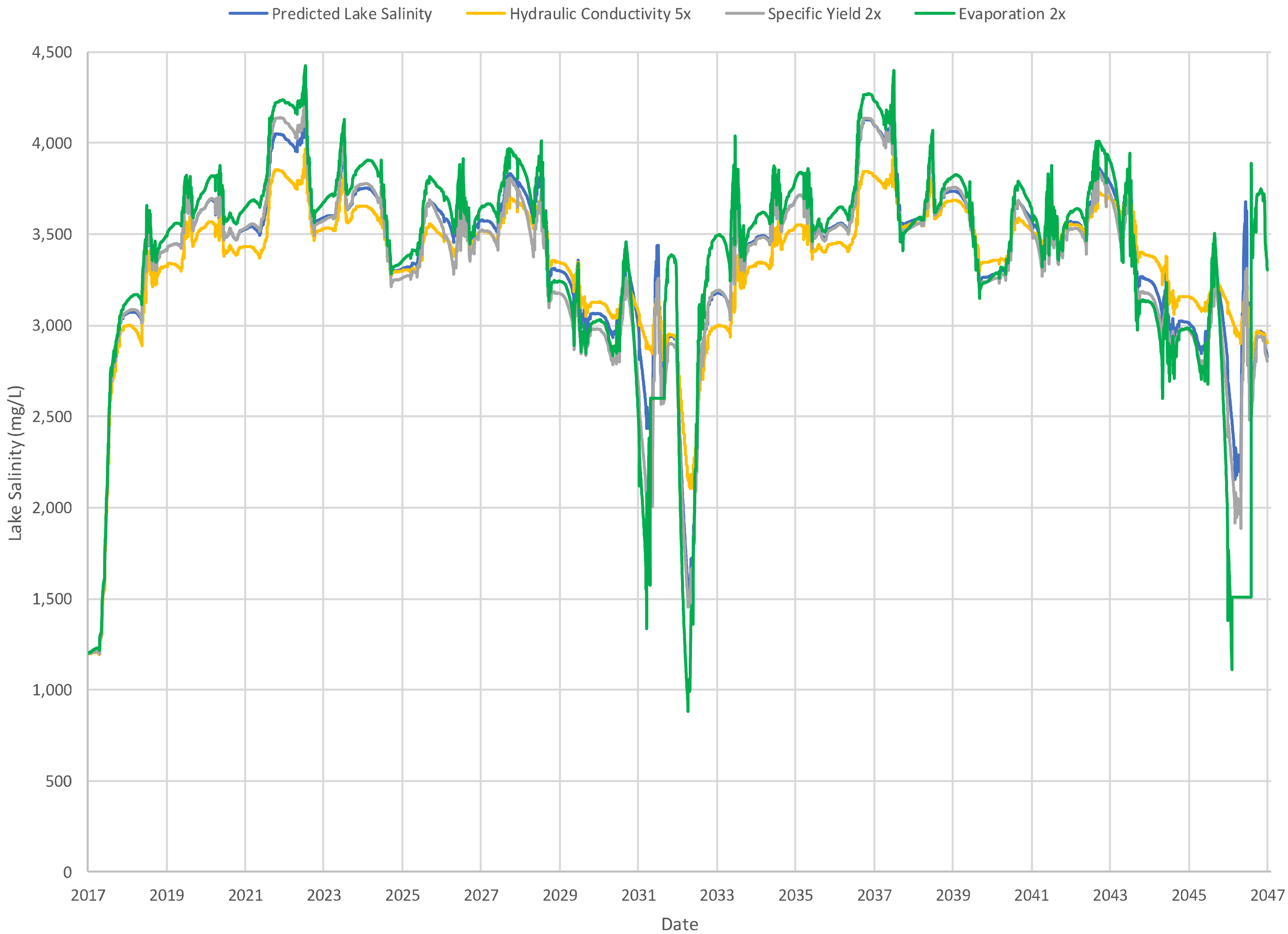
| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>FEFLOW FORWARD MODEL AND SENSITIVITY ANALYSIS<br>MODELLED LAKE WATER LEVELS | |
| PSM3200-002R | Figure 5-4 |

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Muja Void Groundwater Interactions

Z SYSTEM
FEFLOW FORWARD MODEL AND SENSITIVITY ANALYSIS
MODELLED PIT LAKE SALINITY

| PSM3200-002R | Figure 5-5 |
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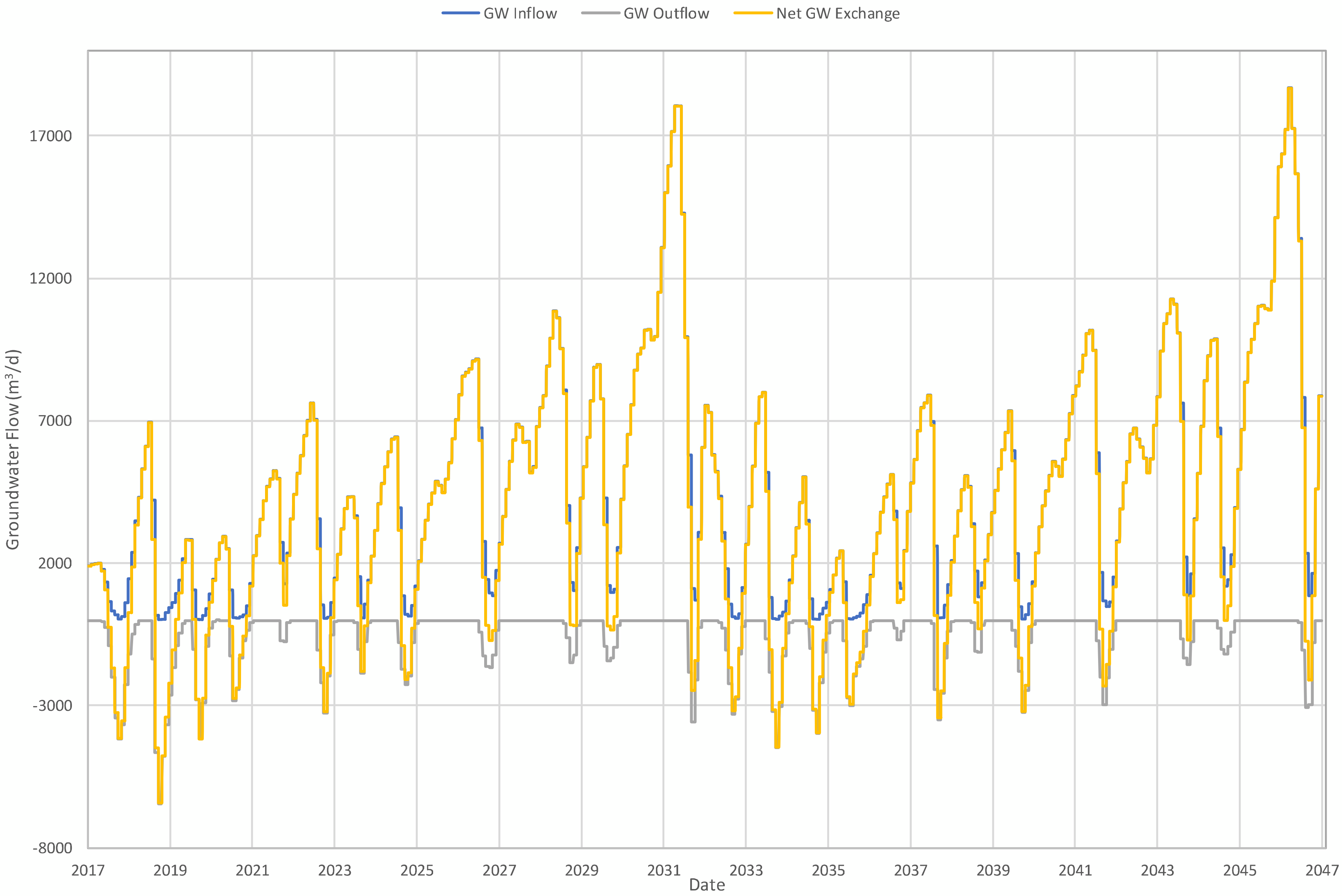


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Muja Void Groundwater Interactions

Z SYSTEM
FEFLOW FORWARD MODEL AND SENSITIVITY ANALYSIS
MODELLED GROUNDWATER INFLOW / OUTFLOW

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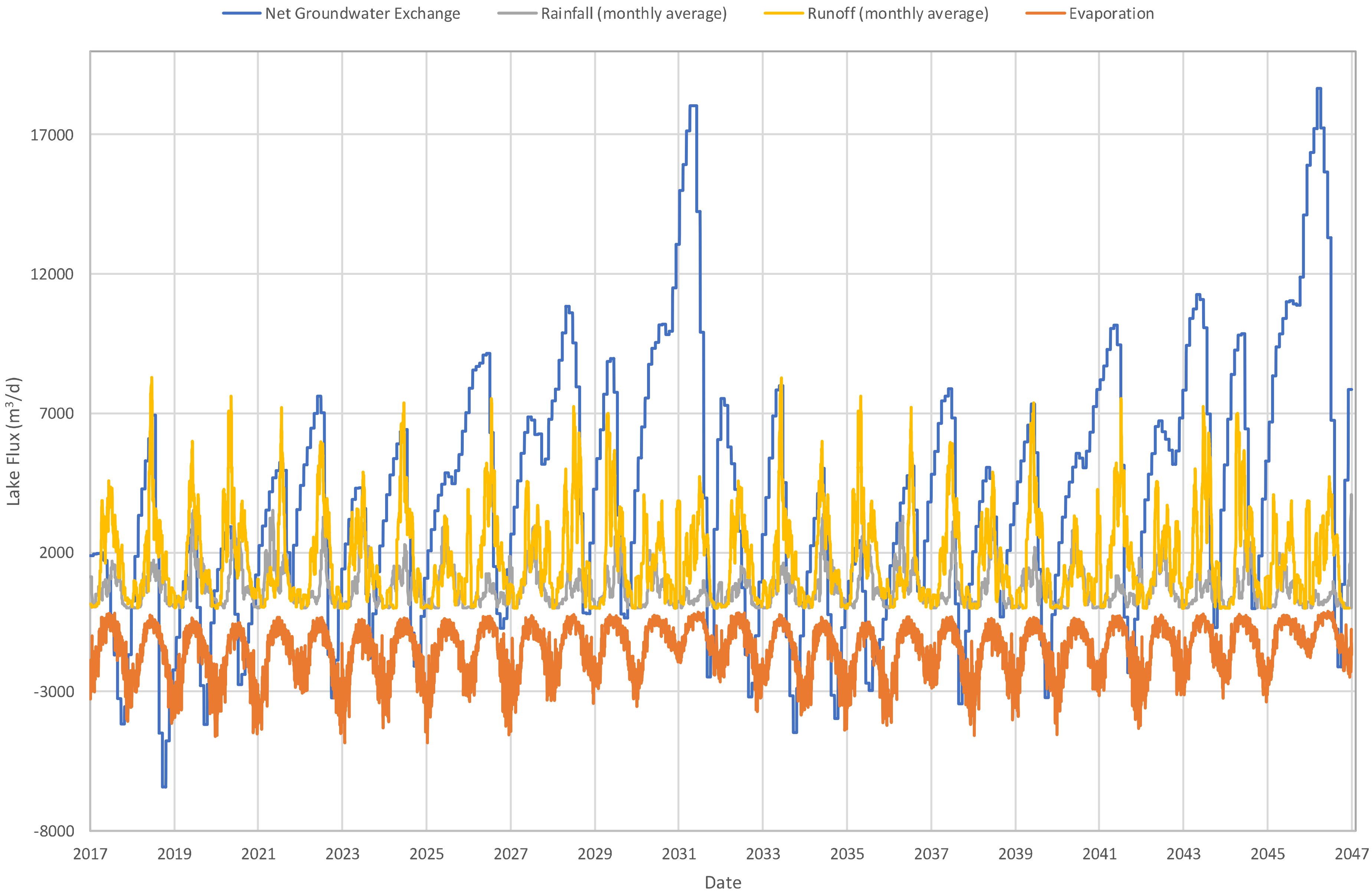
| PSM3200-002R | Figure 5-6 |

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| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>FEFLOW FORWARD MODEL<br>MODELLED LAKE FLUXES | |
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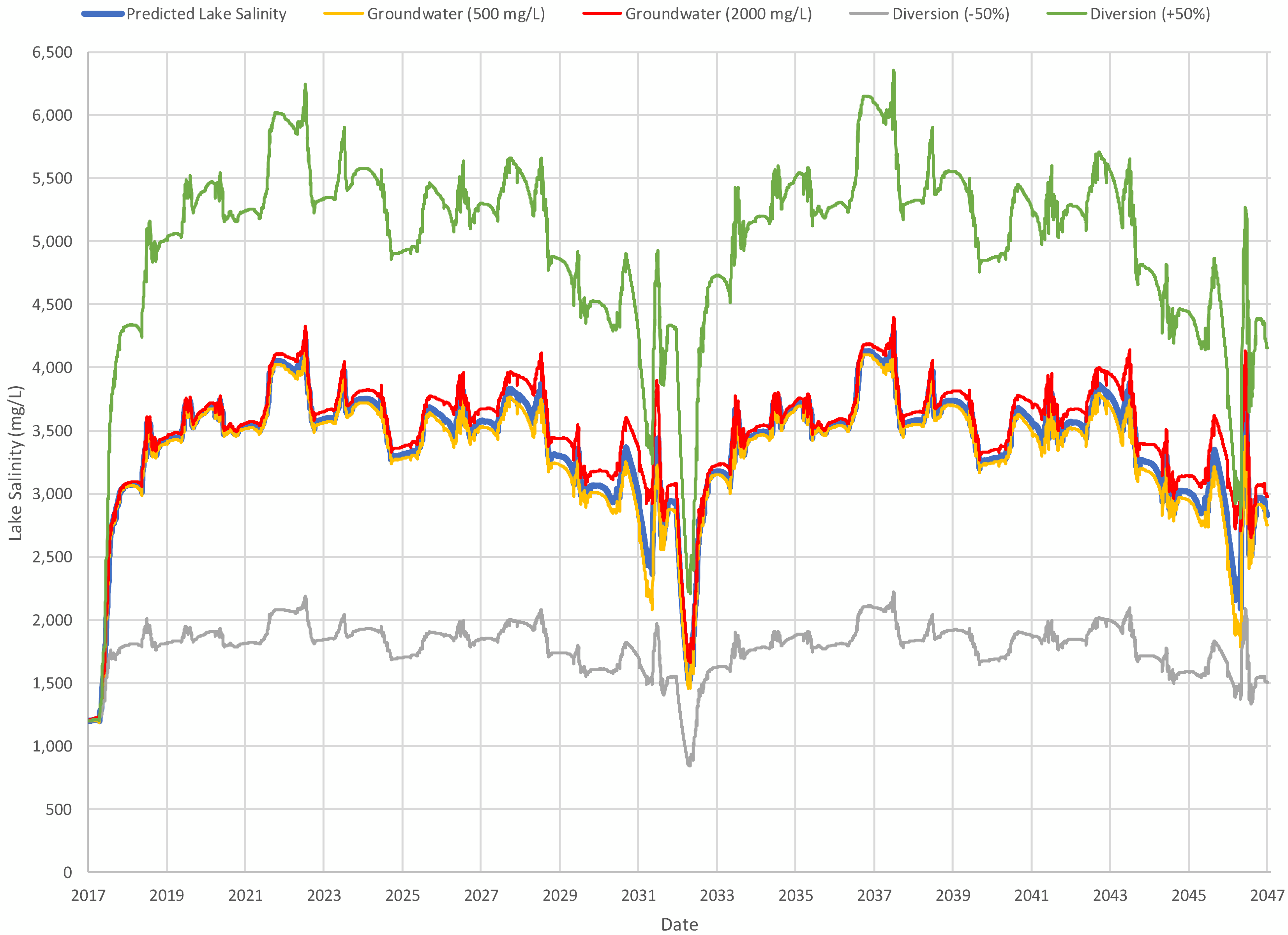
| PSM3200-002R | Figure 5-7 |




| Muja Void Groundwater Interactions<br><br>Z SYSTEM<br>FEFLOW FORWARD MODEL LAKE SALINITY<br>SENSITIVTY TO ASSUMED SOURCE CONCENTRATIONS | |
|---|---|
| PSM3200-002R | Figure 5-8 |

PSM Pells Sullivan Meynink