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Modelling report

Annexure B to water assessment

Prepared for Snowy Hydro Limited
September 2019

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Modelling report

Annexure B to water assessment

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Executive Summary

ES1 Overview

Snowy Hydro Limited (Snowy Hydro) proposes to develop Snowy 2.0, a large-scale pumped hydro-electric storage and generation project which would increase hydro-electric capacity within the existing Snowy Mountains Hydro-electric Scheme (Snowy Scheme). Snowy 2.0 is the largest committed renewable energy project in Australia and is critical to underpinning system security and reliability as Australia transitions to a decarbonised economy. Snowy 2.0 will link the existing Tantangara and Talbingo reservoirs within the Snowy Scheme through a series of underground tunnels and a new hydro-electric power station will be built underground.

This report details groundwater and surface water modelling undertaken to describe the impacts of the proposed Snowy 2.0 project on:

- groundwater head and drawdown in the vicinity of the project;
- groundwater inflow rates to the various tunnels and excavations;
- the baseflow component of streamflow; and
- overall streamflow statistics within the project area.

Modelling of the groundwater flow system was undertaken using MODFLOW USG via the Groundwater Vistas graphical user interface, while modelling of the surface water system was undertaken using eWater Source. These two models were loosely coupled, with data transfer occurring during model calibration and scenario modelling phases.

ES2 Peer review

A pre-eminent hydrogeologist, Hugh Middlemis, was engaged to peer review the numerical groundwater model and coupled surface water model.

The peer reviewer deemed that:

- the catchment model was been prepared in a manner consistent with best practice surface water modelling guidelines published by eWater (Black, et al., 2011);
- the groundwater model was developed in accordance with the principles of the best practice Australian Groundwater Modelling Guideline (Barnett, et al., 2012); and
- the coupled models are fit for the purpose of assessing catchment water balance impacts, and to inform management strategies and licensing.

ES3 Groundwater

ES3.1 Model setup

The groundwater model domain encompasses all underground excavations of the Snowy 2.0 project, Yarrangobilly Caves, all major rivers and creeks as well as all project-related groundwater monitoring sites. Hydrostratigraphic units were assigned to the model for each of the geological units mapped by drilling and geophysical surveys along the project alignment and the model design considered the water balance reporting required as per the NSW Aquifer Interference Policy (AIP), NSW DPI Water, 2012.

As the project is located within Kosciuszko National Park, with no existing suitable groundwater monitoring network or third party groundwater supply wells, no groundwater monitoring data were available within or near the model domain prior to the proposal of Snowy 2.0. As part of the water assessment for the project a network of bores was drilled, largely along the project alignment. The earliest groundwater monitoring data date from late November 2017 and many of the monitoring sites have significantly shorter records. Whilst the data do span a full set of seasons, the monitoring of long-term seasonality of groundwater behaviour is limited but is only one month short of the guideline duration for baseline of two years (DPI Water, 2014). and the response to prolonged wet or dry periods was not available to inform calibration of the model.

The combination of hydraulic head measurements, baseflow calculations and hydraulic property testing were used to inform calibration of the model in both steady state and transient modes. Calibration achieved a scaled RMS statistic of 3.6% for the steady state model, and 3.9% for the transient model.

ES3.2 Scenarios modelled

One scenario was modelled, representing:

- the pre-construction groundwater system;
- construction of the project, with model boundary conditions added in accordance with the project tunnel design and schedule, considering wet, dry and average climate sequences;
- a 20-year operation period; and
- post-construction steady state groundwater conditions representing long-term stable conditions.

Tunnel inflow mitigation measures were not included in the model scenario presented in this document.

Climate change was not explicitly modelled. Tests utilising wet and dry climate sequences indicated that groundwater inflow rates to the power waterway are insensitive to climate.

ES3.3 Model conservatism

The model predictions are considered conservative due to the design scenario assumptions (unlined and unmitigated) and the adoption of conservative hydraulic parameters (as per field measurements). Therefore, it is considered that the predicted inflow (and subsequent impacts) will be lower than predicted due to mitigation and management measures committed to during construction (ie pre-grouting and segmental lining).

Groundwater flow into the tunnel is expected to occur primarily as a function of secondary porosity (ie via fractures and along bedding planes). The groundwater model assumes significant connection between the tunnel and the watertable in the Gooandra Volcanics and the Kellys Plains Volcanics due to the hydraulic testing undertaken throughout the unit. It is possible that additional field testing may reveal that locations with vertical connection occur only in isolated locations.

The model cannot simulate individual fractures because the locations and conductivity of individual fractures will not be known until the tunnel intersects them. Because the exact locations and extent of inflow mitigation strategies are not yet known, the groundwater modelling adopted a conservative approach of simulating all excavations as non-mitigated/controlled. Attempts to simulate unknown geological occurrences or design elements are not in-line with the Australian Groundwater Modelling Guidelines (a core requirement of NSW Governments

AIP for groundwater modelling) and have therefore not been undertaken. The modelling results are therefore conservative for two reasons:

- modelling does not consider mitigating activities;
    - conservative as during construction the discrete fractures that yield excess water will be grouted and will reduce the actual overall tunnel inflow volume;
- hydraulic parameters within the numerical model for the Gooandra Volcanics and the Kellys Plain Volcanics are assume significant connection to the water table based on limited pumping test data;
    - potentially conservative as the entirety of the Gooandra Volcanics and the Kellys Plain Volcanics may not behave like this, with some parts being less permeable or less connected.

Therefore, the model predictions of tunnel inflow, baseflow reduction and water table drawdown are likely to be over estimating project impacts. The results of this conservative model approach need to be considered within this overall context to accurately assess the project on its true merits for impacts to water resources.

ES3.4 Results

The groundwater model predicted that groundwater would flow into the project excavations during construction, and into the power waterway during operation. The total inflow to excavations is expected to peak at 160 L/s (5 GL/year) in the final year of construction, and reducing to 85 L/s (2.7 GL/year) during operation (Figure ES1). Inflows to excavations will be from groundwater sourced from the fractured rock groundwater sources of the Lachlan Fold Belt Murray Darling Basin (MDB) Groundwater Source and the Lachlan Fold Belt South Coast Groundwater Source.

Groundwater flow to the excavations and power waterway will result in groundwater head drawdown developing over time. Groundwater drawdown is predicted to occur at the surface primarily near the Tantangara adit, and in the vicinity of the Gooandra Volcanics geological unit (near Gooandra Creek and the Snowy Mountains Highway) (Figure ES3). The model also predicts scattered pockets of groundwater drawdown within the Yarrangobilly River catchment. No change in groundwater level was predicted at the Yarrangobilly Caves.

As a result of groundwater drawdown at the surface, rates of groundwater discharge to surface water features (ie groundwater available for baseflow) will decline within some river and creek catchments in the vicinity of the tunnel alignment. Although streams remaining gaining (continue to receive groundwater baseflow), a reduction in baseflow is expected to develop over time, with the peak impact being realised a number of decades after the completion of the project (Figure ES2). Long-term peak baseflow reductions are predicted to approximately match the long-term inflow rate to the power waterway. Upper Tumut, Murrumbidgee and Lake Eucumbene surface water sources are each predicted to receive less baseflow due to inflows to the power waterway, with the largest impact occurring within the Murrumbidgee (Gooandra Creek) catchment, followed by the Eucumbene River headwaters (Figure ES2).

The hydraulic conductivity of the rock to be excavated by the project has been estimated using appropriate hydrogeological techniques and pumping test methods. However, fracture flow is not uniform and local scale and overall tunnel groundwater inflow will only be known once the project commences and groundwater flows into the tunnel are measured. Until that time, the groundwater drawdown and baseflow reduction predictions of the groundwater model will carry a degree of uncertainty. Should the hydraulic conductivity of the rock be higher than modelled (ie there are more fractures encountered than anticipated), then impacts to creeks at the surface may be larger than estimated. This could take the form of more severe impacts within creeks already predicted to be impacted, or it could take the form of impacts to creeks previously estimated to be unaffected by the project. Conversely, if fewer fractures are encountered, or if these fractures are not regionally connected, or if mitigation measures are applied (which is planned) then the estimated tunnel inflows may be significantly reduced, and reduction to baseflow in creeks would be lower.

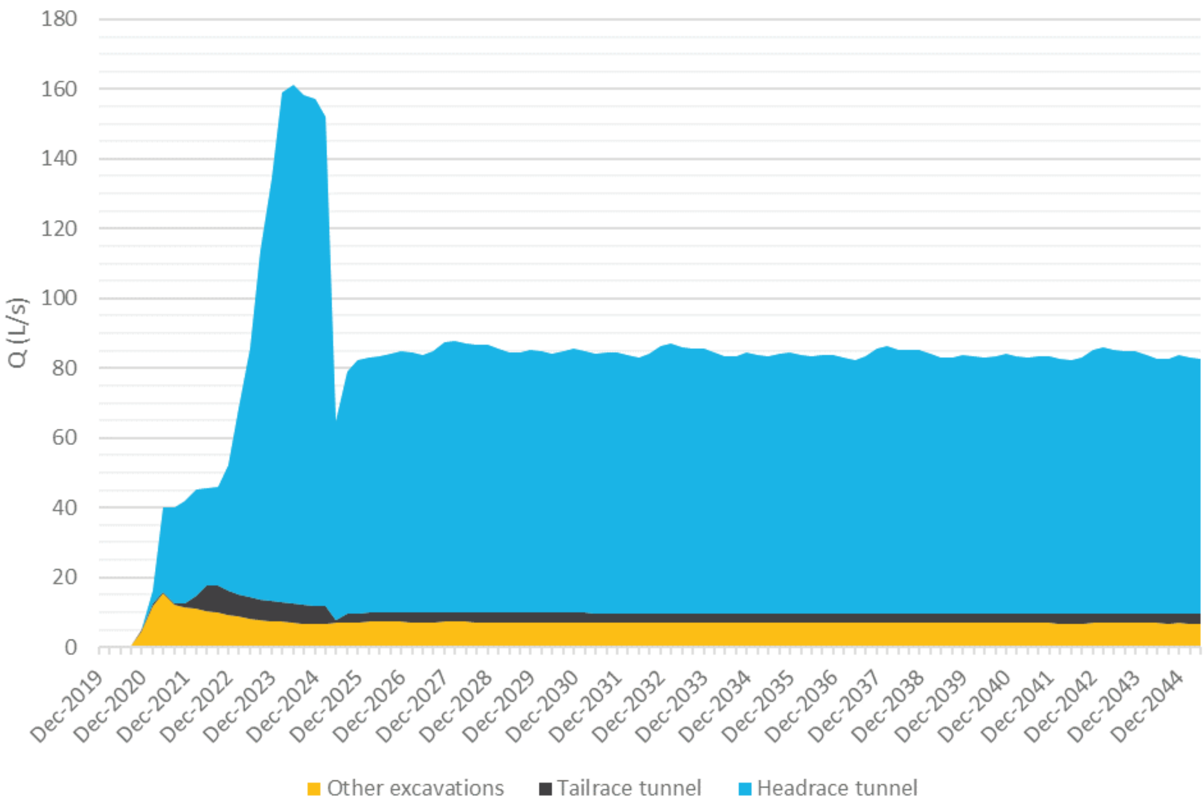


Figure ES1 Predicted inflow to excavations during construction and operation

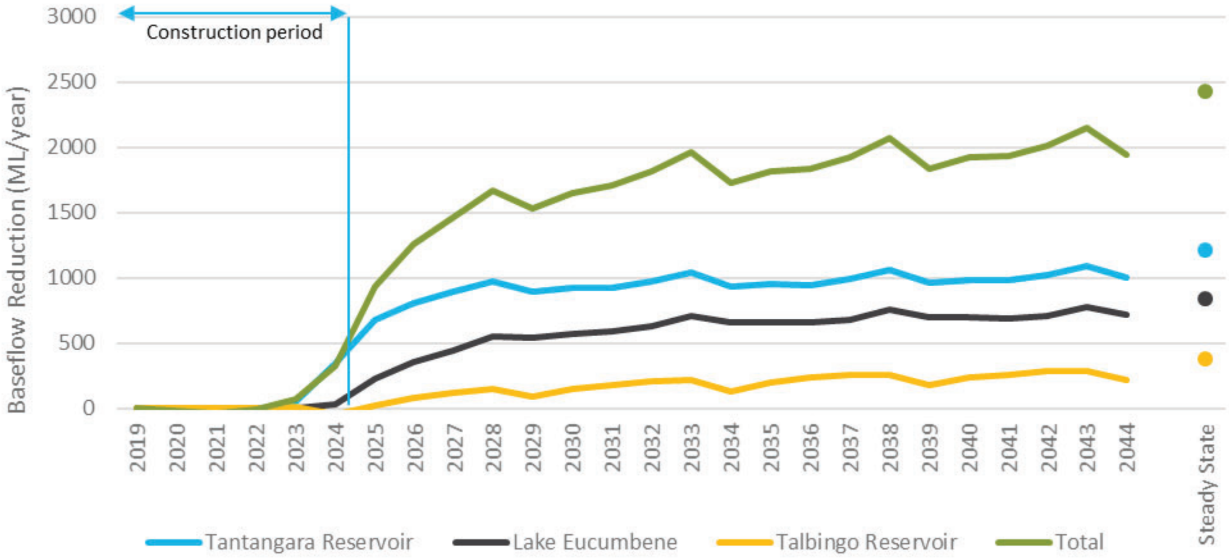
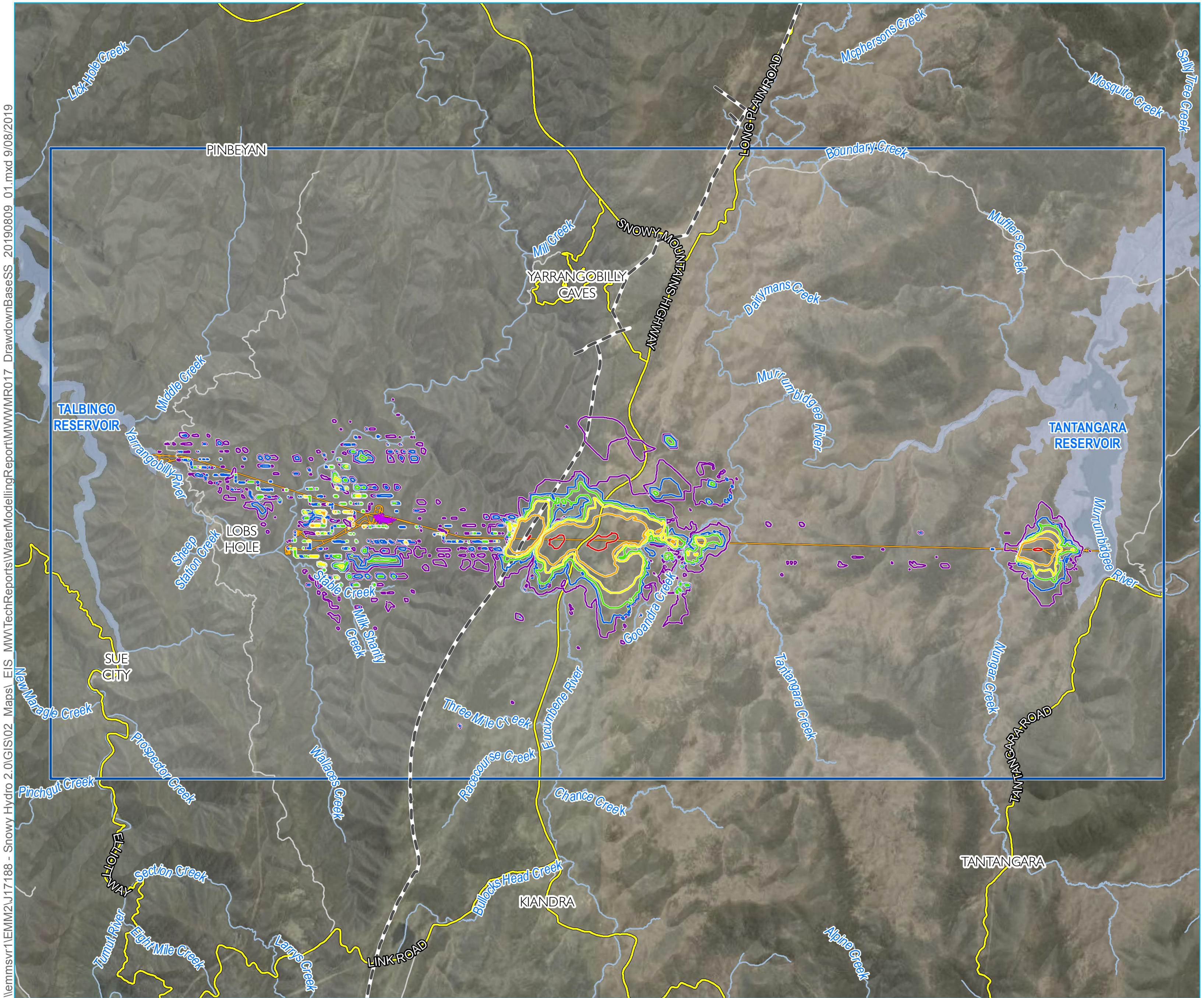


Figure ES2 Predicted baseflow reduction



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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

Predicted base case drawdown in steady state, operational

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Figure ES3

Table ES1 Predicted long-term (steady state) streamflow impacts

Surface water management unit	Catchment	Baseflow Reduction (ML/yr)	Total (ML/yr)
Murrumbidgee	Murrumbidgee River (including Gooandra Creek and Tantangara Creek)	1123	**1,179**
	Nungar Creek	56	
Lake Eucumbene	Eucumbene River	840	**840**
Upper Tumut	Yarrangobilly River (including Wallaces Creek and Stable Creek)	373	**375**
	Middle Creek	2	
Total			**2,394**

ES4 Surface water

ES4.1 Model setup

The surface water catchment model extent covered the Murrumbidgee River upstream of the Tantangara Reservoir, the Yarrangobilly River upstream of the Talbingo Reservoir, the Eucumbene River within the groundwater model domain extent, Nungar Creek and Middle Creek (Figure ES5). This extent included the area where groundwater drawdown was predicted to reach the surface.

The model was calibrated using approximately 40 years' daily streamflow data at gauges 410535 and 410574 located on the Murrumbidgee and Yarrangobilly rivers. Model validation was undertaken using streamflow data collected at several locations across the plateau, via manual and automated gauging.

ES4.2 Model coupling

The catchment water balance and runoff model utilised by the surface water model is illustrated in Figure ES4, in which a number of processes relating to runoff, infiltration, evapotranspiration and streamflow are illustrated. This runoff model is a modified version of the SIMHYD runoff model. Alterations to the standard SIMHYD model were made to enable better representation of interflow and groundwater recharge processes occurring at the project site and resulted in improved model calibration.

Processes modelled by the groundwater model are included within the green box labelled 'Groundwater Model' in Figure ES4. Recharge estimates produced by the surface water model were utilised by the groundwater model as an input. Each model produced independent estimates of baseflow discharge, on different time scales, and the calibration process ensured consistency.

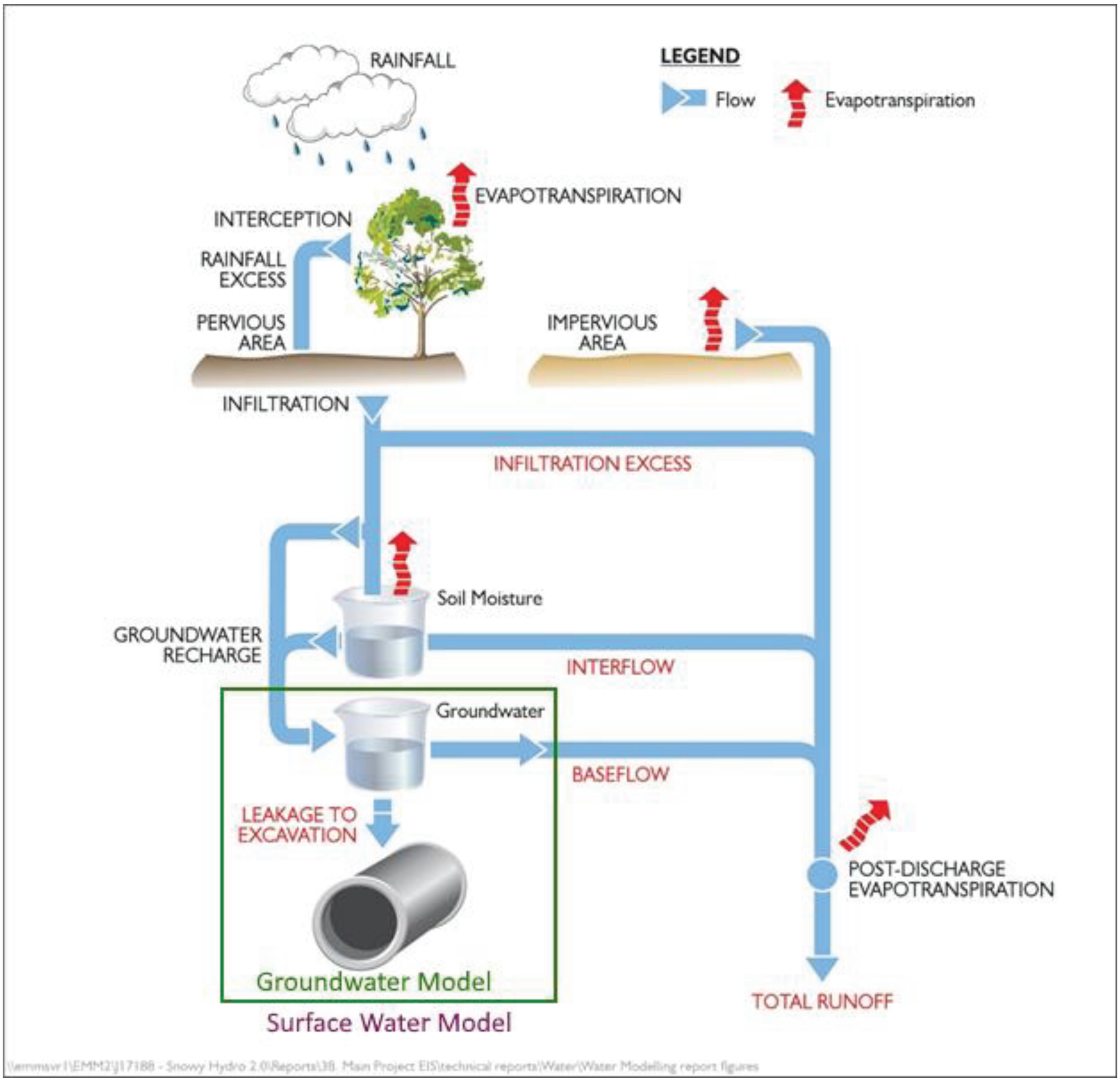
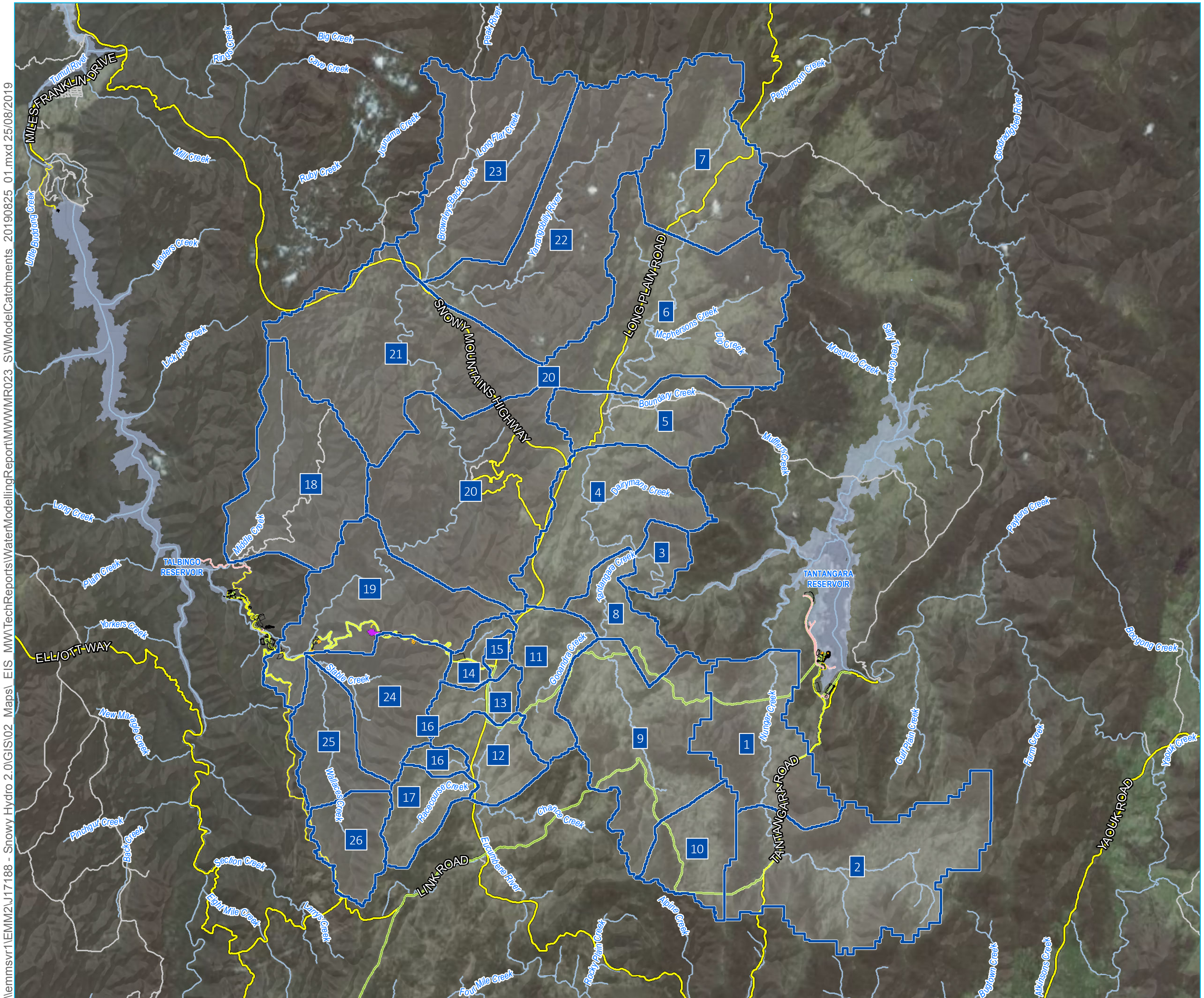


Figure ES4 Processes modelled using the surface and groundwater models

Baseflow reductions predicted by the groundwater model were applied in the surface water model using a 'leakage' term in the Modified SIMHYD rainfall runoff model. This term caused the model groundwater store to empty at a faster rate and resulted in reduced baseflow. Leakage rates were only applied within model subcatchments substantially affected by groundwater drawdown.



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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KEY

Catchments

Snowy 2.0 Main Works operational elements

Power station

Utilities

Permanent road

Snowy 2.0 Main Works construction elements

Temporary construction compounds and surface works

Temporary access road

Existing environment

Main road

Local road

Perennial watercourse

Scheme storage

Surface water model sub-catchments

Snowy 2.0

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Figure ES5

snowy 2.0

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ES4.3 Scenarios modelled

As per the groundwater modelling, one scenario was modelled, representing the following project phases:

- the pre-construction surface water system;
- construction of the project considering wet, dry and average climate sequences; and
- operation of the project (ie post-construction steady state groundwater conditions).

Climate change was not explicitly modelled. Sensitivity analysis indicated that runoff statistics are sensitive to changes in rainfall, but that the change to runoff statistics due to project impacts is relatively insensitive to changes in rainfall or evapotranspiration.

ES4.4 Results

The groundwater model predicted that impacts to creek and river baseflows would develop over time, with the largest impacts seen after construction is complete, and showed that groundwater drawdown at the surface will mainly occur in the vicinity of Gooandra Creek and the Eucumbene River headwaters (Figure ES3). The groundwater model predicted that during construction and in the areas directly overlying the tunnel alignment:

- baseflow to Gooandra Creek may decline by up to 20%, beginning in year 4 of construction; and
- baseflow to the uppermost 1.5 km of the Eucumbene River headwaters may cease, beginning in year 5 of construction.

The surface water catchment model was used to investigate the effect of these baseflow reductions on the streamflow regimes downstream of the impacted catchments, and showed that:

- Gooandra Creek is likely to change from a perennial streamflow regime to ephemeral, as days with less than 0.1 ML/day streamflow at the downstream end of the creek increase from 0% to 9%; and
- north of the Snowy Highway the Eucumbene River could also become ephemeral, as days with less than 0.1 ML/day streamflow at this location increase from 0% to approximately 25%.

It is expected that the quickflow component of streamflow (surface runoff in response to rainfall) will not be affected by groundwater drawdown and baseflow reduction.

In each catchment, the modelled impact reduced with distance downstream as flows from catchment areas unaffected by the project entered the creek system.

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1 Introduction

1.1 Overview

Snowy Hydro Limited (Snowy Hydro) proposes to develop Snowy 2.0, a large-scale pumped hydro-electric storage and generation project which would increase hydro-electric capacity within the existing Snowy Mountains Hydro-electric Scheme (Snowy Scheme). Snowy 2.0 is the largest committed renewable energy project in Australia and is critical to underpinning system security and reliability as Australia transitions to a decarbonised economy.

Snowy 2.0 will link the existing Tantangara and Talbingo reservoirs within the Snowy Scheme through a series of underground tunnels and a new hydro-electric power station will be built underground. The major construction elements of Snowy 2.0 include permanent infrastructure, temporary construction infrastructure, management and storage of excavated rock material and establishing supporting infrastructure. Snowy 2.0 Main Works also includes the operation of Snowy 2.0.

To assess impacts from the project, an Environmental Impact Statement (EIS) has been prepared (EMM 2019). Chapter 2 of the Snowy 2.0 Main Works EIS describes the construction and operation of the project in detail. In order to assess potential groundwater and surface water related issues from the construction and operation of Snowy 2.0, a water assessment (EMM 2019) has been prepared as an appendix to the Snowy 2.0 Main Works EIS. The water assessment has a number of supporting technical reports which are termed annexures. Each annexure has further supporting technical reports which are termed attachments.

This modelling report is an annexure to the water assessment. The document structure of the technical reports and assessments which support the overall water assessment are shown in Figure 1.1.

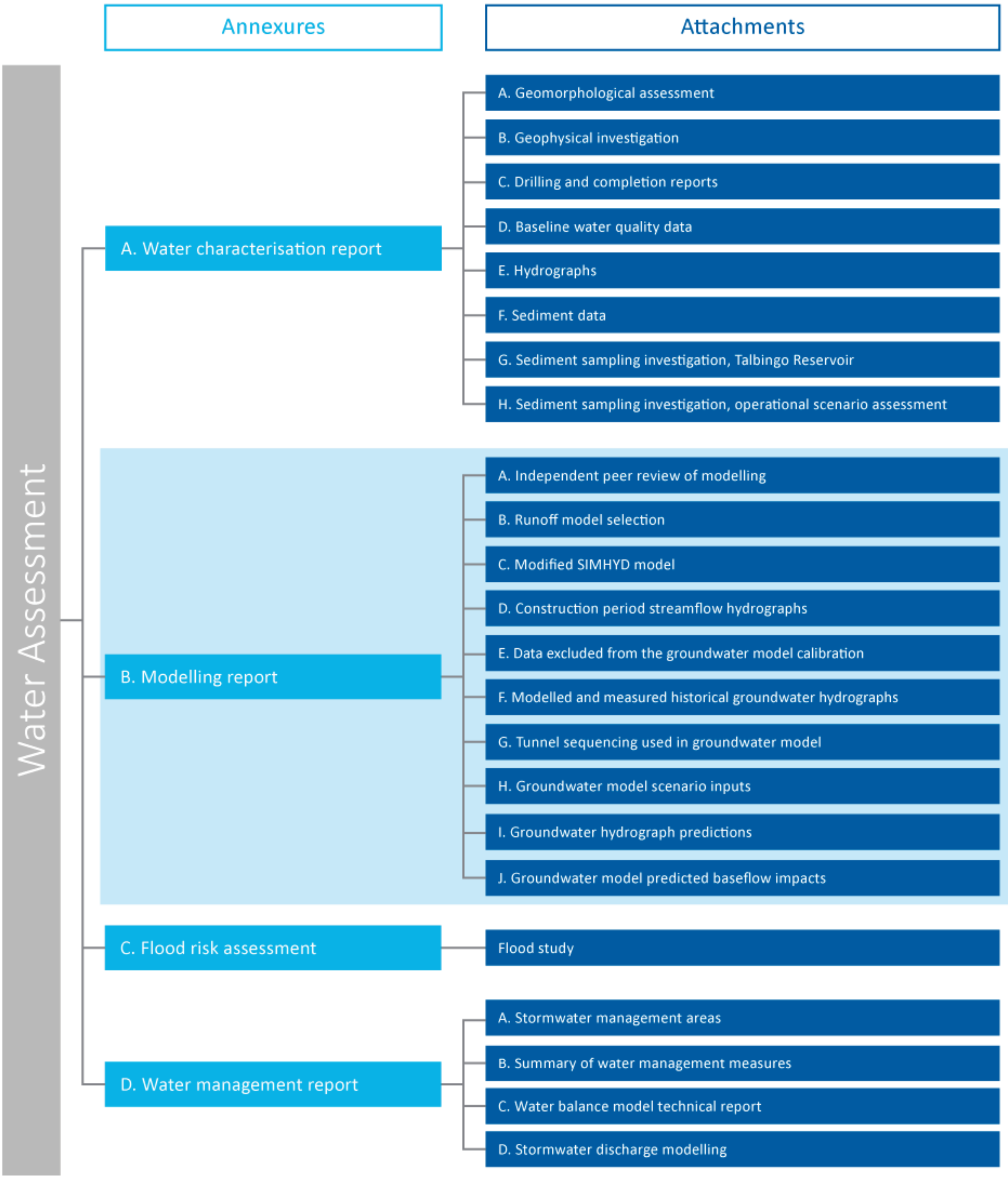


Figure 1.1 Document structure

1.2 Scope of this report

This report describes groundwater and surface water modelling undertaken to describe the impacts of the proposed Snowy 2.0 project on:

- groundwater head and drawdown in the vicinity of the project;
- groundwater inflow rates to the various tunnels and excavations;
- the baseflow component of streamflow; and
- overall streamflow statistics within the project area.

Flooding is discussed in Annexure C of the water assessment.

Stormwater quality is discussed in Annexure D of the water assessment.

1.3 Modelling approach

Modelling of the groundwater flow system was undertaken using MODFLOW USG via the Groundwater Vistas graphical user interface, while modelling of the surface water system was undertaken using eWater Source. These two models were loosely coupled (ie using a methodology similar to that applied to the Murray-Darling Basin Sustainable Yields project; CSIRO 2007,2008), with data transfer occurring during model calibration and scenario modelling phases (Figure 1.2).

The surface water model (see chapter 2) was developed using a rainfall runoff model that explicitly described the movement of water through the soil unsaturated zone into the aquifer, and discharge of groundwater as baseflow to streams. Seasonal groundwater recharge rates estimated by the calibrated surface water model were provided as input to the groundwater model (see chapter 3) such that the two models utilised a consistent catchment water balance.

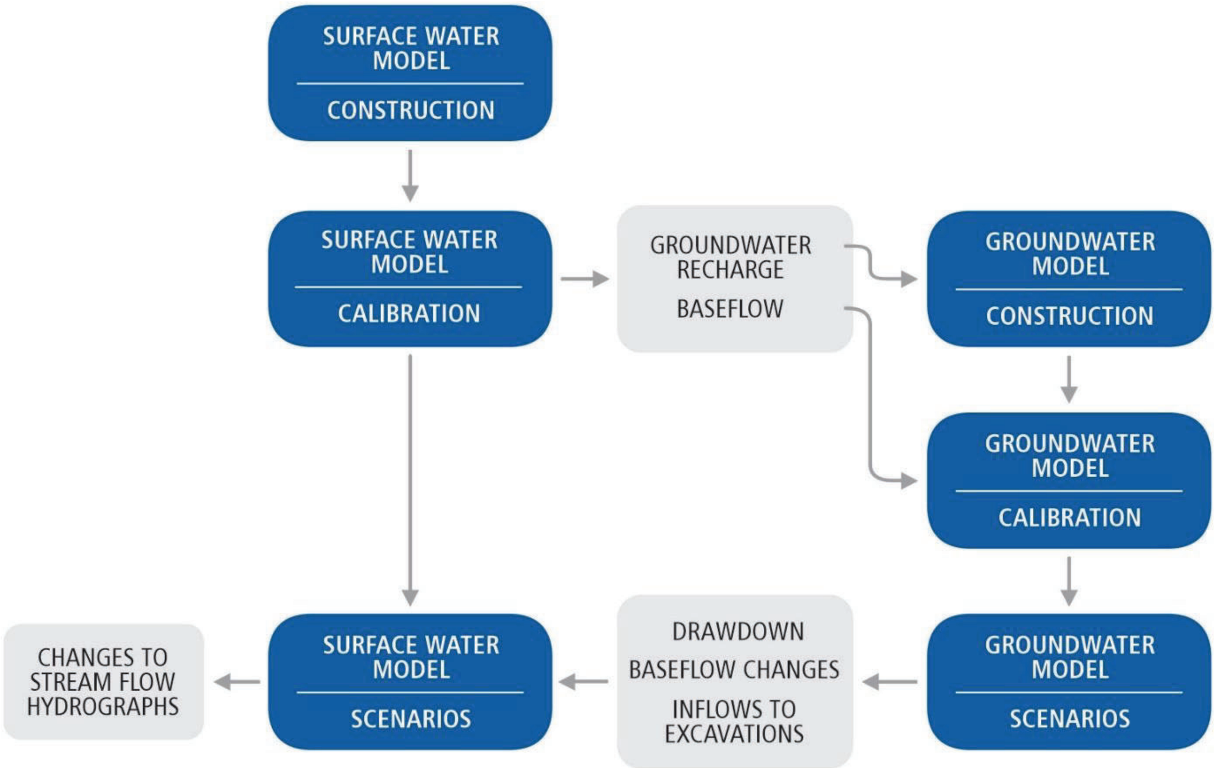


Figure 1.2 Data transfer between model stages

Rainfall interception, evapotranspiration prior to groundwater recharge, and evapotranspiration post baseflow discharge were modelled within the surface water model. The total evapotranspiration flux extracted from within the surface water model is consistent with the calibrated whole of catchment water balance. The recharge rates provided to the groundwater model were a net rate post evapotranspiration within the soil and root zone.

To avoid double accounting for evapotranspiration, the groundwater model was not used to directly estimate additional evapotranspiration from saturated groundwater (although the evapotranspiration package was applied in the groundwater model to estimate distributed/diffuse groundwater discharge to the surface and near surface; see chapter 3 for details). The groundwater model was used to model the movements of water underground from recharge to baseflow discharge locations, with a focus on estimating flow into the excavated tunnels and caverns.

The catchment water balance utilised by the surface water model is illustrated in Figure 1.3, in which a number of processes relating to runoff, infiltration, evapotranspiration and streamflow are illustrated. Processes modelled by the groundwater model are included within the green box labelled 'Groundwater Model'. The recharge and flow to excavation rates were each the result of one model, used as an input to the other (Table 1.1). Each model produced independent estimates of baseflow discharge, on different time scales, and the calibration process ensured consistency. The quarterly sum of baseflow discharges predicted by the surface water model was compared to the baseflow predictions made by the groundwater model during the groundwater model calibration process (see section 3.2.7). The daily baseflow predictions produced by the surface water model were used for developing descriptions of changes to streamflow and related statistical measures.

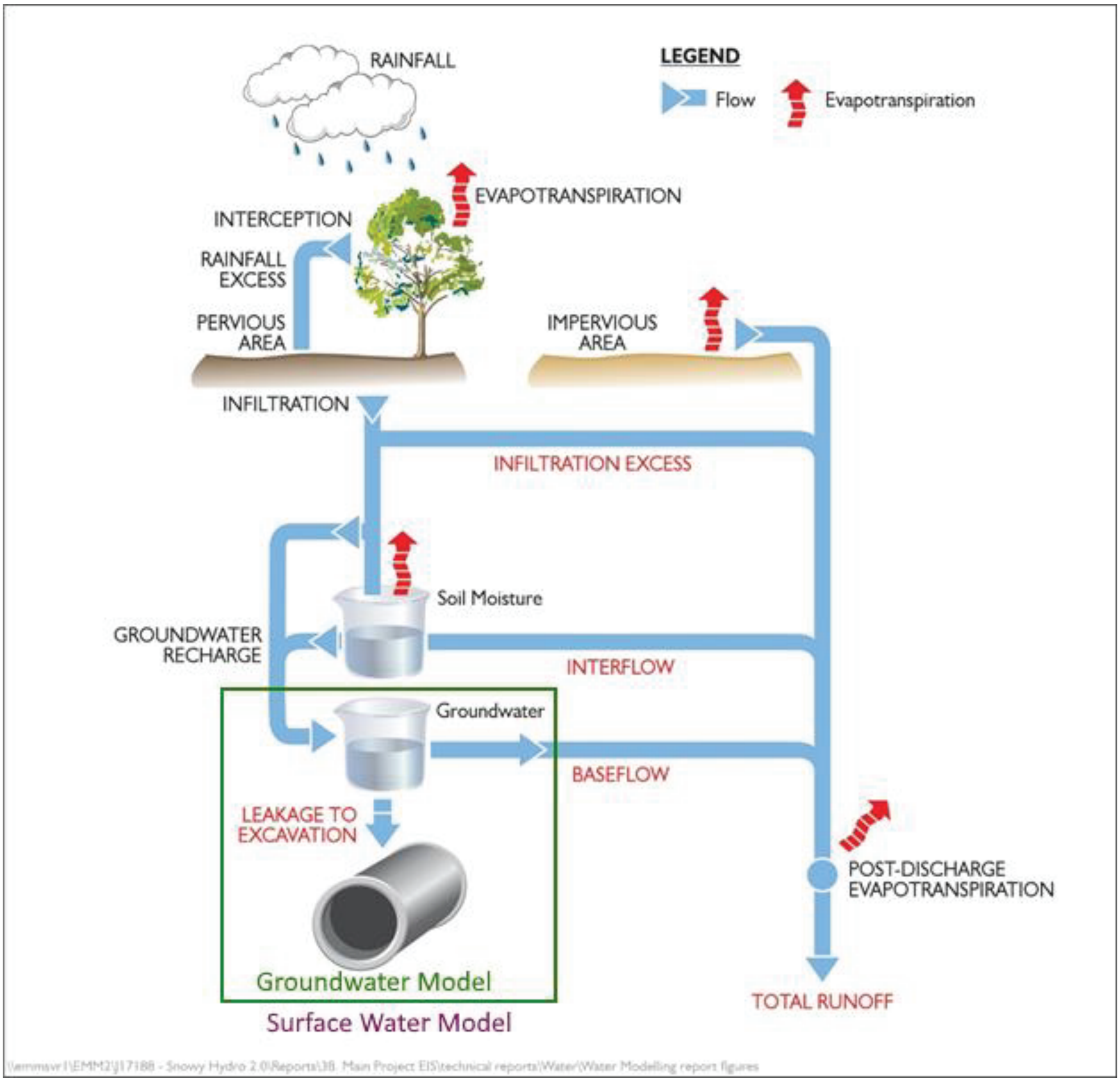


Figure 1.3 Processes modelled using the surface and groundwater models

Table 1.1 Processes modelled by the coupled groundwater and surface water models

Catchment Process	Status in surface water model	Status in groundwater model
Groundwater recharge	Result	Input
Leakage to excavation	Input	Result
Baseflow discharge	Result	Result

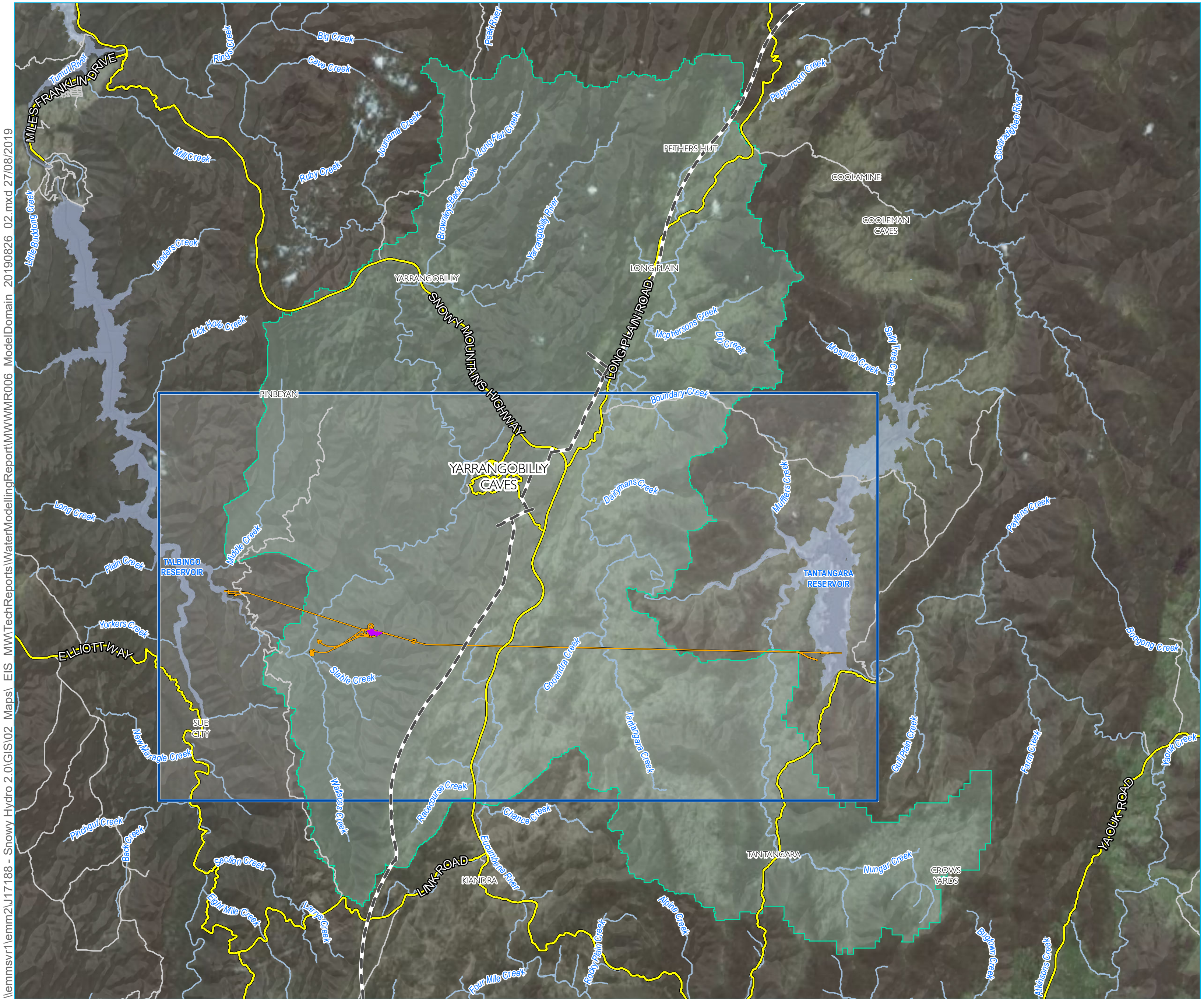
Baseflow discharge from the groundwater model was estimated via two methods:

- discharge directly to the base of creeks and rivers; and
- distributed groundwater discharge in catchment headwaters.

Discharge directly to the base of creeks and rivers was modelled using river boundary conditions along mapped creek alignments in the groundwater model. The concept of distributed baseflow discharge was utilised to model discharges at springs located away from the creek and river alignment, for example on flood plains or at break of slope on hill sides. Distributed baseflow discharge was modelled using the built-in evapotranspiration package within MODFLOW, as this allows water to be removed from the model wherever it nears or reaches the surface.

The groundwater model extent was a 30 km by 17 km rectangle centred on the power waterway location (section 3.2.2). The surface water model extent encompassed the headwaters of the Murrumbidgee River, Yarrangobilly River, Eucumbene River, and the entirety of the Nungar Creek and Middle Creek catchments, extending further north and south than the groundwater model extent. A comparison of model extents is provided in Figure 1.4.

The groundwater model produced estimates of inflow to the excavations during construction and flow exchanges during operations, as well as the induced impact on surface water features (section 3.4) using a quarterly (seasonal) time period. These impacts were temporally disaggregated using the surface water model, which ran with a daily time step. Changes to streamflow hydrographs were assessed using the surface water model and are described in section 2.7.



KEY

- Long Plain Fault
- Model domain
- Surface water model extent

Snowy 2.0 operational elements

- Tunnels, portals, intakes, shafts
- Power station

Existing environment

- Main road
- Local road
- Perennial watercourse
- Scheme storage

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

Model domains

Snowy 2.0
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Figure 1.4

2 Surface Water

2.1 Surface water modelling overview

2.1.1 Catchment model purpose

Catchment scale water balance and rainfall-runoff modelling was undertaken for the surface water catchments in the vicinity of the tunnel alignment for two purposes.

Firstly, to develop a catchment scale daily water balance consistent with measured streamflow data and the hydrological concept of the area that includes surface runoff, groundwater recharge, and discharge flow processes. Quarterly groundwater recharge rates post evapotranspiration from soil were taken from this water balance and utilised by the groundwater model as an input.

Secondly, to develop a framework in which project impacts to surface water flows might be assessed. The model was set up such that changes to baseflow due to tunnelling (an output from the groundwater model), or discharges of excess water, might be modelled and compared to unaffected runoff. Streamflow hydrographs and changes to streamflow statistics were then provided to project ecologists as an input to the ecological impact assessment.

The development of recharge estimates alleviated the potential for non-uniqueness within the groundwater model parameter set, narrowing the range of possible aquifer property values.

2.1.2 Peer review

A pre-eminent hydrogeologist, Hugh Middlemis, was engaged to peer review the numerical groundwater model and coupled surface water model.

The peer reviewer deemed that:

- the catchment model has been prepared in a manner consistent with best practice surface water modelling guidelines; and
- the coupled models are fit for the purpose of assessing catchment water balance impacts, and to inform management strategies and licensing.

The peer review report (Middlemis, August 2019) is included in Attachment A.

2.2 Baseflow component of streamflow

The contribution of groundwater discharge (baseflow) to the Murrumbidgee River and Yarrangobilly River was estimated by several methods prior to commencing catchment modelling:

1. automated baseflow separation using the Lyne and Hollick digital filter;
2. analysis of groundwater monitoring bore data during streamflow recession; and
3. analysis of stream and groundwater salinity.

Each of these are discussed below.

2.2.1 Recession analysis

As a precursor to applying automated methods to separate the baseflow component from the streamflow records, recession analysis of the streamflow data was undertaken. It was assumed that baseflow recession would follow the relationship shown in Equation 2.1.

Equation 2.1 Recession equation

$$Q = Q_0 k^t$$

Where

- Q is the flow on a particular day t days after the recession began
- Q_0 is the initial flow when t=0
- k is the recession constant

Results of the analysis are presented in Figure 2.1 to Figure 2.3 for the Murrumbidgee (gauge site 410535), Eucumbene (gauge site 22522) and Yarrangobilly (gauge site 410574) rivers, in which it can be seen that:

- when the streamflow in each river is above 1 kL/s, the recession constant k is around 0.925; and
- when the streamflow in each river is below 1 kL/s a higher k value fits the data better, with k = 0.95 - 0.98 fitting well for each river during the end of summer low flow period.

Note that the Eucumbene River gauge 22522 is outside the domain of the surface water model described in this report, and streamflow at this gauge was not used for model calibration.

The low flow recession rate at the Wallace's Creek gauge was around 0.925 as presented in Figure 2.4.

It is likely that during the end of summer low flow period baseflow occurs only from groundwater discharge sources. During wetter months when river flows are higher, the streamflow recession may be influenced by other factors in addition to groundwater discharge, such as snow melt and interflow processes.

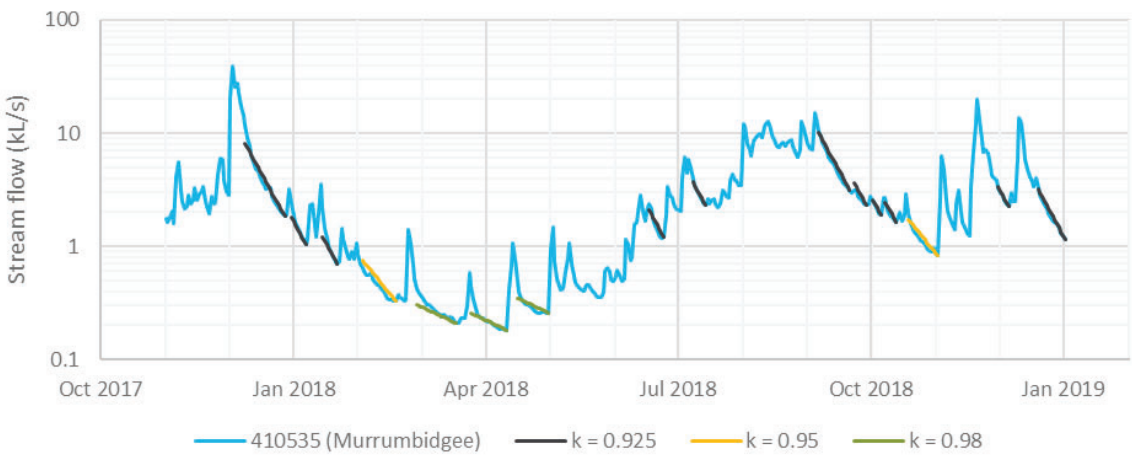

Figure 2.1 Murrumbidgee River recession

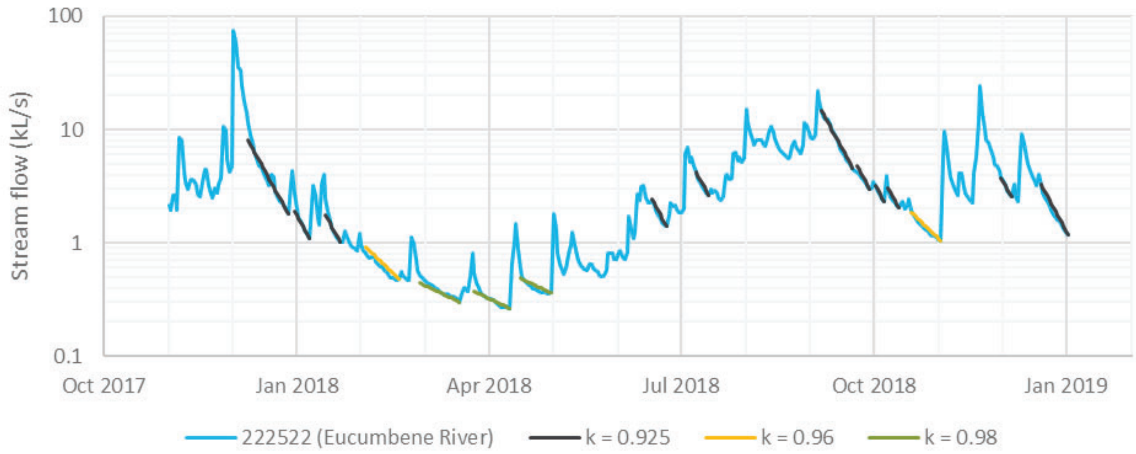

Figure 2.2 Eucumbene River recession

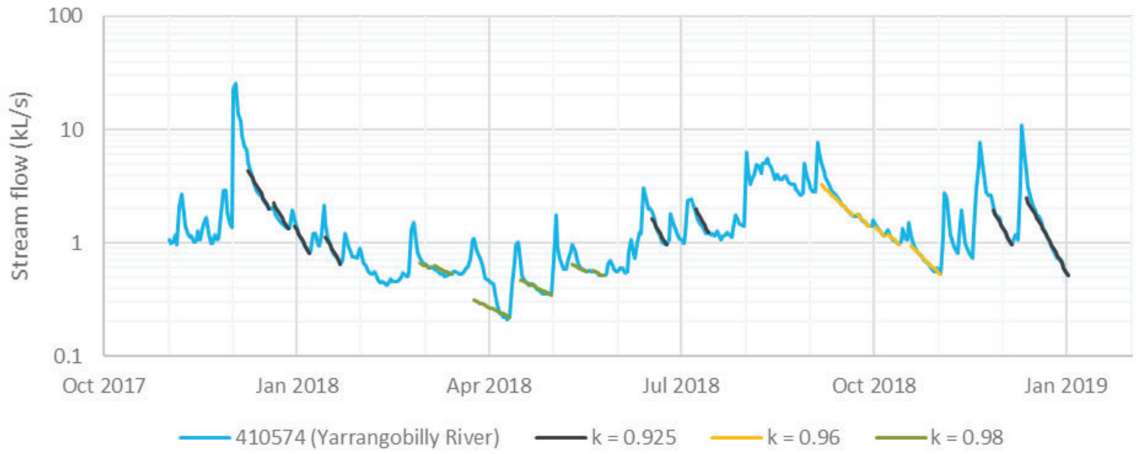

Figure 2.3 Yarrangobilly River recession

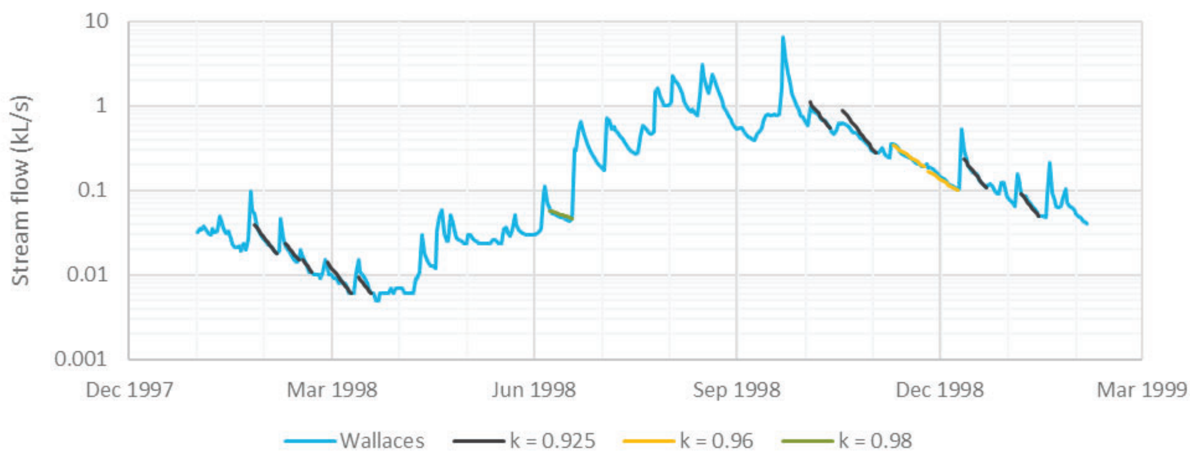

Figure 2.4 Wallaces Creek recession

2.2.2 Baseflow separation using the Lyne and Hollick filter

Digital filtering is a repeatable automated mathematical method of separating quickflow and baseflow using streamflow hydrograph data alone. Rapid rises and subsequent recessions in the hydrograph are located and apportioned as quickflow, while the remainder of the flow is apportioned as baseflow. A number of digital filtering methods were assessed for use in Australia by the *Australian Rainfall and Runoff Revision Project 7* team, as discussed in Murphy et al (2009), with the Lyne and Hollick filter (Equation 2.2) recommended for use across Australia in the release of *Australian Rainfall and Runoff* (2016) as it produces plausible splits between quickflow and baseflow for all daily streamflow datasets.

Equation 2.2 Lyne and Hollick filter equation

$$Q_f(i) = k.Q_f(i-1) + \frac{(Q(i) - Q(i-1)).(1+k)}{2}$$

Where

- $Q_f(i) \geq 0$
- $Q_b(i) = Q(i) - Q_f(i)$
- $Q_b(i)$ is the filtered baseflow at day *i*
- $Q_f(i)$ is the filtered quickflow at day *i*
- $Q(i)$ is the original streamflow at day *i*
- *k* is the filter parameter, sometimes labelled α, equivalent to the recession constant

As the Lyne and Hollick filter uses 'blind' frequency filtering mathematics and takes no catchment specific or climatic inputs (it uses streamflow records alone), it cannot distinguish between groundwater discharge, snow melt, and other forms of slow water release. In locations such as the project site where alluvial materials adjacent to creeks, bogs, and snow may each detain runoff, the rate of groundwater discharge may be lower than the 'baseflow' reported by this method.

The Lyne and Hollick filter requires the filter parameter *k* to be specified. This parameter influences the nature of attenuation of the streamflow hydrograph and thus the percentage of streamflow predicted to be from baseflow. A parameter value of 0.925 is generally accepted as appropriate (Nathan & McMahon, 1990), providing similar results to manual baseflow separation methods for catchments in NSW and Victoria, though a value of 0.98 has been found in some cases to provide a better result for some Murray-Darling Basin catchments (Ladson, Brown, Neal, & Nathan, 2013).

Baseflow analysis results for the range of *k* values between 0.92 and 0.98 are presented in Table 2.1 for streamflow recorded at the Murrumbidgee River gauge (410535) and Table 2.2 for the Yarrangobilly River gauge (410574) following analysis using streamflow data from the beginning of the data record until the end of 2018, and for the Wallaces Creek gauge (Table 2.3) using streamflow data from 1982 to 1999.

Regression analysis using rainfall and the filtered baseflow was utilised to select the optimum *k* values for each catchment. It was found that the best fit parameter value for the Murrumbidgee River was in the range 0.94–0.95, giving a baseflow index estimate of around **53%.** For the Yarrangobilly River the best fit *k* value was 0.935, giving a baseflow index estimate of **56%**. The best fit *k* value for the Wallaces Creek catchment was 0.97, giving a baseflow index estimate of **38%**.

The recession analysis (section 2.2.1) indicated that a *k* value of 0.98 may be appropriate for separating the groundwater discharge component of baseflow for both the Murrumbidgee River and Yarrangobilly River. When utilising a *k* of 0.98, the baseflow index for the Murrumbidgee River reduces to **38%.** Similarly, the baseflow index for the Yarrangobilly River reduces to **41%** when using a *k* of 0.98.

Within Wallaces Creek, the summer recession *k* of 0.925 results in a baseflow index of **53%**.

Table 2.1 Regression results for Murrumbidgee River Lyne and Hollick baseflow separation

k	R^2	Trend	BFI
0.925	82.3%	-0.1%	58%
0.93	82.4%	-0.1%	57%
0.935	82.6%	-0.1%	56%
0.94	82.7%	0%	55%
0.945	82.7%	0%	54%
0.95	82.7%	0%	52%
0.955	82.4%	0%	51%
0.96	81.6%	0%	49%
0.965	80.7%	0.1%	47%
0.97	78.6%	0.1%	44%
0.975	75.0%	0.1%	41%
0.98	68.7%	0.2%	38%

Table 2.2 Regression results for Yarrangobilly River Lyne and Hollick baseflow separation

k	R^2	Trend	BFI
0.925	72.60%	-1.0%	58%
0.93	72.60%	-1.0%	57%
0.935	73%	-1.0%	56%
0.94	72.70%	-0.9%	55%
0.945	72.70%	-0.9%	54%
0.95	72.60%	-0.9%	53%
0.955	72.3%	-0.9%	52%
0.96	69.0%	-0.8%	50%
0.965	70.7%	-0.8%	48%
0.97	69.0%	-0.8%	46%
0.975	66.1%	-0.8%	44%
0.98	61%	-0.8%	41%

Table 2.3 Regression results for Wallaces Creek Lyne and Hollick baseflow separation

k	R^2	Trend	BFI
0.925	68.2%	8.3%	53%
0.93	69.0%	7.6%	52%
0.935	70.0%	6.9%	51%
0.94	70.8%	6.3%	49%
0.945	71.8%	5.6%	48%
0.95	72.8%	5.1%	47%
0.955	73.8%	4.5%	45%
0.96	74.8%	3.9%	43%
0.965	75.4%	3.4%	41%
0.97	75.6%	2.8%	38%
0.975	75.1%	2.2%	36%
0.98	74.0%	1.6%	32%

2.2.3 Manual baseflow separation using monitoring bore data

Manual baseflow separation was performed for the Murrumbidgee River gauge 410535 and Eucumbene River gauge 222522 utilising analysis of baseflow recession curves and nearby groundwater well hydrographs.

The streamflow during times assumed to be dominated by baseflow discharge was correlated with the groundwater level recorded in nearby groundwater monitoring bores. This correlation was then used to predict the contribution of groundwater during higher flow periods, and thus provide an estimate of the contribution of groundwater to total streamflow. Approximately one year of groundwater monitoring data was utilised for this assessment at bores within the Murrumbidgee River and Eucumbene River catchments. See Annexure A of the water assessment section 7.2.2 for further description of the method.

This analysis showed that during 2018, the baseflow index for the Murrumbidgee River at gauge 410535 was around **43%**, and the baseflow index for the Eucumbene River at gauge 222522 was also around **43%**.

2.2.4 Baseflow separation using salinity as an environmental tracer

Snowmelt and rainfall have a freshening effect on streamflow, while groundwater discharges (baseflow) tend to be more saline. This relationship was used to separate the groundwater discharge component of streamflow from surface flows, using salinity (EC) as a chemical tracer, as per the method described in Miller et al (2014), summarised by Equation 2.3.

Equation 2.3 Salinity mass balance baseflow separation (Miller et al, 2014)

$$BFI = \left(\frac{EC - EC_P}{EC_{GW} - EC_P}\right)$$

Where BFI = the groundwater baseflow component (percent) of streamflow

EC = the salinity of the mean daily flow

EC_P = the salinity of precipitation (rainfall and snow)

EC_{GW} = the salinity of groundwater

Between May 2007 and December 2011, the Bureau of Meteorology and CSIRO (Crosbie, et al., 2012) analysed rainfall chemistry at 21 sites across Australia. The average rainfall salinity at each of the study sites is presented in Figure 2.5, in which it can be seen that there is a general trend of decreasing salinity with distance from the coast. Rainfall measurements at Woomera appear to be an outlier (potentially due to the proximity of salt lakes) and were not included in the analysis presented here. The project site lies approximately 128 km from the coast and was assumed to have an average rainfall salinity of 5.5 mg/L based on the Australia-wide trend.

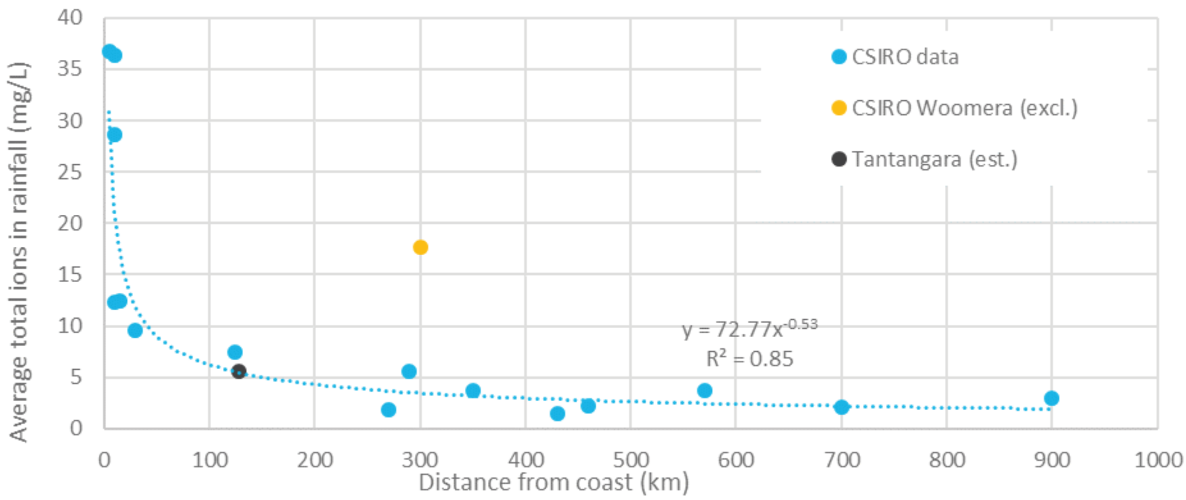

Figure 2.5 Rainfall salinity as a function of distance from the coast

Surface water and groundwater sampling was undertaken monthly during February - November 2018 within the Murrumbidgee River catchment.

The average salinity of the Murrumbidgee River (and tributaries) and local groundwater varied through the year, with samples generally fresher during winter months and more saline during summer months (Figure 2.6). The average salinity in surface water samples was 26 mg/L; for groundwater sampled within 15 m of the surface was 64 mg/L; and for groundwater sampled within 50 m of the surface was 89 mg/L. Due to the increase of groundwater salinity with depth, the analysis was limited to sites at which groundwater was sampled at less than 15 m depth as it is likely that shallow groundwater contributes a greater proportion of baseflow than deep groundwater.

The application of Equation 2.3 produced results shown in Figure 2.7, in which it can be seen that groundwater discharge accounted for between 5 and 125 ML/d of the flow measured at the Murrumbidgee gauge. This analysis shows that over the course of the analysis period, groundwater discharge accounted for **33%** of total streamflow. This estimate may be lower than the actual groundwater discharge component if very shallow groundwater from recent rainfall recharge containing very low salt concentrations was actually a significant portion of the groundwater discharge volume.

2.2.5 Summary of baseflow separation

A summary of the baseflow separation results is provided in Table 2.4. From these data it is apparent that the methods applied each support a yearly average baseflow index of around **40%** for each of the three rivers assessed, with low and high estimates giving a range of around 30–55 %. This is consistent with previous work completed by van Tol (2016), who found that the mean baseflow index for Snowy Mountain rivers was 41%, with a range of 29–55%.

Table 2.4 Summary of baseflow separation methods

	Murrumbidgee	Eucumbene	Yarrangobilly	Wallaces
Baseflow Separation method	**Gauge 410535**	**Gauge 222522**	**Gauge 410574**	
Lyne and Hollick (best R^2)	53% ↑		56% ↑	38%
Lyne and Hollick (summer recession)	38%		41%	53%
Manual separation	43%	43%		
Chemical tracer (salinity)	33% ↓			

Note: ↑ : Likely to be an overestimate
↓ : Likely to be an underestimate

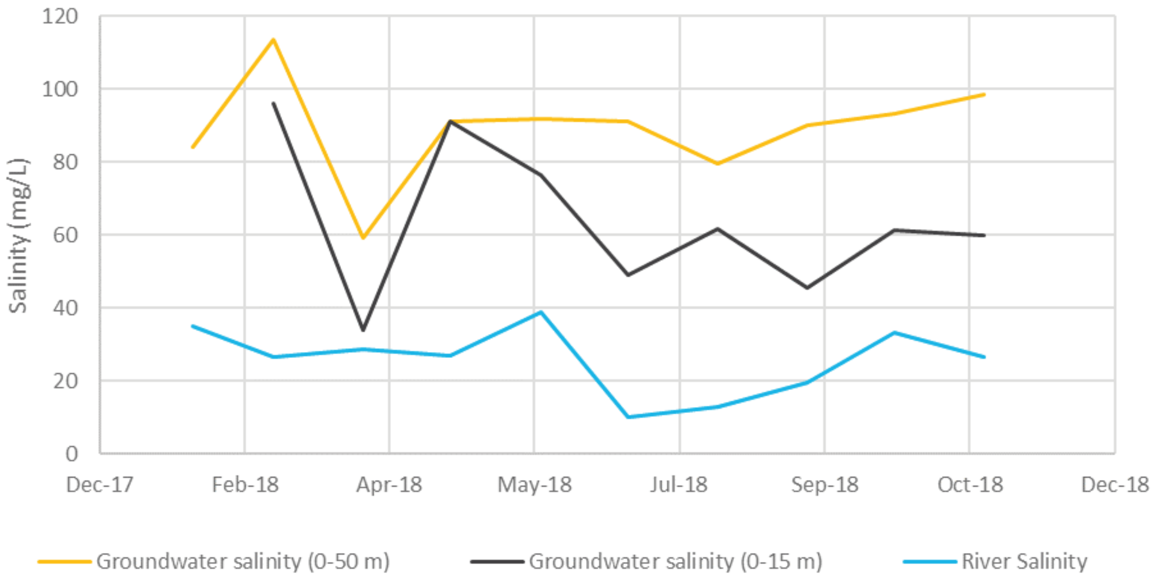

Figure 2.6 Groundwater and surface water salinity within the Murrumbidgee River catchment

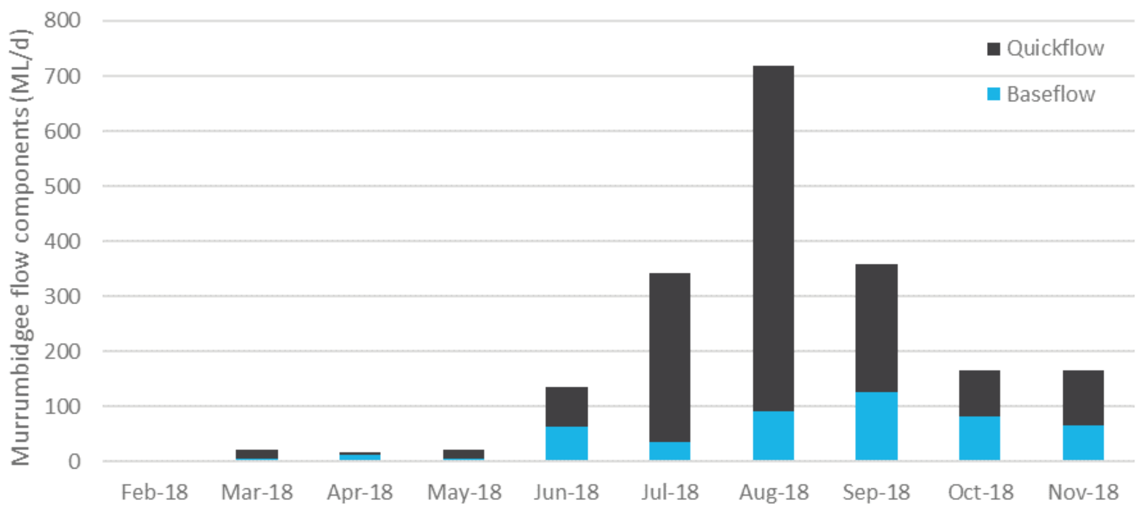

Figure 2.7 Murrumbidgee flow components when spilt using salinity as a tracer for groundwater discharge (utilising groundwater salinity measured in the upper 15 m of the aquifer)

2.3 Baseflow discharge lag analysis

The relationship between rainfall and baseflow discharge was investigated using the Q-Lag method (Brodie, Hostetler, & Slatter, 2007) as a tool to provide understanding about groundwater pathways. The key steps in the application of the Q-Lag analysis were:

- Separating each daily streamflow record by day of year (0-365);
- Deriving flow statistics for each daily flow population of streamflow data; and
- Cross correlating daily flow percentiles with rainfall data.

Low flow (greater than 50% exceedance probability) percentiles for the Murrumbidgee River at gauge 410535 are presented in Figure 2.8 with the 25%ile 14 day average daily rainfall (14R25[1]) and 25%ile 14 day average net daily rainfall (rain minus evaporation). This plot shows that net rainfall tends to increase during April–June, then decline September–December. Low flows tend to increase in June–August (two months after the net rainfall increase), then decline September–December (matching the timing of the net rainfall decline).

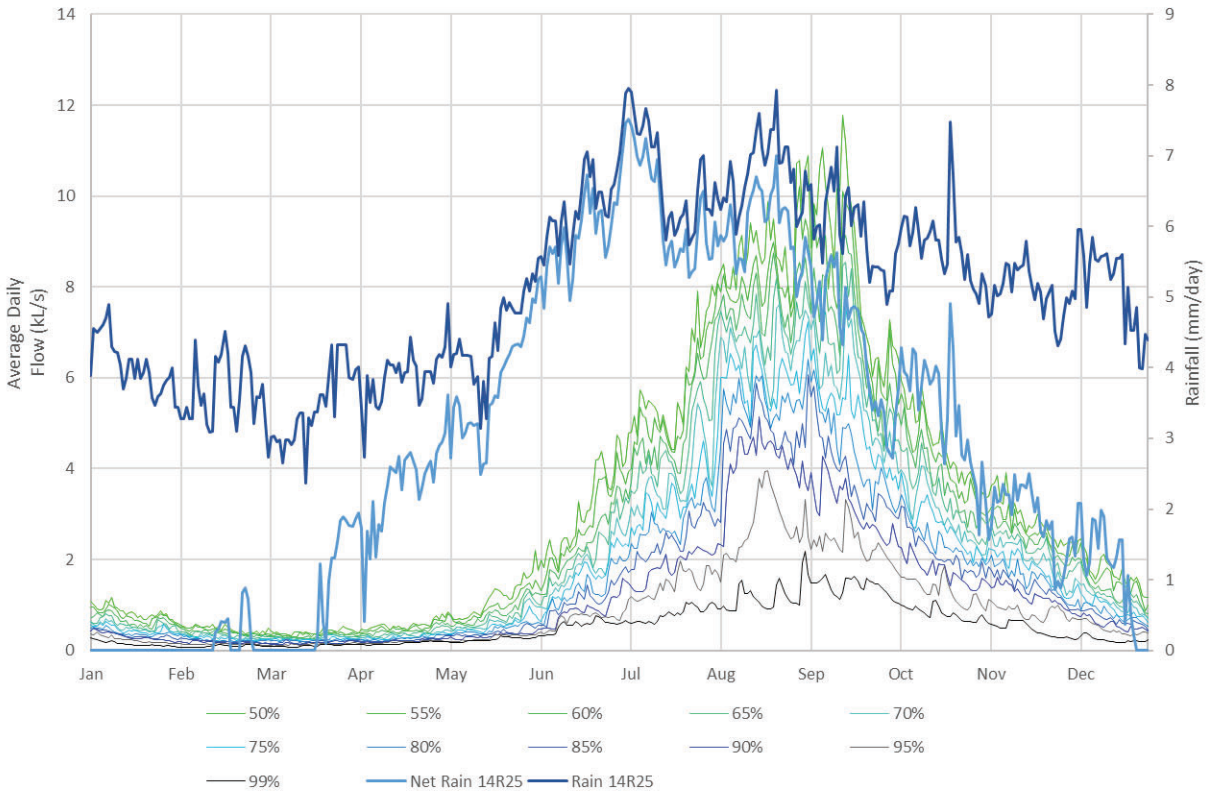

Figure 2.8 Daily discharge for various low flow percentiles of Murrumbidgee River flow at gauge site 410535 compared with 14R25 SILO rainfall and net rainfall (SILO rainfall minus SILO Morton's PET)

[1] This chapter has followed the convention of Brodie, Hostetler & Slatter (2007) in referring to rainfall data in terms of the averaging period in days, and the exceedance probability. 25%ile rainfall was used as approximately 50% of days had no rain, and 25%ile provided a data series for analysis not dominated by either dry days or extreme events.

Rainfall was cross correlated with August–December streamflow for time lags of 0–180 days using Equation 2.4. The results of the cross correlation analysis are presented in Figure 2.9, which shows that the decline in low (Q99[2] and Q90) and high flows (Q50 and Q10) fitted the decline in net rainfall best when a lag of around 10–30 days was applied. The extreme flow (Q1) data appeared anomalous, likely due to the intermittent nature of extreme flow events and is not relevant to discussion of baseflow.

Equation 2.4 Cross correlation equation

$$r_m = \frac{COV_{1,2}}{s_1 . s_2}$$

Where

- r_m is the cross-correlation statistic (closer to 1.0 indicates a better fit);
- $COV_{1,2}$ is the covariance of the two data sequences; and
- s_z and s_2 are the standard deviations of the two data sequences.

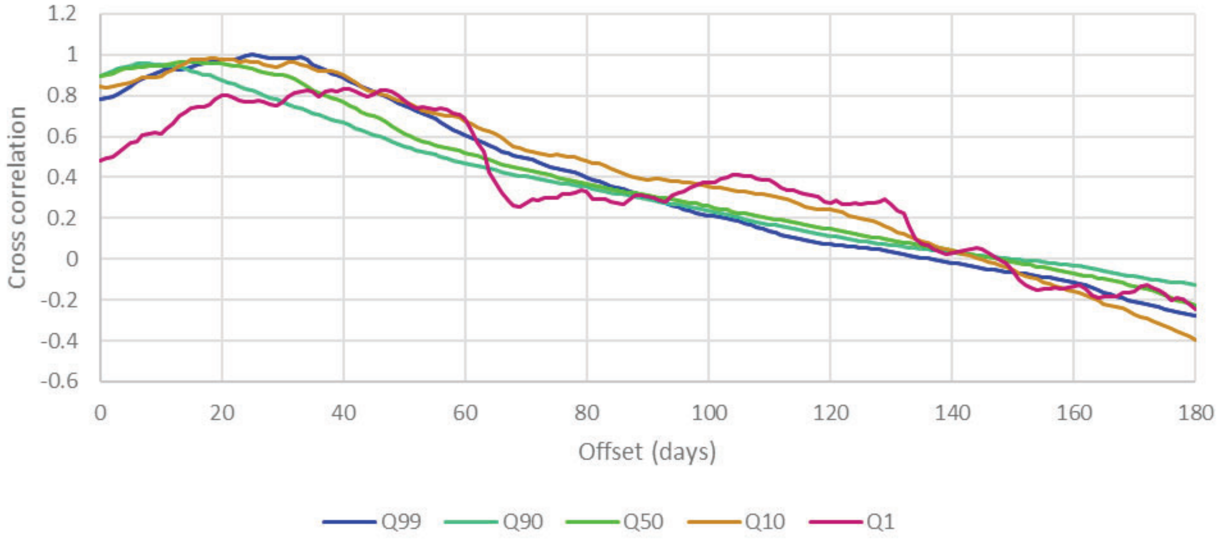

Figure 2.9 Cross correlation statistics for offset net 14R25 rainfall data with various percentiles of Murrumbidgee gauge 410535 streamflow data

The analysis was repeated for the Yarrangobilly gauge 410574, with results again indicating a lag of about two months between increases in net rainfall and increases in streamflow (Figure 2.10), and maximised cross correlation between streamflow and 14R25 net rainfall for lags of <30 days (Figure 2.11).

[2] Qx in this chapter refers to the flow exceedance probability. Q99 indicates a 99% probability of exceedance, i.,e., a low flow likely to be baseflow. Q50 indicates median flow. Q10 indicates a flow with a 10% exceedance probability, a higher flow rate likely to be dominated by quickflow

The Q-Lag analysis showed:

- there is a lag of approximately two months between net rainfall increases and streamflow increases, likely caused by a need to wet the catchment following summer prior to significant runoff occurring; and
- both quickflow[3] and baseflow[4] decline within weeks of net rainfall declines, indicating that baseflow may be discharging after only a short residence time within the groundwater system.

A short groundwater residence time implies that a large portion of the groundwater discharge travels through relatively short pathways underground, likely remaining at a shallow depth and discharging close to the point of infiltration. A significant component of infiltration occurring along ridge lines thus may be discharging in nearby gullies high in the catchment, with deeper and longer flow paths to the larger rivers and creeks contributing a smaller volume of water.

This conceptualisation is consistent with the two month discharge lag following the onset of positive net rainfall, as groundwater levels fluctuate with a greater magnitude higher in the catchment and are more stable in the river valleys. During summer the groundwater level high in the catchment may fall to a level such that short pathway discharge doesn't occur. During this time, groundwater discharge may still occur in the large river valleys where groundwater remains close to the surface, likely supported by longer/slower flow paths. Following net rainfall increase, the groundwater level in the upper catchment must rise prior to discharge commencing discharge, leading to the two month lag.

The groundwater model does not include all upper catchment discharge features as river boundary conditions as there are an innumerable number of small features, many of which may discharge only intermittently. Groundwater approaching the surface in locations not served by a river boundary condition was removed from the groundwater model as distributed baseflow using the evapotranspiration model package (section 1.3).

These Q-Lag results show that the groundwater model estimates of discharge to cells with river boundary conditions may match the baseflow data in the surface water model during drier times, but during wet times when discharge is occurring higher in the catchment to minor stream features distributed baseflow discharge estimation will form an important part of the groundwater model discharge water balance.

[3] The component of streamflow that has travelled through the catchment as interflow or across the surface as overland flow or is released from bank storage during the recession from a flood peak.

[4] The component of streamflow supplied by groundwater discharge. Baseflow is characterised by an exponential decay curve following the cessation of surface runoff.

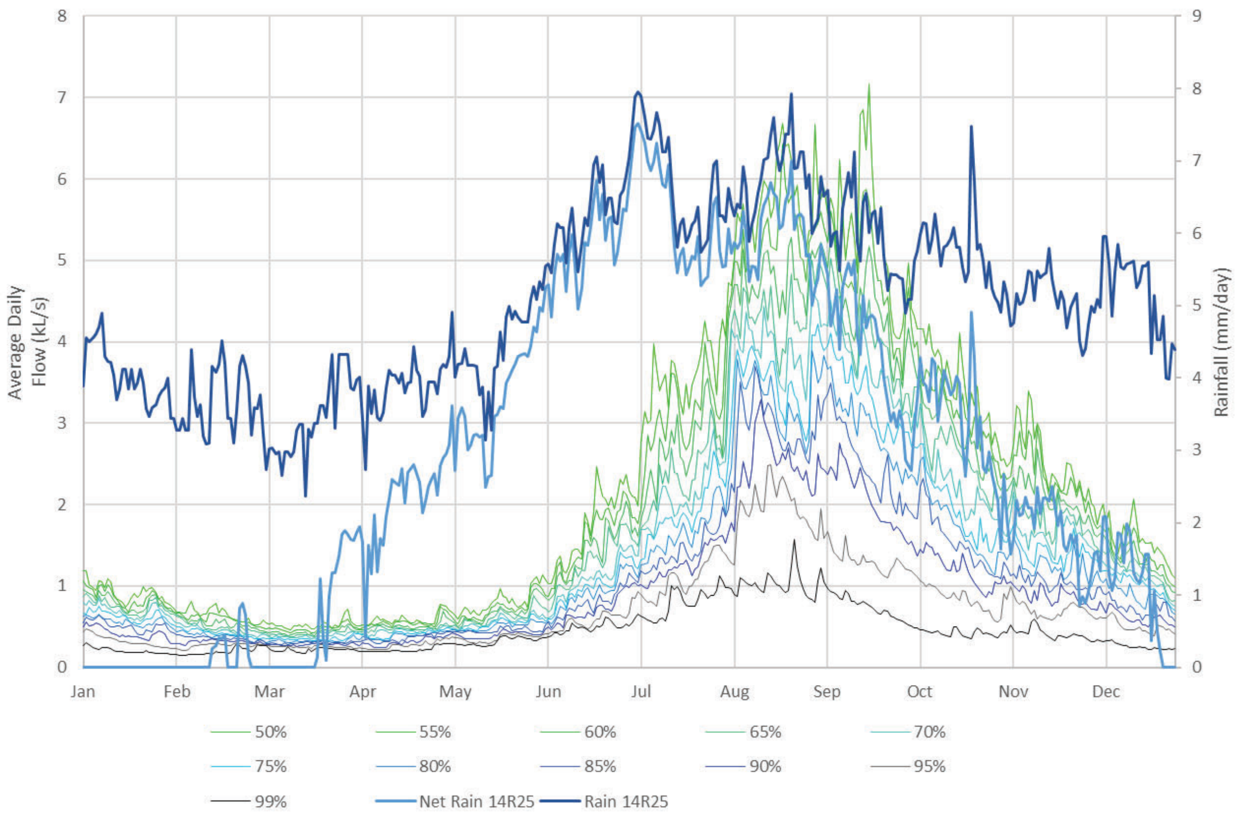

Figure 2.10 Daily discharge for various low flow percentiles of Yarrangobilly River flow at gauge site 410574 compared with 14R25 SILO rainfall and net rainfall (SILO rainfall minus SILO Morton's PET)

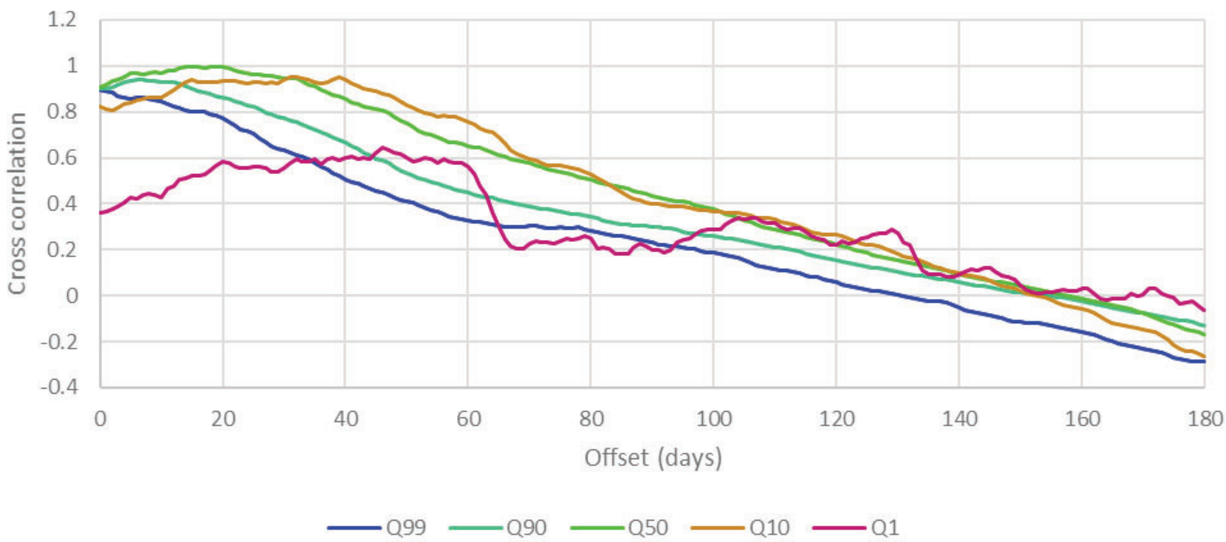

Figure 2.11 Cross correlation statistics for offset net 14R25 rainfall data with various percentiles of Yarrangobilly gauge 410574 streamflow data

2.4 Model design

2.4.1 Model software

The catchment model was developed using the eWater Source software (Source)[5]. Source is a hydrological modelling platform originally developed by the eWater Cooperative Research Centre (CRC) until June 2012, with development post June 2012 undertaken by eWater Limited. The software supports planning of water resource systems at catchment scales by providing a flexible framework in which to integrate spatial, climate and hydrological data with published rainfall runoff models and a plugin interface for customisation (Carr & Podger, 2012).

Within the Source framework, a number of runoff models were tested to determine the numerical approach best suited to the project.

2.4.2 Data utilised in model construction

Data use to create the Source model were:

- rainfall;
- potential evaporation/evapotranspiration (PET);
- digital elevation model (DEM);
- recorded streamflow data; and
- aerial imagery.

The nearest precipitation gauges maintained by the Bureau of Meteorology and Snowy Hydro are described Annexure A of the water assessment section 4.2. Other than the Bureau of Meteorology gauge 71000 (Adaminaby Tourist Park), the rainfall records at these stations are significantly shorter than the recorded streamflow records. To enable modelling to utilise the entire streamflow record period for calibration, rainfall data were sourced from the SILO (Scientific Information for Land Owners) Data Drill website. SILO is hosted by the Science Division of the Queensland Government Department of Environment and Science (DES). The datasets are interpolated from observed climate data obtained from the nearby Australian Bureau of Meteorology stations. SILO data are available nationally at a 0.05 degree (approximately 4.5 km) grid resolution. Thirteen SILO grid points were utilised in the preparation of the Source model, with each sub-catchment utilising data from the closest SILO data drill grid point location (Figure 2.13).

Potential evapotranspiration data were obtained from the same 13 SILO grid points utilised for rainfall data. As per the Source User Guide 4.5 (eWater, n.d.) Morton's areal potential evapotranspiration was used in the model, as this data set is developed for the purpose of estimating evapotranspiration from vegetated landscapes.

A LiDAR derived DEM was utilised when developing sub-catchments, such that sub-catchment boundaries aligned with geographical features.

The model was calibrated using recorded streamflow data for Murrumbidgee River gauge 410535 and Yarrangobilly River gauge 410574, with data obtained from the Bureau of Meteorology website *Water Data Online* (Australian Government Bureau of Meteorology, n.d.).

[5] eWater Source 4.7.0.b.8947

Manual streamflow readings were taken during 2018-2019 using a handheld propeller meter at a number of sites within the Murrumbidgee River catchment. Streamflow velocity measurements were taken at monitoring points in an approximate grid pattern (across the stream, and at various depths) with the total streamflow estimated via integration of the measurements. These manual streamflow readings were not used for calibrating the model, but were visually compared to model hydrographs developed at the monitoring locations to provide confidence that the calibrated model did not contain gross errors at the sub-catchment scale.

Aerial imagery was used together with GIS analysis to confirm pertinent dimensions such as creek alignments, and vegetation cover.

2.4.3 Sub-catchment delineation

The Source model domain included the Murrumbidgee River upstream of gauge 410535, the Yarrangobilly River upstream of gauge 410574, Middle Creek upstream from Talbingo Reservoir, Nungar Creek upstream from Tantangara Reservoir, and the Eucumbene River upstream (north) of 35.85° S. Each catchment was split into sub-catchments based on the following rules:

- the upper limit for sub-catchment area was approximately 50 km^2;
- the minimum size was determined by:
  - sub-catchment boundaries aligned with watershed divides; and
  - reporting locations at:
    - the downstream end of groundwater model stream reaches;
    - locations at which manual streamflow readings had been recorded; and
    - established gauge sites.

The model has 26 sub-catchments, illustrated in Figure 2.12, along with stream links and flow measurement points. The SILO grid data were applied to the model sub-catchments as per Figure 2.13.

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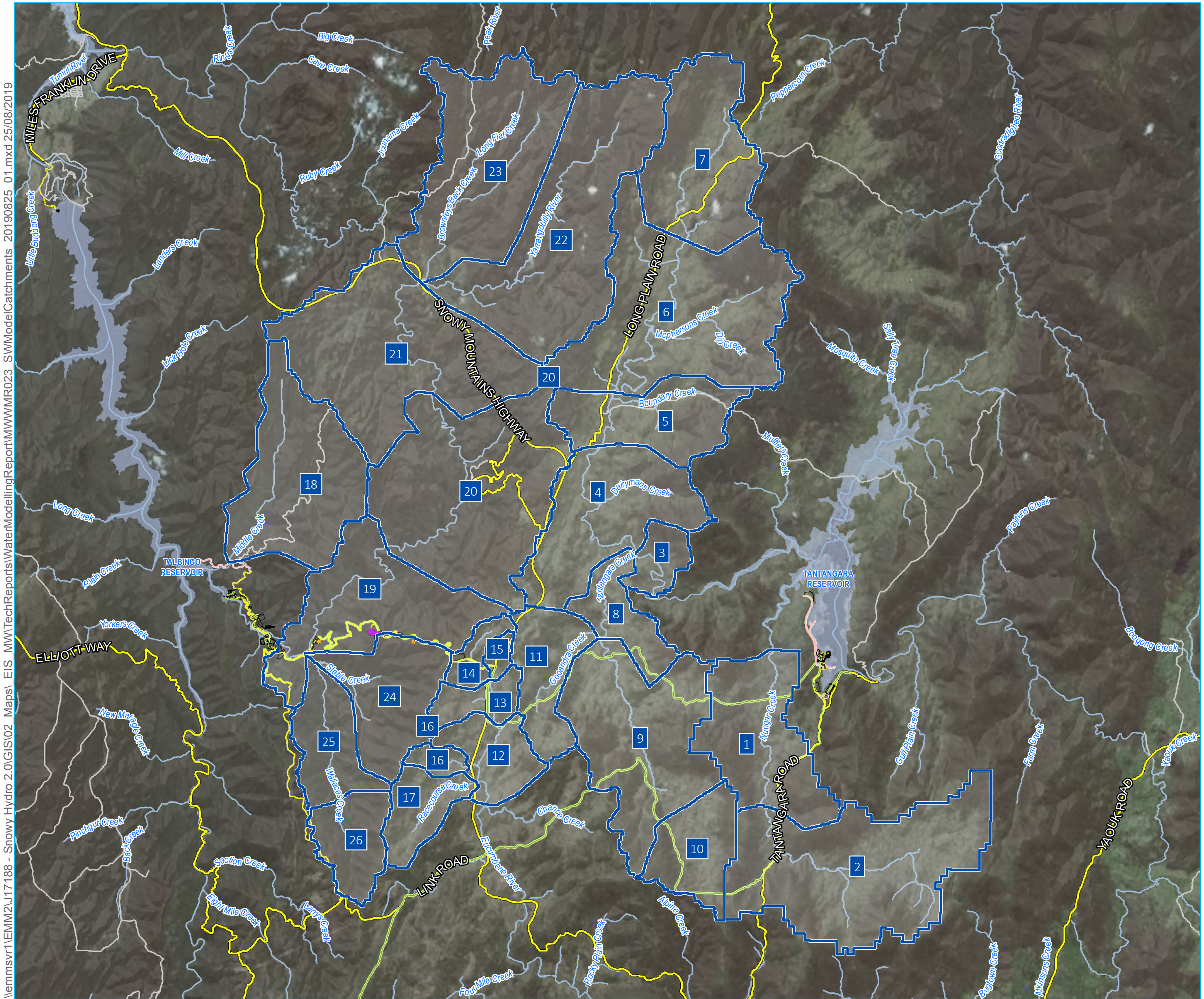


Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

Catchments

Snowy 2.0 Main Works operational elements

- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements

- Temporary construction compounds and surface works
- Temporary access road

Existing environment

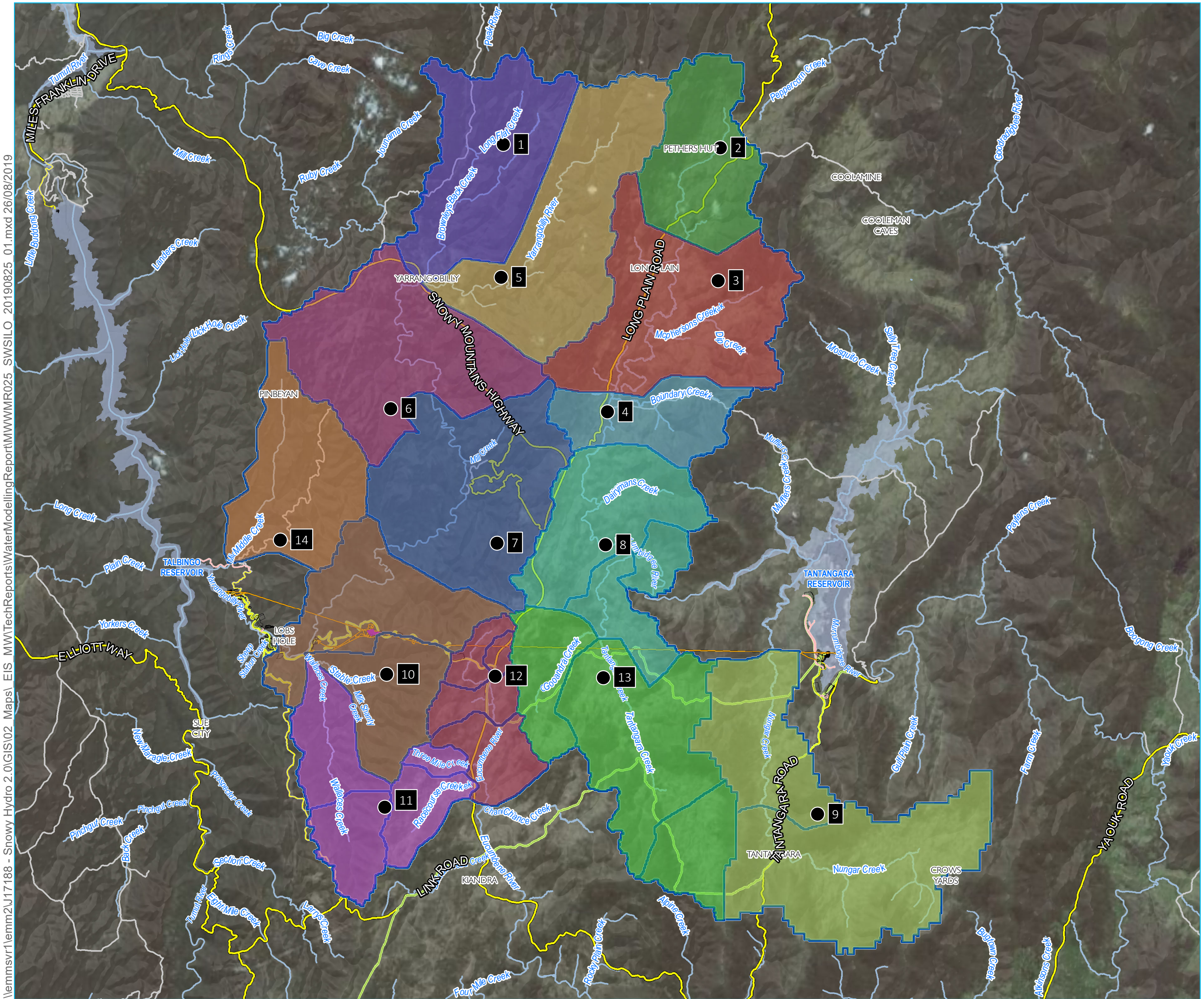
- Main road
- Local road
- Perennial watercourse
- Scheme storage

Surface water model sub-catchments

Snowy 2.0
Modelling Report
Main Works
Figure 2.12

snowy 2.0

EMM creating opportunities



KEY

- ● SILO grid points

SILO source

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- Catchments

Snowy 2.0 Main Works operational elements

- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements

- Temporary construction compounds and surface works
- Temporary access road

Existing environment

- Main road
- Local road
- Perennial watercourse
- Scheme storage

Surface water model sub-catchments and SILO grid points

Snowy 2.0
Modelling Report
Main Works
Figure 2.13

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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snowy 2.0

EMM creating opportunities

2.4.4 Functional Units

A key concept within the eWater Source modelling framework is the application of runoff response (or 'functional') units at a sub-catchment scale, each with different runoff models or parameter sets. Within the model domain, the following potential functional unit sources were identified:

- land use (ie forested areas, grassland, exposed rock faces, etc);
- catchment slope;
- soil type; and
- underlying geology.

While Crosbie and Jolly et al (2010) report that groundwater recharge is controlled by soil type and vegetation rather than the underlying geology, it was considered possible that geology could affect runoff model terms relating to baseflow discharge. During calibration this theory was tested by applying a functional unit split based on the presence or absence of Gooandra Volcanics, as this geological unit appears to be distinctly different to other geological units in the project area in terms of its higher hydraulic conductivity. Calibration performance was not improved by creating functional units based on the presence or absence of Gooandra Volcanics, and so the presented model does not use functional units created on this basis.

The Digital Atlas of Australian Soils (Northcote, et al., 1960-1968) describes soils across the project area predominantly as kurosols. As the soil type was largely consistent across the model domain, soil type was not used to define separate functional units.

Catchment slope varies markedly between the plateau region containing the Murrumbidgee and Eucumbene rivers, and the ravine region containing the Yarrangobilly River. The land use also varies significantly between these two regions, with the plateau area dominated by low grasses, and the ravine area heavily forested. On this basis, the model domain was split into ravine and plateau functional units.

While the plateau is dominated by grasses, there are stands of trees throughout. The plateau region was not split into grassland and treed functional units as the distribution of forested areas appears to be relatively even between plateau sub-catchments, and so a runoff model parameter set representing a grassland/tree mix is broadly applicable across each plateau sub-catchment.

The Wallaces Creek catchment within the ravine region has a steeper slope than the rest of the Yarrangobilly River catchment, and could have a different runoff relationship. This catchment was gauged from 1969-1999. A separate set of runoff model parameters was used within the Wallaces Creek catchment to attempt calibration to the Wallaces Creek gauged flows, but this produced runoff model parameters outside believable ranges. This was ultimately abandoned and the Wallaces Creek gauge data was used instead for comparison/validation. The presented model utilises the same parameter sets within the Wallaces Creek catchment as within the rest of the Yarrangobilly River catchment.

2.4.5 Runoff model

Source facilitates the use of a number of rainfall runoff models commonly used by hydrologists to describe catchment processes. SIMHYD, AWBM and GR4J were trialled (Attachment B), and it was found that each contained weaknesses that made their use less than ideal for meeting the modelling objectives:

- the SIMHYD model did not allow interflow processes to occur on days following rain;
- the AWBM model utilised a fixed baseflow index that did not respond to seasonality or catchment wetness; and
- the GR4J model did not provide an explicit groundwater recharge and discharge pathway.

A custom runoff model was created to address these weaknesses. This custom model was conceptualised as a modification of SIMHYD, utilising the explicit groundwater recharge and discharge pathways but altering the recharge and discharge equations to align with the conceptual model of the site hydrology. A number of alterations were tested (see Attachment B.5), with those contributing to improved calibration retained in the final model.

To allow groundwater recharge and interflow to occur on non-rain days, the equations relating to flow out of the soil moisture store were altered. A new variable was introduced describing the minimum soil saturation threshold required for recharge to the groundwater store or interflow. A 'saturation variable' utilised for scaling recharge and interflow rates was then calculated as per the example in Figure 2.14. When the soil moisture store was saturated, groundwater recharge and interflow occurred at the maximum allowed rate, while when the soil moisture was at or below the saturation threshold no recharge or interflow was allowed. At intermediate soil moisture saturation the rates were linearly interpolated.

The groundwater recharge and interflow equations were altered to take the form shown in Equation 2.5. The soil moisture minimum threshold, interflow coefficient, and recharge coefficient were each varied through the model calibration process.

Evapotranspiration equations were not altered and were not subject to the minimum soil moisture threshold.

Equation 2.5 Altered interflow and recharge equations

$$Interflow\left(\frac{mm}{d}\right) = Interflow\ Coefficient\left(\frac{mm}{d}\right).Saturation\ Variable(\%)$$

$$Recharge\left(\frac{mm}{d}\right) = Recharge\ Coefficient\left(\frac{mm}{d}\right).Saturation\ Variable(\%)$$

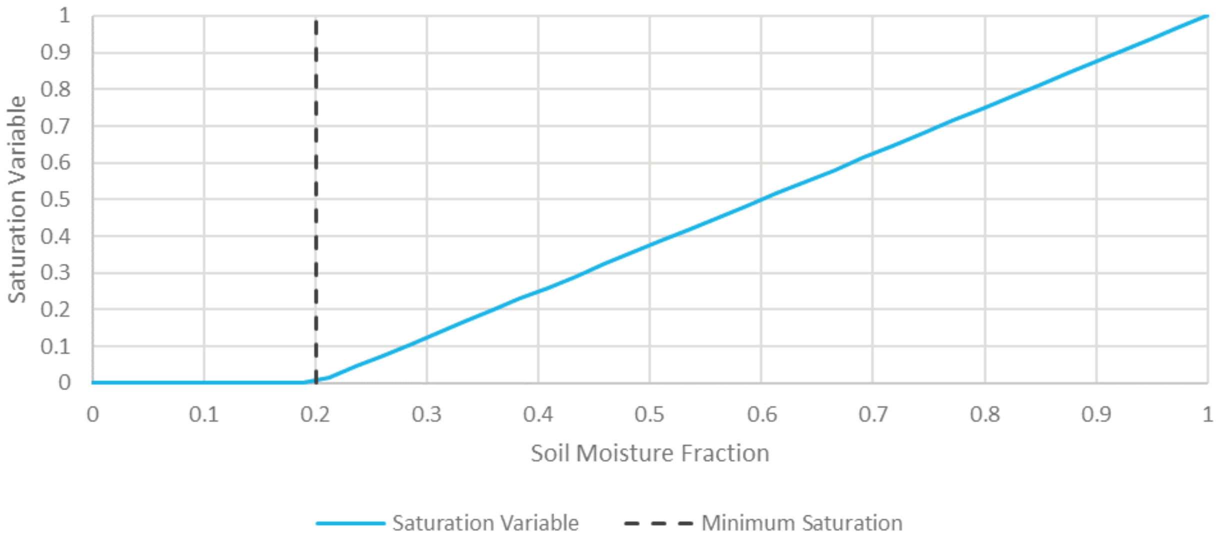


Figure 2.14 Example saturation variable using a minimum saturation for drainage of 20%

During field investigations within the plateau region, it was noted that:

- downstream from groundwater discharge locations there was often a significant area of saturated soil, with vegetation utilising the discharged water prior to it reaching the larger creeks. In many cases, saturated alluvial material; and
- adjacent to some creeks was a significant width of saturated alluvial material supporting dense populations of grasses (see Photograph 2.1).

An analysis of the project stream network spatial dataset was undertaken to determine the approximate portion of the plateau catchments that might contribute to post-discharge/runoff evapotranspiration. While some creeks appeared to support saturated alluvial systems in the order of 100 m wide, tributaries to these creeks and vegetation supported by groundwater seeps covered a smaller area. Spatial analysis showed that that approximately 5% of the plateau lies within 10 m of a mapped creek or creek tributary, which was taken as a reasonable estimate of the area that might contribute to post-discharge/runoff evapotranspiration. The estimated post-discharge evapotranspiration flux was calculated as the daily potential evapotranspiration rate multiplied by the affected area, and was removed from the model at the downstream end of the runoff calculations.

Photograph 2.1 Grasses rooted in saturated soil adjacent to a small creek (not visible)

The runoff model was modified to allow the baseflow loss predicted by the groundwater model to be simulated by adding a 'leakage' term to the groundwater store. This 'leakage' was varied seasonally in accordance with the groundwater model stress periods, and spatially so that the impacts to baseflow predicted by the groundwater model were applied within the appropriate sub-catchments. The leakage rate for each season and sub-catchment was adjusted manually until the baseflow loss matched the scaled impact predicted by the groundwater model. Through the application of a leakage rate, the Modified SIMHYD groundwater store emptied at a faster rate than it would have if no leakage were applied.

A schematic of the modified SIMHYD model is presented in Figure 2.15. The equation set for the modified SIMHYD model is supplied in Attachment C.

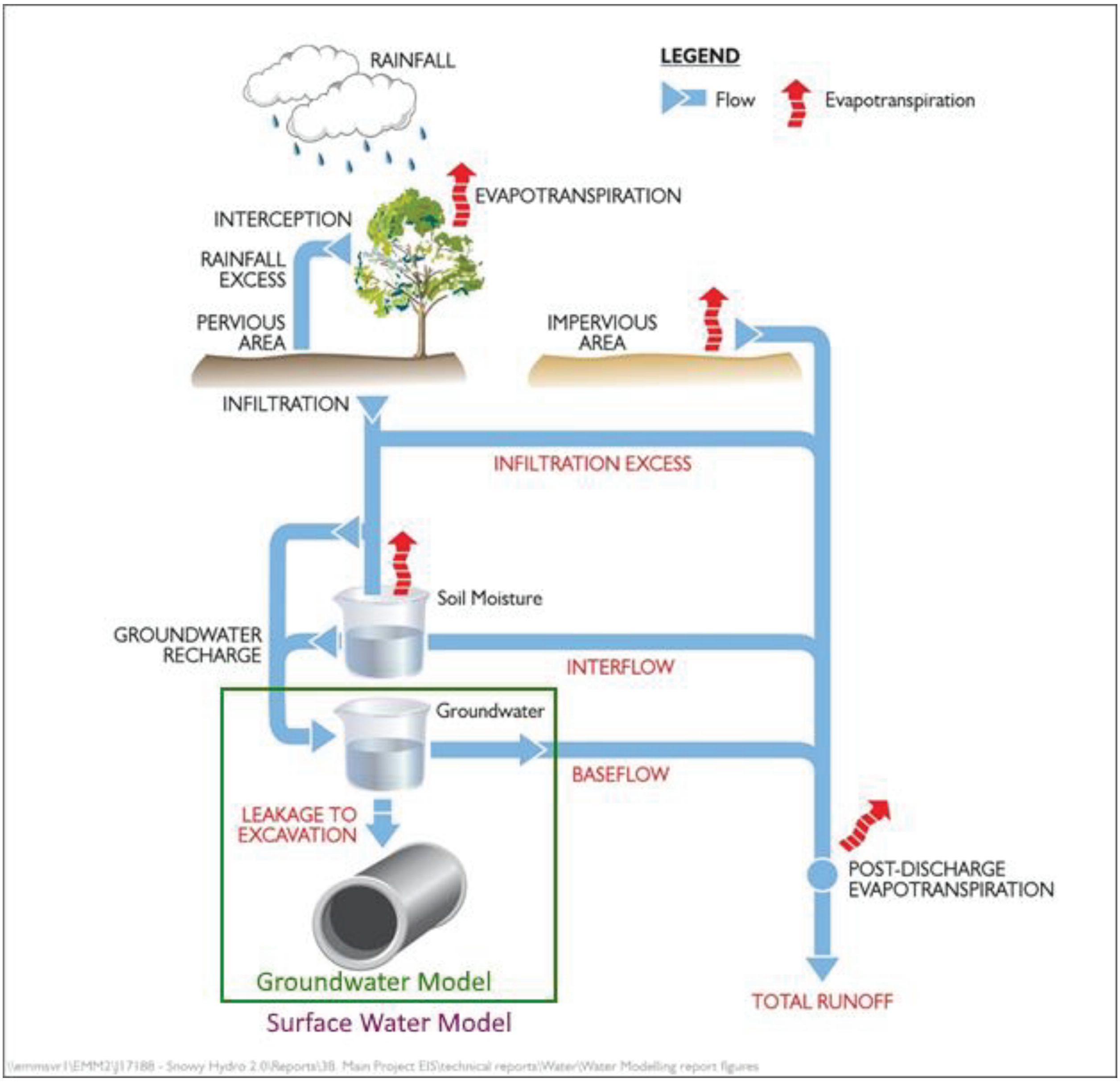


Figure 2.15 Modified SIMHYD runoff model

2.5 Calibration and sensitivity analysis

2.5.1 Calibration method

Optimal model parameters were obtained through the use of the Rosenbrock optimiser contained in Source.

The final parameter set was selected after considering the following metrics:

- Nash-Sutcliffe Efficiency (NSE) for daily flow, log daily flow, daily flow and log flow duration, and monthly flow at:
  - Murrumbidgee River gauge 410535; and
  - Yarrangobilly River gauge 410574.

  The Nash-Sutcliffe Efficiency (NSE) is a normalised statistic that determines the relative magnitude of the residual variance ('noise') compared to the measured data variance ('signal' or 'information'). Values of NSE between 0.0 and 1.0 generally indicate acceptable levels of performance, with a value of NSE greater than 0.5 indicating nominally satisfactory performance. Values of NSE less than zero indicate that the mean observed value is a better predictor than the simulated value (ie NSE<0 indicates unacceptable model performance).
- flow exceedance goodness of fit, particularly the low flow (baseflow) portion of the curve, at:
  - Murrumbidgee River gauge 410535; and
  - Yarrangobilly River gauge 410574.
- average split between baseflow and surface flow discharges from:
  - model sub-catchment 6, located in the plateau region, within the Murrumbidgee catchment; and
  - model sub-catchment 30, located in the ravine region, within the Yarrangobilly catchment.

Model calibration considered the full data record at gauges 410535 and 410574 (approximately 40 years of daily streamflow data). Validation was achieved through comparison of model results to streamflow data collected at other points in the model catchments.

2.5.2 Calibration statistics

Moriasi et al (2007) recommended that watershed model calibration should be assessed against monthly NSE, volume bias, and the ratio of the ratio of the monthly root mean square error to the monthly standard deviation of the measured data (RSR), and suggested calibration statistic target ranges should be provided (Table 2.5). In addition to these statistics the calibration considered the log daily NSE, a combined daily and log flow duration NSE statistic, and the baseflow index.

When assessed against the target ranges provided by Moriasi et al (2007), the modified SIMHYD model calibration achieved a good to very good calibration at the Murrumbidgee and Yarrangobilly gauges (Table 2.6).

Table 2.5 General performance ratings for recommended statistics

performance Rating	RSR	NSE	Volume Bias
Very Good	0% ≤ RSR ≤ 50%	75% < NSE ≤ 100%	Bias < ±10%
Good	50% < RSR ≤ 60%	65% < NSE ≤ 75%	±10% ≤ Bias < ±15%
Satisfactory	60% < RSR ≤ 70%	50% < NSE ≤ 65%	±15% ≤ Bias < ±25%
Unsatisfactory	RSR > 70%	NSE ≤ 50%	Bias ≥ ±25%

Source: Moriasi et al (2007)

Table 2.6 Calibration performance

	Murrumbidgee		Yarrangobilly	
	Calibration Statistic	Interpretation[1]	Calibration Statistic	Interpretation[1]
RSR Monthly	53%	Good	41%	Very Good
NSE Monthly	72%	Good	83%	Very Good
NSE Log Daily	75%	Good	79%	Very Good
NSE Daily and log flow duration	80%	Very Good	69%	Good
Volume Bias	9%	Very Good	1%	Very Good
Baseflow Index	39%	Very Good[2]	39%	Very Good[2]

Note: 1. As per Moriasi et al (2007)

2. Baseflow index within pre-determined range (see section 2.2.5)

2.5.3 Selected runoff model parameters

The calibrated model parameters are listed in Table 2.7. The application of these parameters may be seen in Attachment C.

While the groundwater model framework was set up to utilise rainfall and evapotranspiration multipliers, it was not necessary to scale either rainfall or evapotranspiration datasets to obtain a good model calibration, and these scaling parameters remained at 1.0.

The calibrated soil moisture store capacity within the plateau area is notably lower than within the ravine area. Due to the vegetation types present, it is likely that the average root depth on the plateau is shallower than in the ravine, and so a shallower soil moisture store is conceptually appropriate on the plateau. Soil moisture infiltrating below the root depth will no longer be subject to evapotranspiration, and is appropriately modelled via the groundwater store.

The calibrated infiltration coefficient for the plateau is higher than for the ravine. As the ravine area contains steeper slopes, it is conceptually appropriate that, given similar soils, infiltration would be lower in the ravine area. It is also likely that exposed rock faces exist within the ravine, which would lead to lower infiltration.

The interflow and recharge coefficients are also higher in the plateau area than in the ravine. The processes represented by the interflow and recharge equations are related to both the saturated and unsaturated hydraulic permeability of the upper soils, about which little is known. Consequently, it is difficult to make firm statements regarding the appropriate ranges of these parameter values.

Table 2.7 Calibrated model parameters

Parameter Name	Parameter Value within plateau area	Parameter Value within ravine area
Rainfall multiplier	1	1
Evapotranspiration multiplier	1	1
Soil Moisture Store Capacity	100 mm	225 mm
Impervious Store Capacity	NA – no impervious fraction modelled	NA – no impervious fraction modelled
Interception Store Capacity	5 mm	2.7 mm
Impervious Fraction	0%	0%
Alluvial Fraction	5%	1%
Pervious Fraction	95%	99%
Infiltration Coefficient	155 mm/day	144 mm/day
SQ	1.39	1.76
Interflow Coefficient	5 mm/day	1.5 mm/day
Recharge Coefficient	2.89 mm/day	0.61 mm/day
Minimum Saturation required for soil drainage	20%	18.4%
Groundwater Store Recession	0.02 (k=0.98)	0.02 (k=0.98)

2.5.4 Calibrated model catchment water balance

The catchment water balance for the model sub-catchment 4 (located near the centre of the Murrumbidgee catchment, just upstream of the Murrumbidgee River and Tantangara Creek confluence) and model sub-catchment 19 (located near the Yarrangobilly River streamflow gauge, upstream of Lobs Hole) are presented in Figure 2.16 and Figure 2.17. While the individual components of the catchment water balance cannot be compared to measured data, the comparison of the water balance for the plateau and ravine areas reveals contrasts consistent with expectations:

- within the ravine area the model produced greater infiltration excess than in the plateau, consistent with the increased relief in the ravine;
- total evapotranspiration was higher in the ravine area, consistent with the extent of deep rooted vegetation; and
- post-discharge evapotranspiration was higher in the plateau area, consistent with the presence of saturated soil supporting vegetation adjacent to creeks and downstream of groundwater discharge zones observed within the plateau.

The data presented in this section represents average data from single sub-catchments. Individual sub-catchments have slightly different water balances due to spatial variation in the SILO precipitation and potential evapotranspiration data. Water balances will also vary year to year with wetter or dryer conditions affecting the proportion of precipitation evaporating or becoming streamflow.

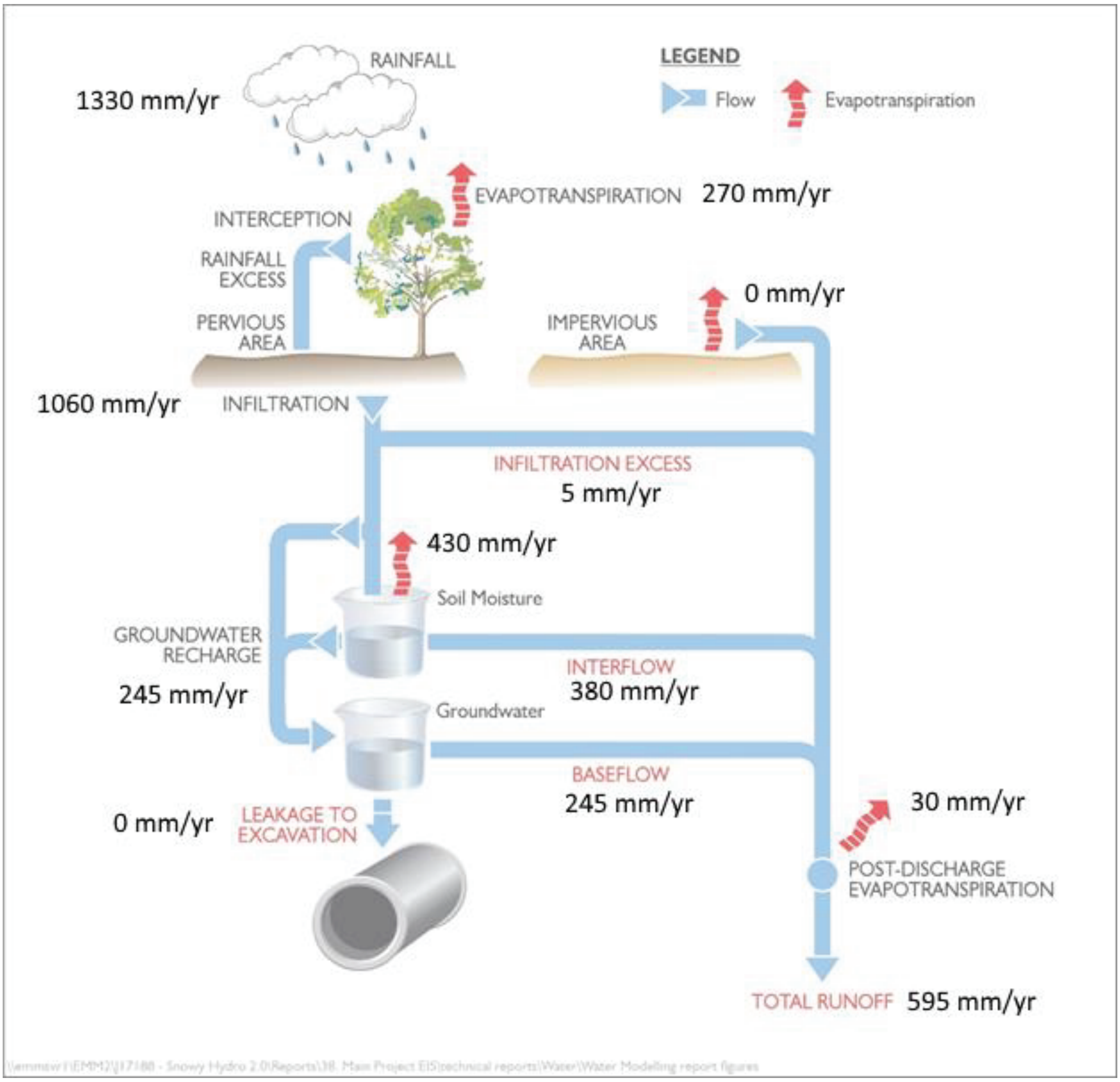


Figure 2.16 Model sub-catchment 4 (plateau) average yearly water balance (calibration period)

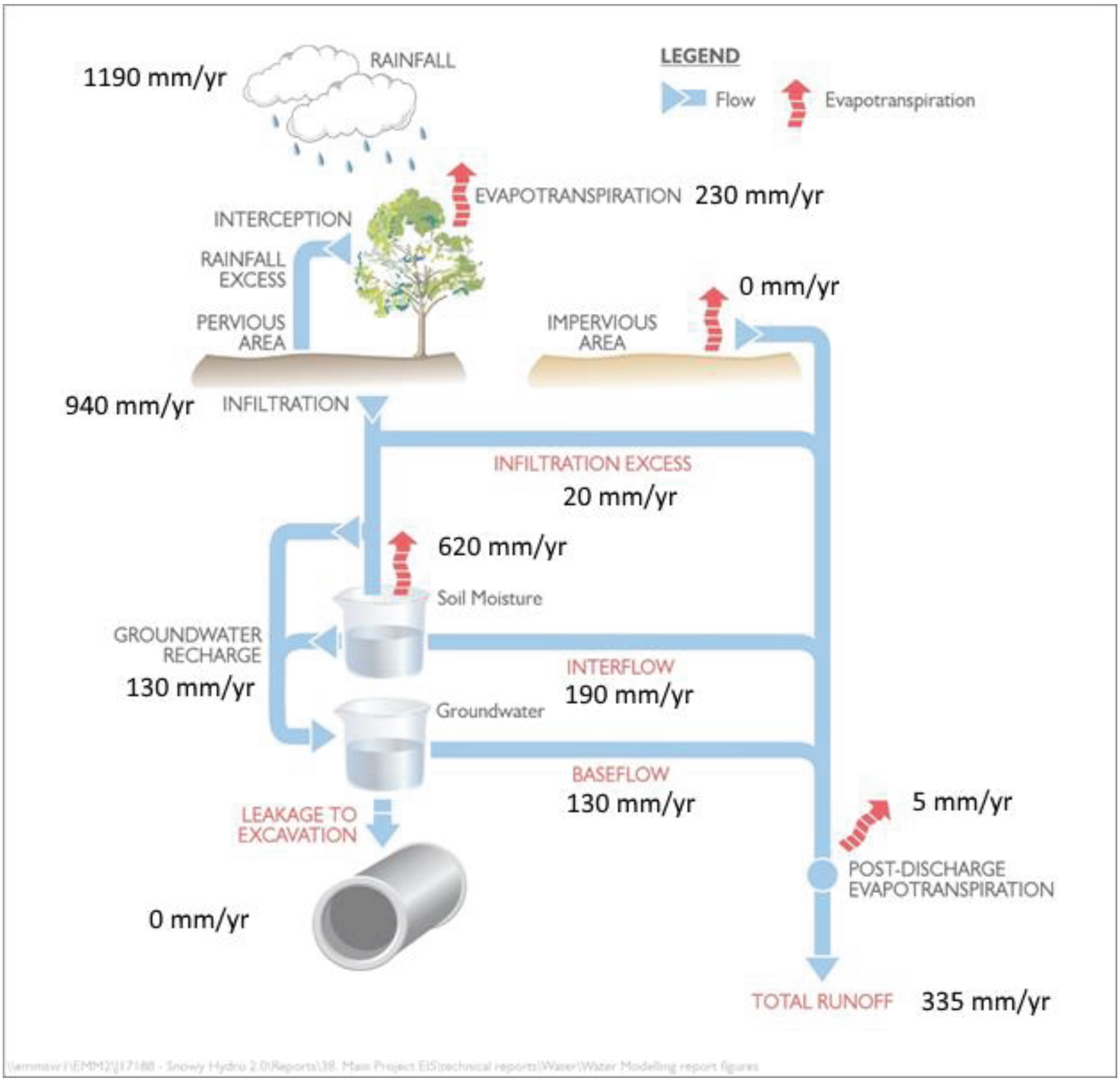


Figure 2.17 Model sub-catchment 19 (ravine) average yearly water balance (calibration period)

2.5.5 Data provided to the groundwater model

Following calibration of the catchment model, groundwater recharge time series data were exported for each sub-catchment for use in the groundwater model. Prior to inclusion in the groundwater model these datasets were spatially aggregated into ravine and plateau regions and temporally aggregated into seasons (Figure 2.18). This data is discussed further in section 3.2.6ii.

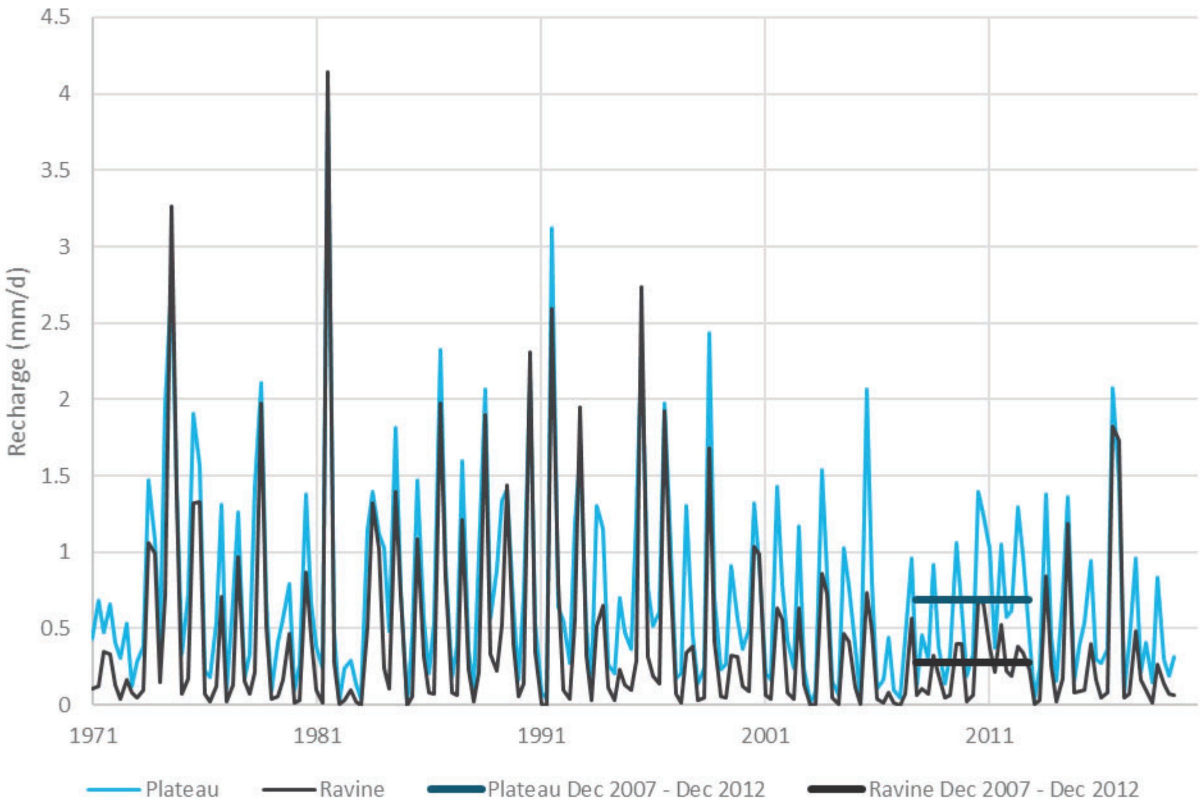


Figure 2.18 Historical quarterly average groundwater recharge predicted by the Source model

2.5.6 Calibration sensitivity

The sensitivity of the model calibration to model parameter selection was evaluated by altering each model parameter through its appropriate range and recording the resulting impact on the combined daily and log flow duration NSE statistic and the baseflow index. Each parameter was varied individually, and the parameters not being tested in each sensitivity run were not altered from the calibrated values. Though not tested, it is likely that in many cases the impacts of altering of one parameter could be offset by recalibration of other parameters.

The results of the parameter sensitivity analysis are presented in Figure 2.19 through to Figure 2.29 with shaded bands indicating the good to very good target range (Moriasi, et al., 2007) for each statistic. These plots show that the calibrated parameter values in each case achieve the best combined fit to the target baseflow index and maximised NSE, indicating that the calibration process reached a local calibration maxima within both the plateau and ravine.

When rainfall and evapotranspiration factors were varied, significant volume bias changes were observed (Figure 2.19 and Figure 2.20). Variation of other parameters had minimal impact on the volume bias, and so volume bias has been reported for rainfall and evapotranspiration sensitivity only.

When reading Figure 2.19 through to Figure 2.28, the calibrated range for each parameter has been taken as the range for which each reported statistic lies within the shaded target ranges. For example, when assessing sensitivity of the calibration at the Yarrangobilly gauge to the recharge coefficient, good NSE statistics were obtained through the parameter range 0.2–5.0 mm/day. Appropriate baseflow statistics were obtained through the parameter range 0.3–1.2 mm/day. The parameter range with good NSE and baseflow statistics is thus 0.3–1.2 mm/day; the appropriate range for this parameter is controlled by the baseflow response.

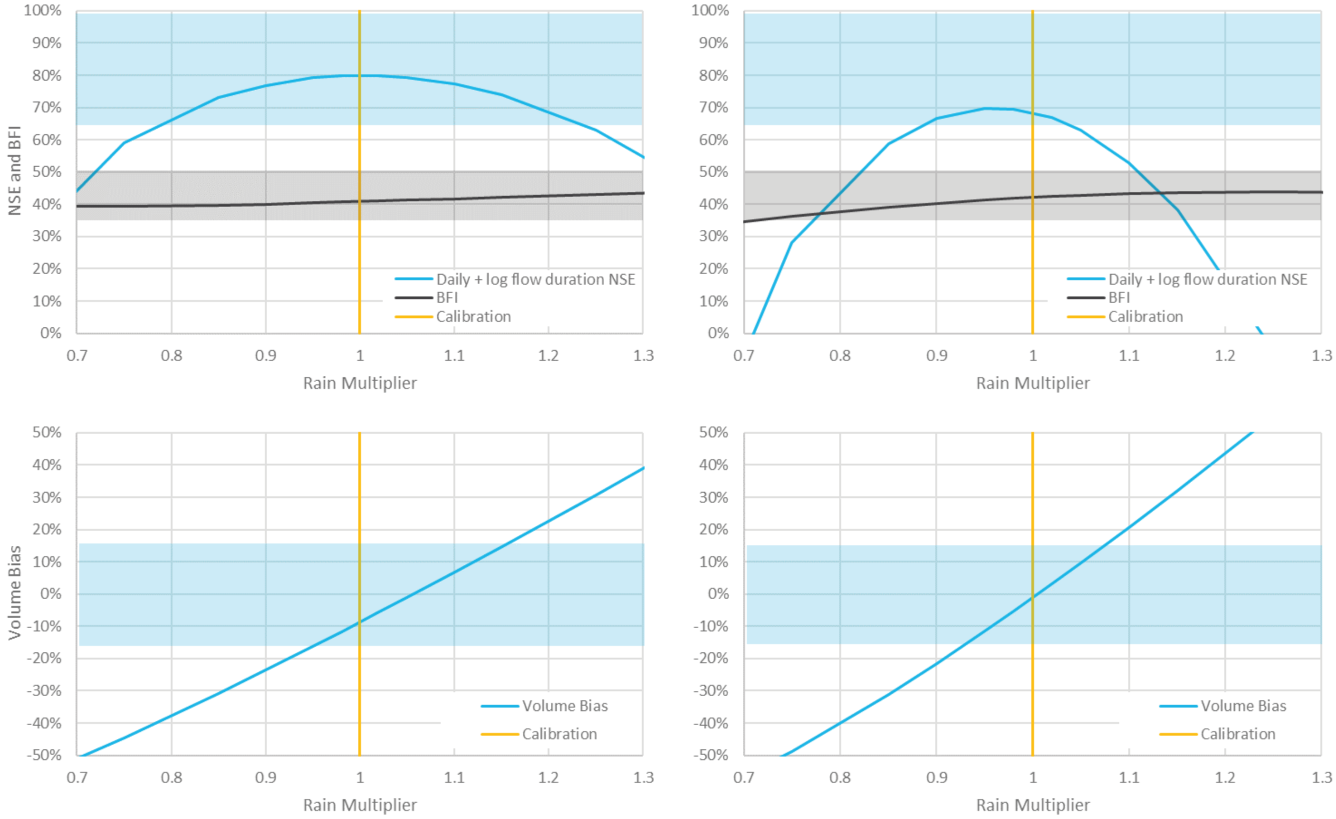


Figure 2.19 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the Rainfall Multiplier

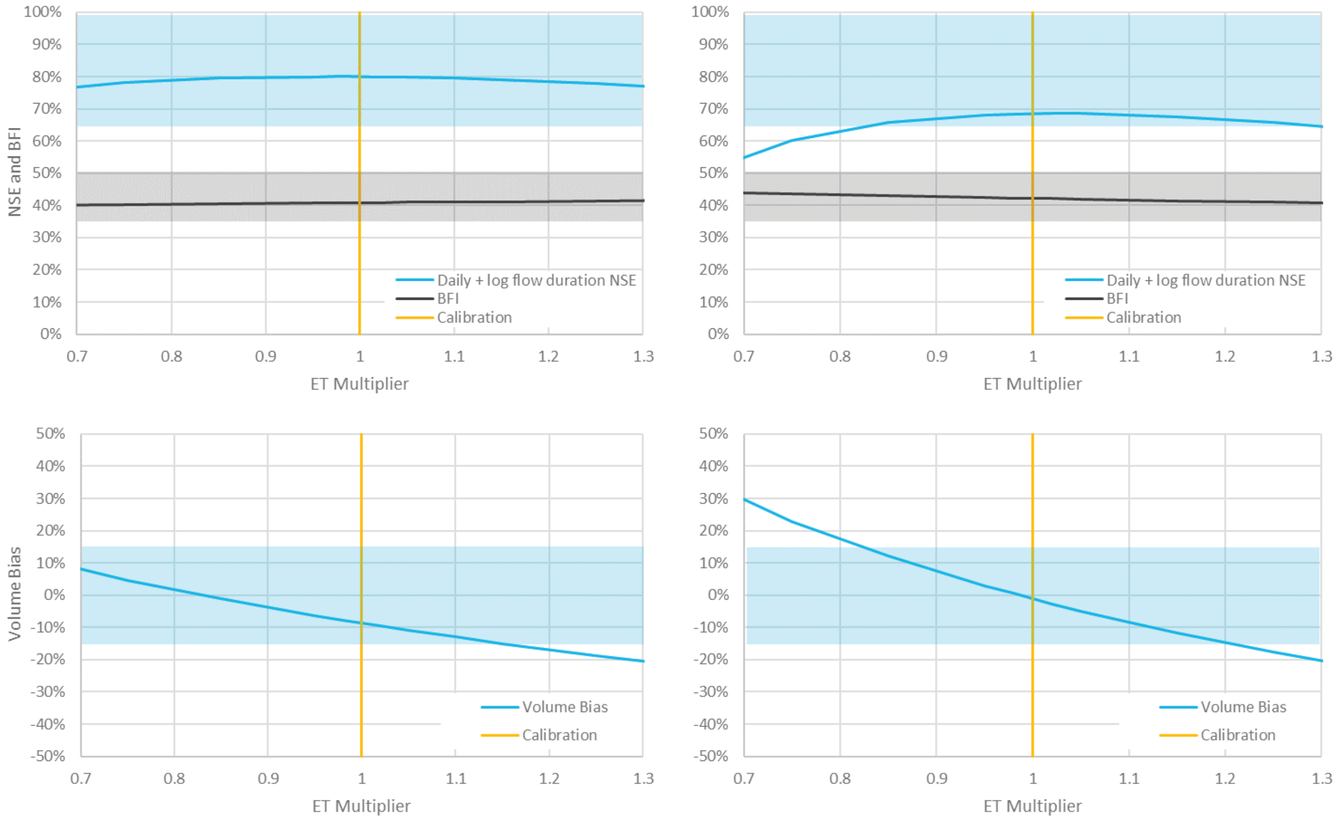


Figure 2.20 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the ET Multiplier

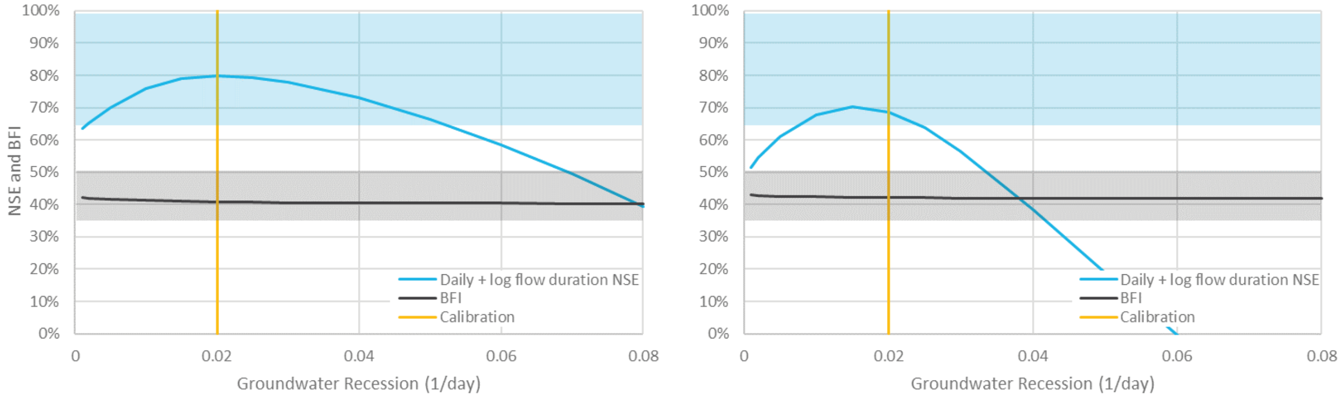


Figure 2.21 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the Groundwater Recession parameter

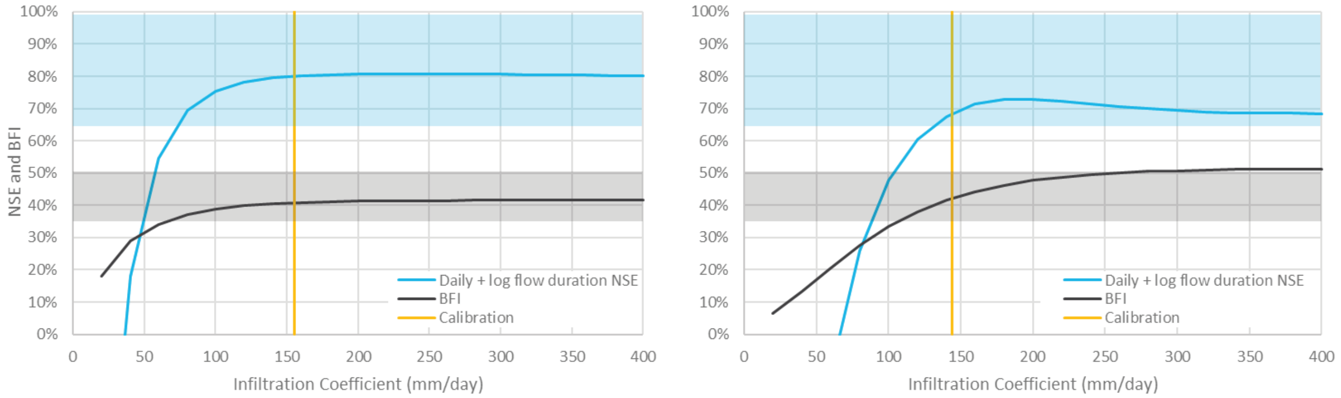


Figure 2.22 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the Infiltration coefficient

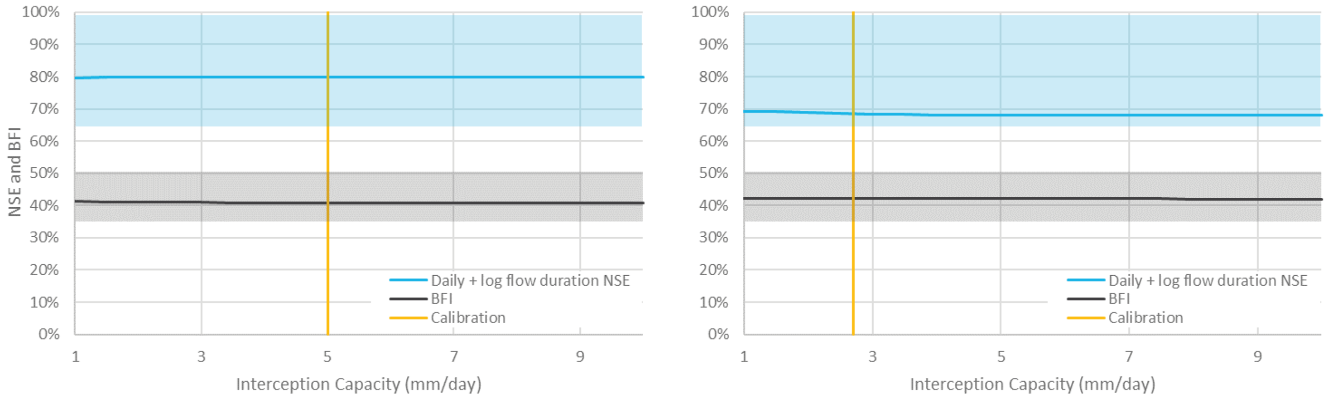


Figure 2.23 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the Interception Capacity parameter

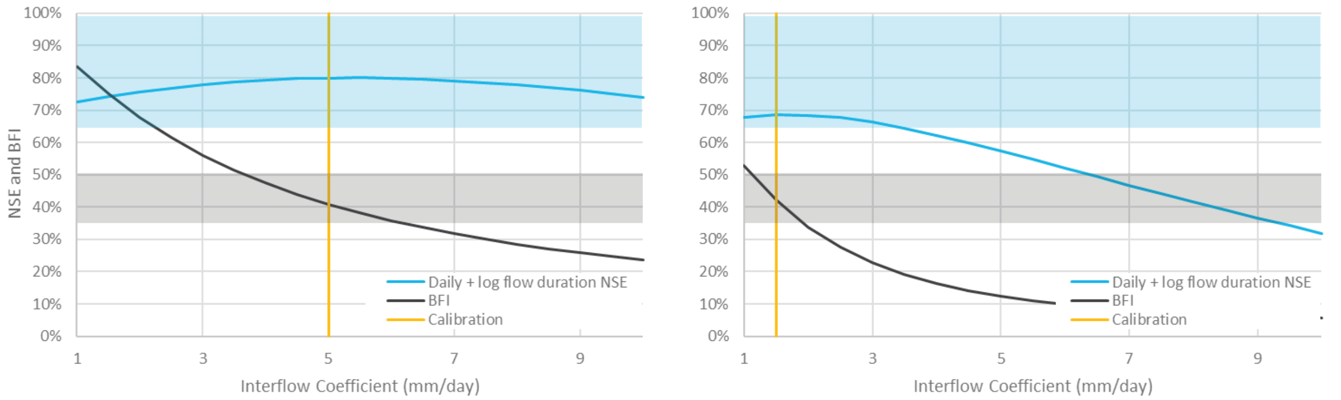


Figure 2.24 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the Interflow coefficient

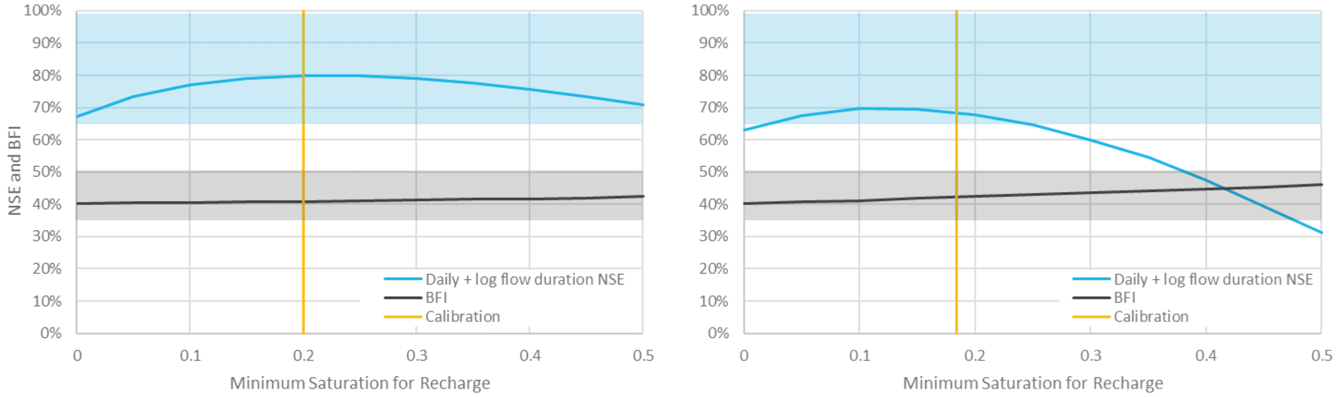


Figure 2.25 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the Minimum Saturation parameter

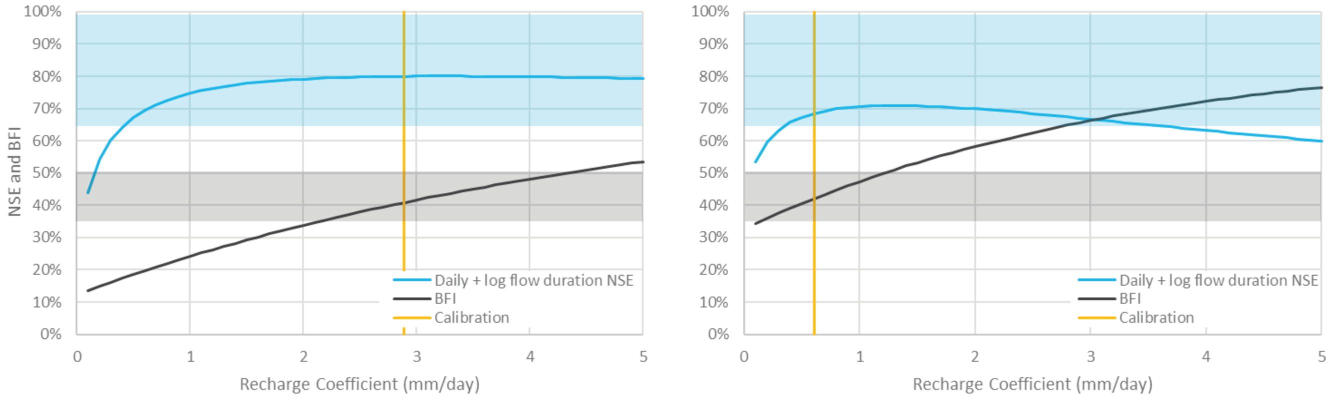


Figure 2.26 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the Recharge coefficient

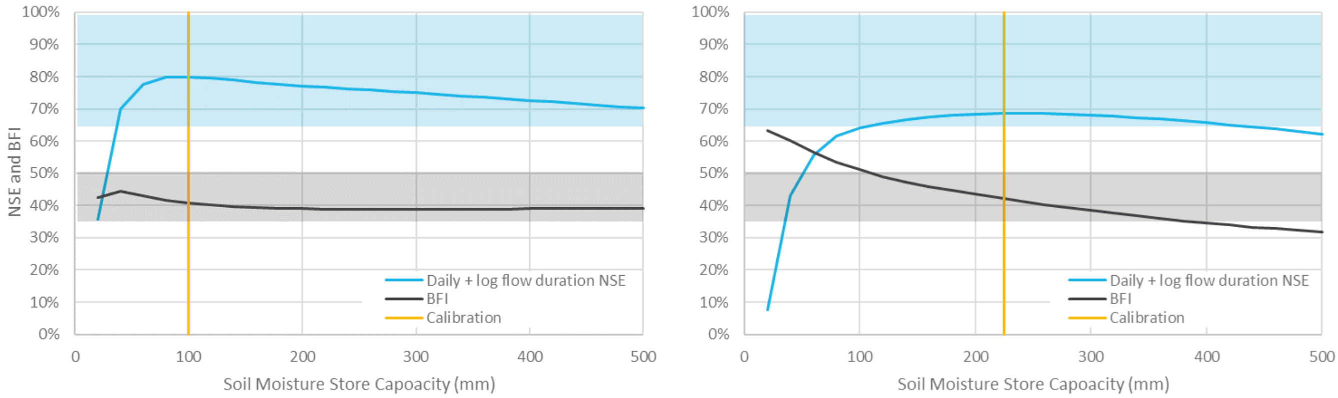


Figure 2.27 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the Soil Moisture Store Capacity

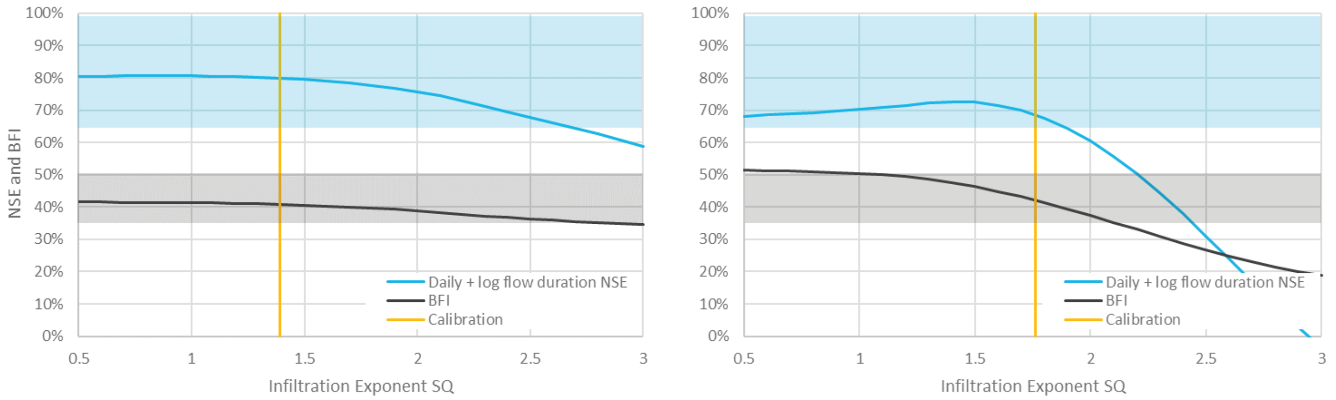


Figure 2.28 Calibration sensitivity at the Murrumbidgee gauge (left) and Yarrangobilly gauge (right) to the Infiltration exponent

The relative sensitivity of the calibration to the runoff model parameters (Figure 2.29) was estimated by assessing the proportion of the reasonable parameter range (Figure 2.19 through to Figure 2.28) which enabled a good calibration for each parameter. This assessment showed that the calibration to the Yarrangobilly River gauge (Ravine area parameters) was much more sensitive than the calibration to the Murrumbidgee River gauge. The model was most sensitive to the rainfall multiplier and the interflow coefficient, and least sensitive to the interception capacity.

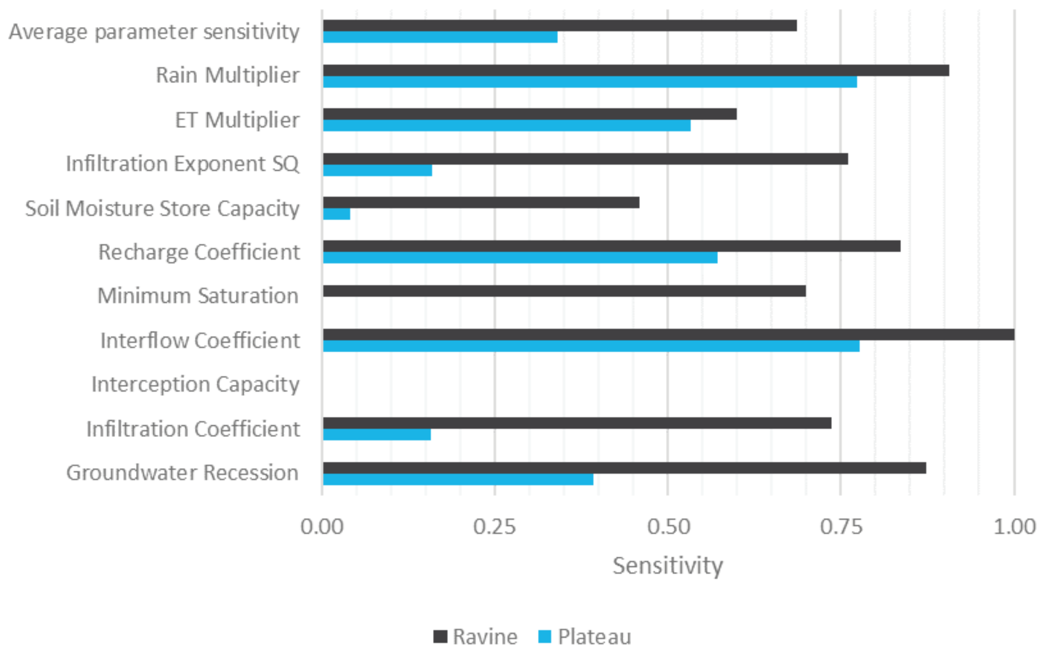


Figure 2.29 Calibration sensitivity to runoff model parameters

2.6 Validation

2.6.1 Method

The predicted runoff was qualitatively compared with manual spot flow measurements recorded at 11 sites utilising a hand held propeller flow meter at an approximately monthly frequency between October 2018 and July 2019. The manual flow readings were obtained by sampling the stream velocity across the width of the stream at regular intervals at multiple depths, with the average flow obtained via areally weighted integration of the individual velocity readings.

Data from a depth logger installed at a culvert across the Eucumbene River became available after the catchment model calibration process was complete. A rating curve for the culvert was developed using the 1D streamflow hydraulic modelling software HEC-RAS with measured culvert dimensions and creek cross sections extracted from LiDAR. This rating curve was used to convert the logged depth data into an estimated streamflow hydrograph for comparison with the catchment model results.

Streamflow data recorded at the streamflow gauge on Wallaces Creek within the Yarrangobilly River catchment was compared to the model predictions of flow past this point.

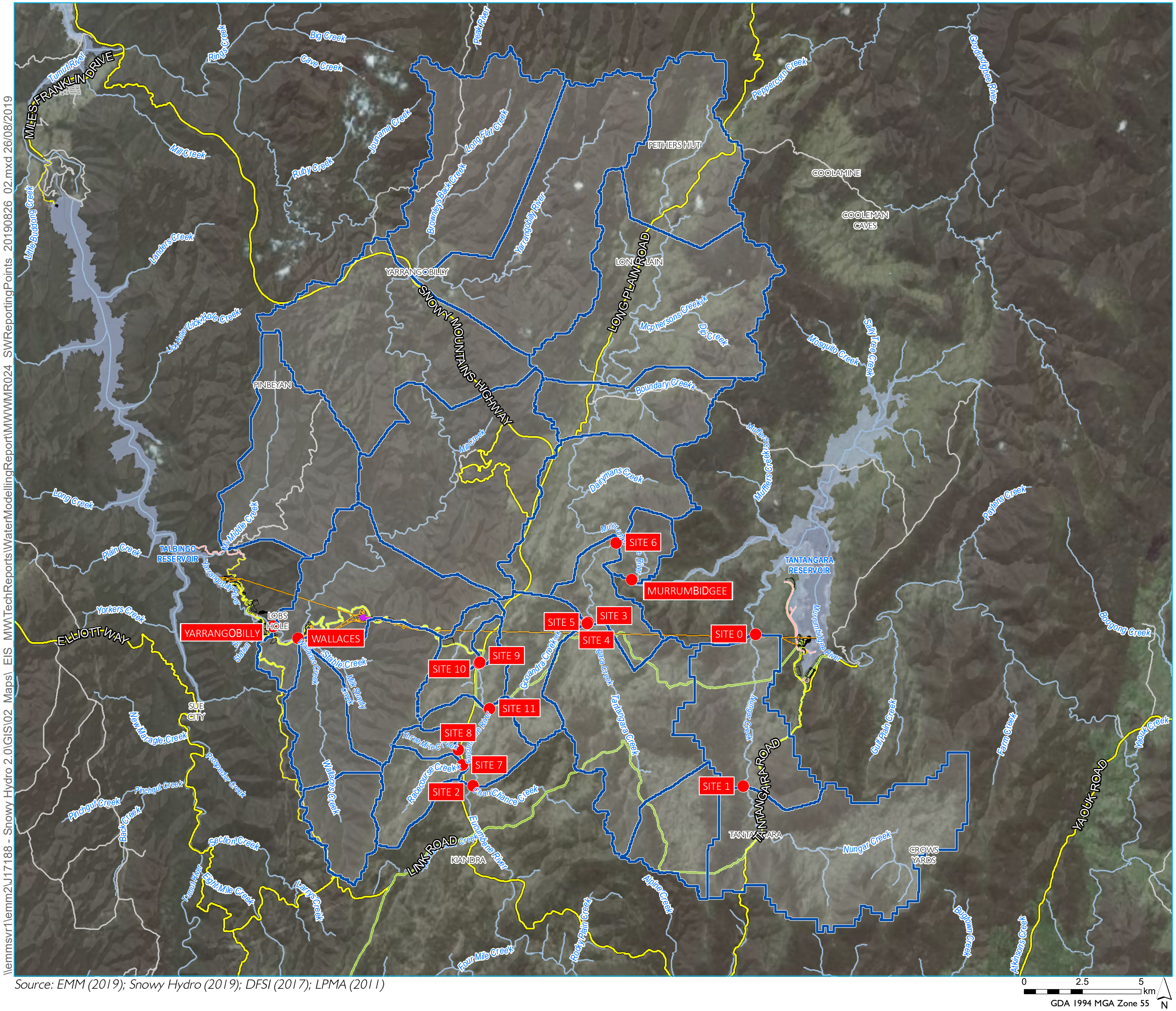
The Q-Lag analysis method (Brodie, Hostetler, & Slatter, 2007) was used to assess the timing and magnitude of median and baseflow components of streamflow, with comparisons made between the modelled and gauged datasets.

2.6.2 Manual flow measurements

Manual flow measurements were recorded at the 11 locations listed in Table 2.8 (coordinates in GDA94 MGA Zone 55) and illustrated in (Figure 2.30). These locations were included within the catchment model at the locations shown in Figure 2.30. Flow measurements were made using a ThermoFisher GLFWP211 protected water turbo prop positive displacement sensor, with a measurement range of 0.1–6.1 m/s. Velocity measurements were taken using a grid sampling approach across the stream channel, at regular depths and distances from bank, with the resulting velocity data integrated to provide a total flow estimate.

Table 2.8 Manual streamflow sites

Site name	Site description	Easting	Northing
Site 0	Nungar Creek Near Tantangara Reservoir	646640	6031810
Site 1	Nungar Creek At groundwater model southern boundary	641210	6042210
Site 2	Eucumbene River At groundwater model southern boundary	635330	6037070
Site 3	Gooandra Creek Upstream of confluence with Tantangara Creek	635380	6037120
Site 4	Tantangara Creek Upstream of confluence with Gooandra Creek	634630	6032710
Site 5	Tantangara Creek Downstream of confluence with Gooandra Creek	635080	6031830
Site 6	Tantangara Creek Upstream of confluence with Murrumbidgee River	639960	6038810
Site 7	Racecourse Creek	640010	6038820
Site 8	Three Mile Creek	639960	6038750
Site 9	Un-named creek	647160	6038300
Site 10	Eucumbene River	634450	6033370



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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KEY

- Reporting points
- Catchments

Snowy 2.0 Main Works operational elements

- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements

- Temporary construction compounds and surface works
- Temporary access road

Existing environment

- Main road
- Local road
- Perennial watercourse
- Scheme storage

Surface water model sub-catchments and reporting points

Snowy 2.0
Modelling Report
Main Works
Figure 2.30

snowy 2.0

EMM creating opportunities

Due to the small sample of manual flow measurements, NSE statistics were not calculated at the manual flow reading sites. Qualitative comparisons were made between the modelled and measured data.

The model predictions at Site 0 and Site 1 on Nungar Creek were a good fit to the measured data (Figure 2.31 and Figure 2.32). The model predicted flows of around 50 ML/day at Site 0 in October–November 2018, similar to the measured data, and flows close to zero in early 2019.

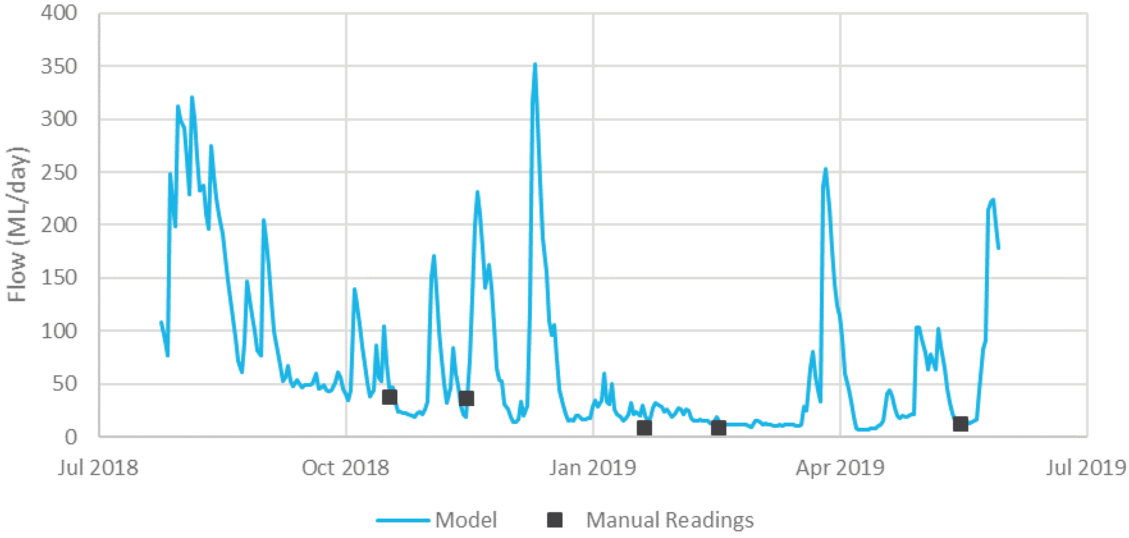


Figure 2.31 Comparison of modelled and measured flow at Site 0 (Nungar Creek)

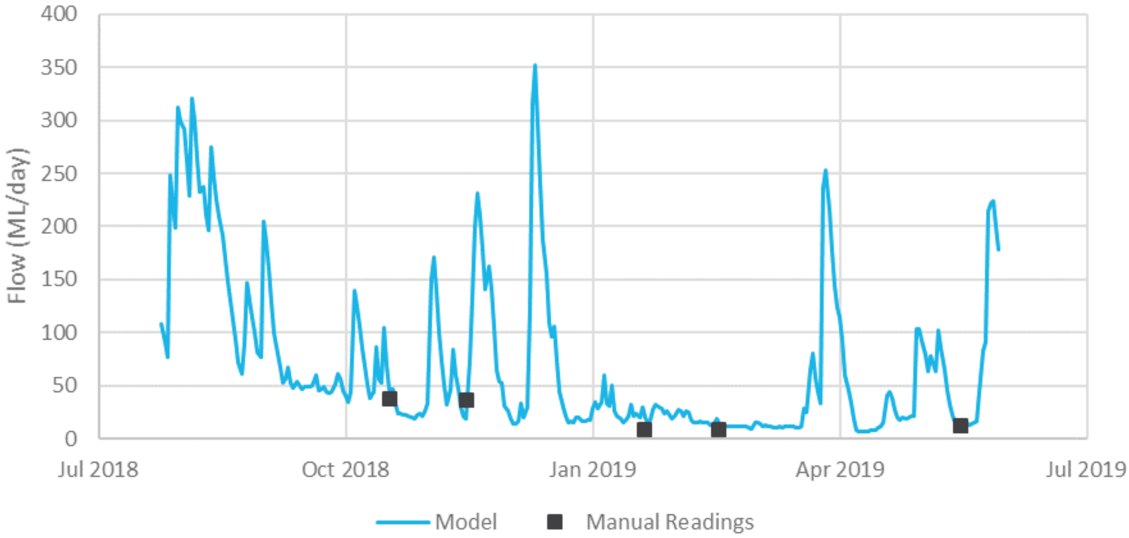


Figure 2.32 Comparison of modelled and measured flow at Site 1 (Nungar Creek)

The model gave a good estimate of flow at Site 2 (Figure 2.33) on the Eucumbene River for low flow conditions in January–February 2019 and a subsequent flow event in response to rainfall in March. There was some disparity between modelled and measured flow in October–November 2018, likely due to the timing and spatial extent of rainfall events occurring during those months not being perfectly represented in the SILO data.

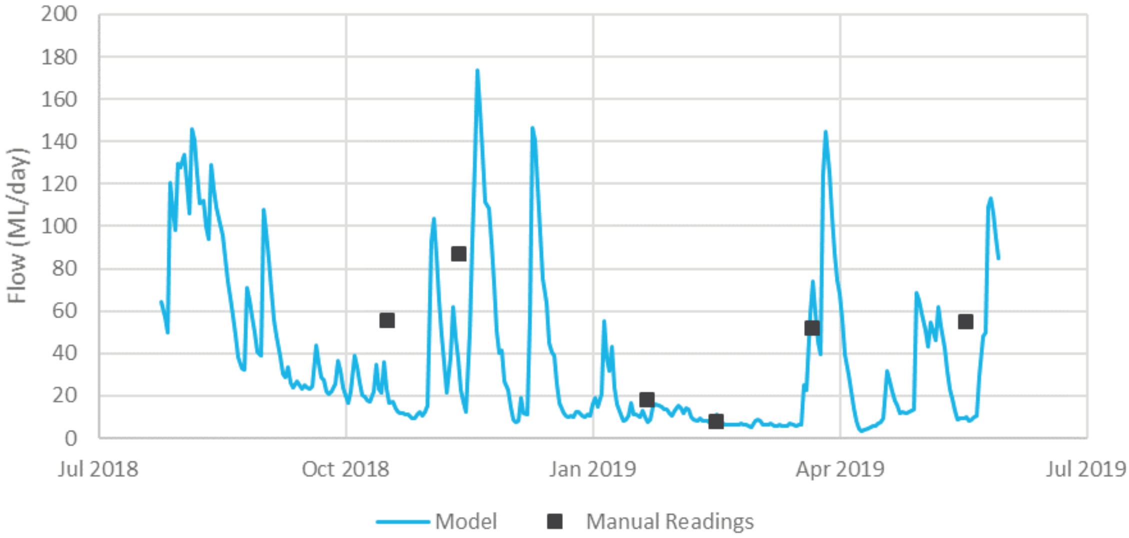


Figure 2.33 Comparison of modelled and measured flow at Site 2 (Eucumbene River)

At the downstream end of Gooandra Creek (Figure 2.34) the model under-predicted creek flow rates at Site 3. In particular, the January–February 2019 manual flow readings are well predicted at other sites but are under-predicted at this site.

This result may indicate that the Gooandra Creek catchment has characteristics that differ from the rest of the plateau catchments. Higher modelled infiltration rates could foreseeably result in higher modelled flows in January due to a larger volume of water in the groundwater store, and would be consistent with the fractured surface geology visible within the Gooandra Creek catchment which occurs along the ridge but not throughout the rest of the plateau.

One alternate plausible explanation is that due to the small dimensions of Gooandra Creek and its upstream catchment, measurement errors of a small magnitude resulted in a large percentage error. The difference between the January 2019 flow measurement and the model prediction is approximately 0.73 L/s, which is of a magnitude that it could be explained as being due to mis-measurement of creek width or depth dimensions.

Another possible explanation is that the Gooandra catchment received higher rainfall than the surrounding catchments in January 2019, and that the spatial rainfall heterogeneity was not represented accurately in the SILO rainfall data.

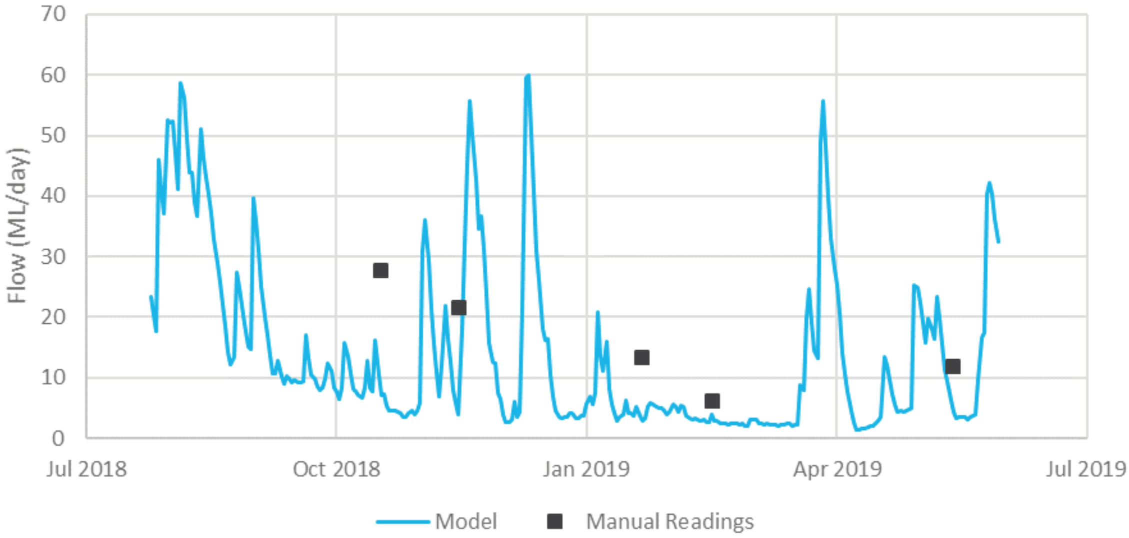


Figure 2.34 Comparison of modelled and measured flow at Site 3 (Gooandra Creek)

The model provided predictions of flow at Site 4, Site 5 and Site 6 in the Tantangara Creek which closely matched the measured flow rates (Figure 2.35, Figure 2.36, and Figure 2.37), other than the October 2018 sampling when it has been presumed there was non-recorded rainfall.

It might be expected that the under-estimation of flow from Gooandra Creek (Site 3; Figure 2.34) would lead to under-prediction of flow downstream of the confluence of Gooandra Creek and Tantangara Creek at Site 5 (Figure 2.36). However, flow prediction at Site 5 appears to have the same level of accuracy as the other sites on Tantangara Creek. This is consistent with the suggestion that the measured flows seen at Site 3 in Figure 2.34 may be higher than the modelled flow due to measurement error.

However, Sites 8–10 (Figure 2.39, Figure 2.40, Figure 2.41) similarly were located on small creeks with catchments of comparable size to Gooandra Creek, yet the modelled and measured flows were closely aligned January–March 2019. This leaves the source of the departure between modelled and measured flows from Gooandra Creek uncertain at the time of writing.

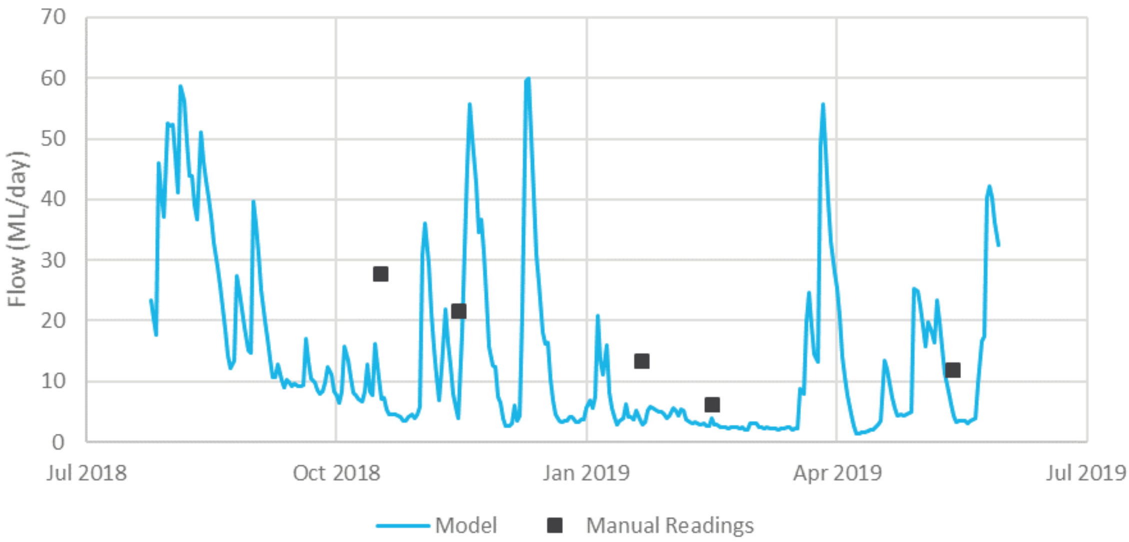


Figure 2.35 Comparison of modelled and measured flow at Site 4 (Tantangara Creek)

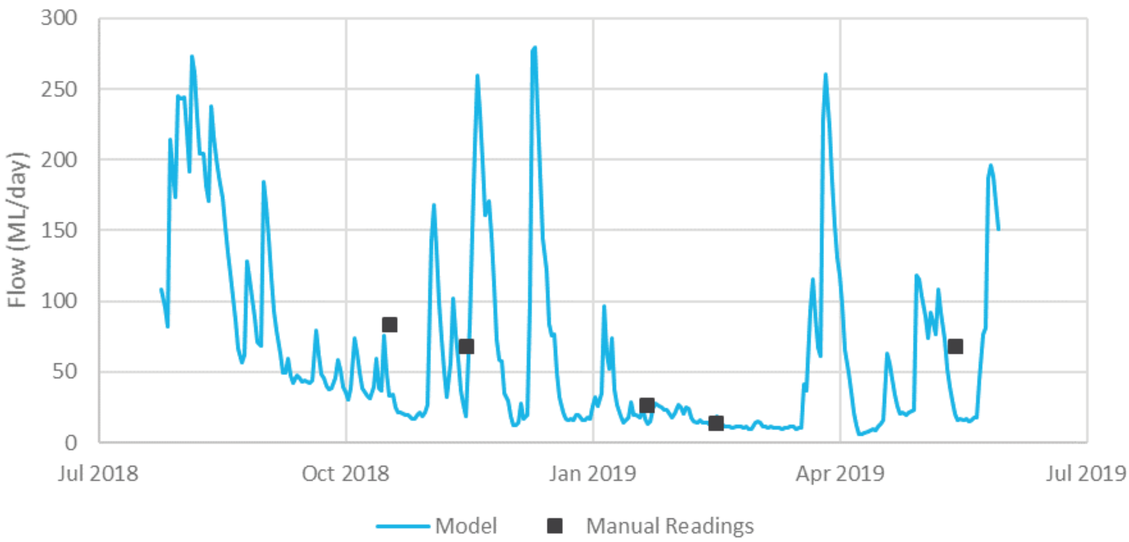


Figure 2.36 Comparison of modelled and measured flow at Site 5 (Tantangara Creek)

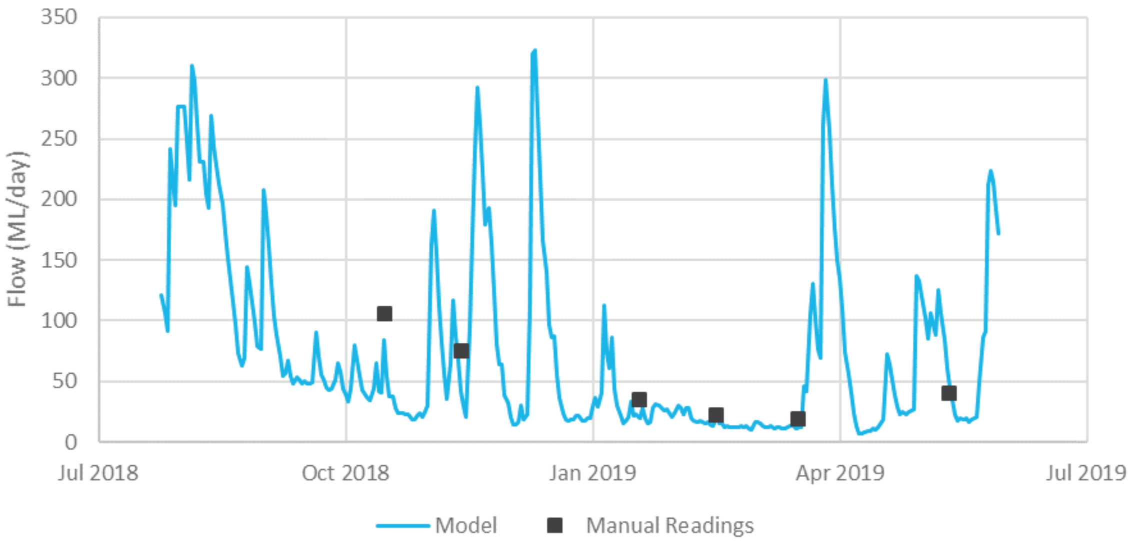


Figure 2.37 Comparison of modelled and measured flow at Site 6 (Tantangara Creek)

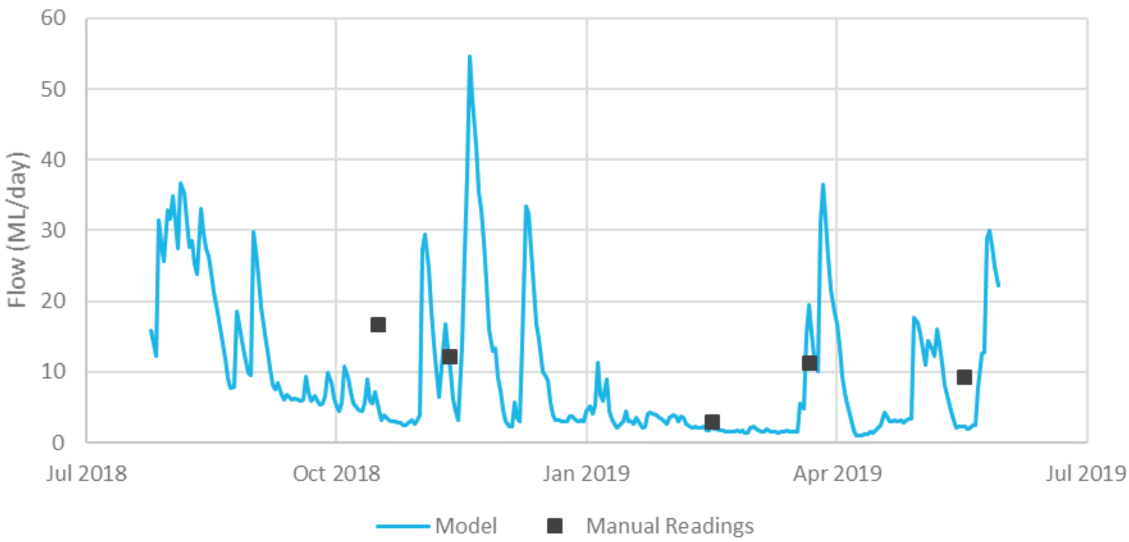


Figure 2.38 Comparison of modelled and measured flow at Site 7 (Racecourse Creek)

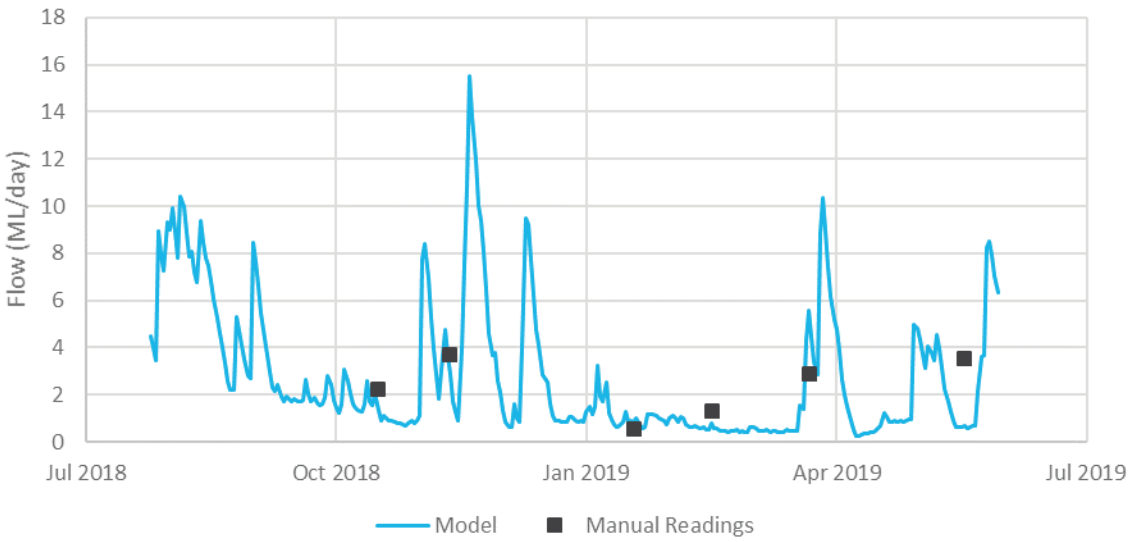


Figure 2.39 Comparison of modelled and measured flow at Site 8 (Three Mile Creek)

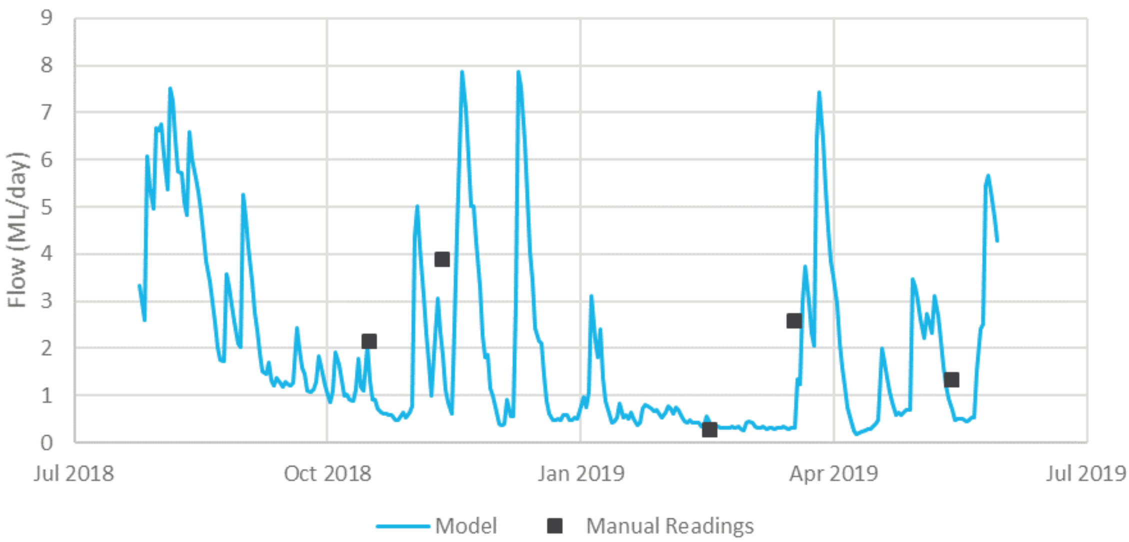


Figure 2.40 Comparison of modelled and measured flow at Site 9 (Un-named creek)

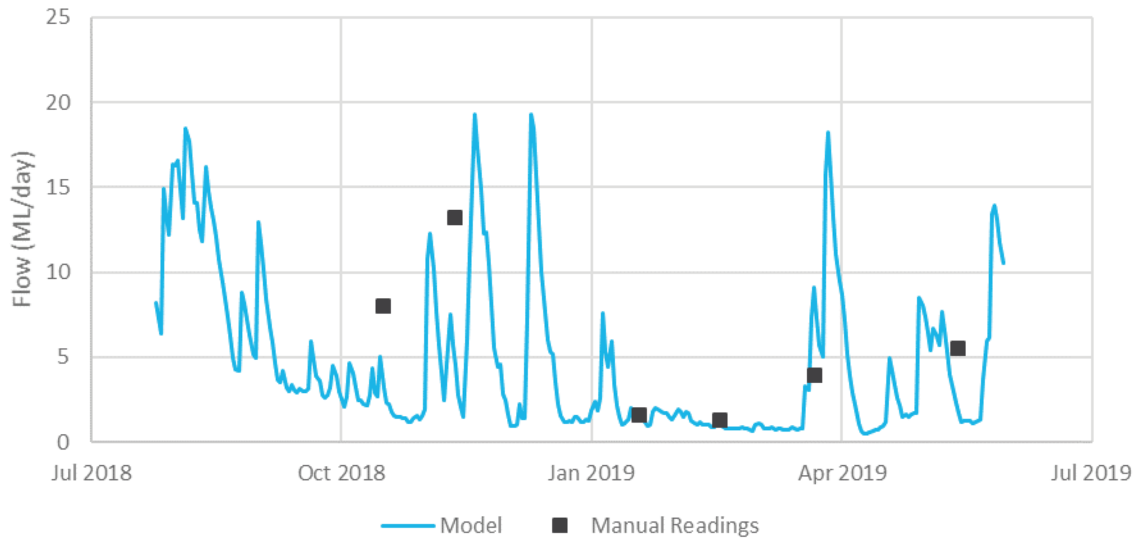


Figure 2.41 Comparison of modelled and measured flow at Site 10 (Eucumbene River)

Overall, the model provided a good fit to manual streamflow measurements, particularly during summer months January–March 2019. It has been hypothesised that unrecorded rainfall in October–November 2018 affected the accuracy of model predictions at a number of the measurement sites in those months.

The predicted flows were systematically lower than the recorded flows at the downstream end of Gooandra Creek. It is currently not certain whether the under-prediction is due to measurement errors (eg in the geometry of the creek at the measurement point) or whether the Gooandra Creek catchment requires an alternate parameter set. Other sites within the plateau have similar elevation and vegetation as Gooandra Creek, and the upper reaches of the Eucumbene River feature the same geology as Gooandra Creek, so there is no clear physical basis for Gooandra Creek to require an alternate parameter set.

2.6.3 Eucumbene River depth logger

A depth logger was installed on the headwall of the box culvert where the Eucumbene River crosses the Gooandra Trail. The logger recorded pressure data at the creek bed at five minute intervals for the period 16 April 2019 to 17 May 2019, and was corrected for barometric pressure via comparison to a project barometric gauge. Photos of the installation are shown in Figure 2.42.

Figure 2.42 Installation of pressure logger – Eucumbene River at the culvert on the Gooandra Trail (Site 11)

The location of the pressure logger is listed in Table 2.9 (coordinates in GDA94 MGA Zone 55) and was included as a gauge node in the catchment model, see Figure 2.30.

Table 2.9 Pressure logger site

Site name	Site description	Easting	Northing
Site 11	Eucumbene River Culvert at Gooandra Trail	635815	6035070

A 1D hydraulic model of Site 11 was developed using the modelling software HEC-RAS[6] with measured culvert dimensions (see Figure 2.43), aerial imagery and stream line and cross sections extracted from the project digital elevation model (1 m resolution LiDAR data). This model was used to develop a rating curve for the culvert which was then used to convert the logged pressure data to an estimated streamflow hydrograph for comparison with the catchment model results.

The HEC-RAS model, illustrated in Figure 2.44, extends approximately 35 m upstream and 85 m downstream of the culvert at Gooandra Trail and includes 20 cross sections. The culvert was modelled as a rectangular box culvert having a '90 degree headwall', as the headwall has rock gabions and is not tapered.

[6] HEC-RAS version 5.0.5

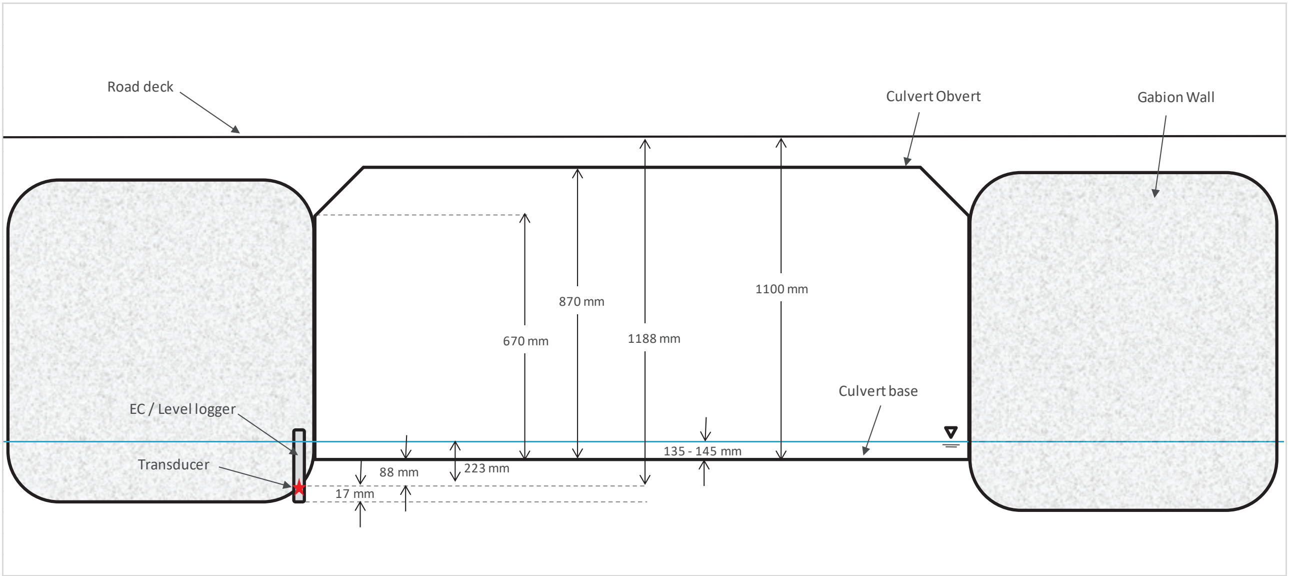


Figure 2.43 Schematic with measured dimensions for the culvert at Site 11

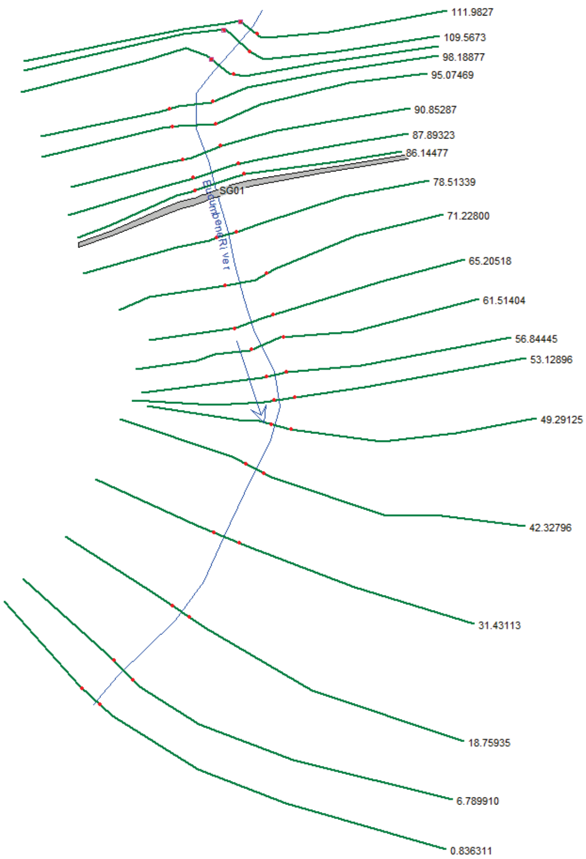


Figure 2.44 HEC-RAS model of Site 11, Eucumbene River (culvert at the Gooandra Trail)

Selection of an appropriate Manning's *n* value is important as it affects the accuracy of computed water surface elevations in HEC-RAS. The value of Manning's *n* is highly variable and depends on a number of factors including but not limited to: surface roughness, vegetation and channel alignment (Brunner, 2016). The HEC-RAS Reference Manual includes guidelines for selecting appropriate Manning's *n* values. For the model of Site 11, the following Manning's n values were applied:

- within the culvert – a Manning's *n* value of 0.015, consistent with unfinished concrete; and
- main channel and floodplain – a Manning's *n* value of 0.05, assuming the following descriptors:
    - main channel: Clean, winding, some weeds, stones; and
    - flood plains: Scattered brush, heavy weeds (NOTE: same Manning's *n* as in channel).

The rating curve was developed by modelling a range of flows through the culvert from 0.01–2.5 m^3/s, extracting and plotting the water surface elevation upstream of the culvert (at the logger location) against the modelled flow. Normal depth was assumed at the downstream end of the model.

In the absence of detailed data/information about conditions at the site for calibration, a higher (0.07) and lower (0.03) creek bed Manning's *n* value were applied in the HEC-RAS model to provide an indicative upper and lower bound to the rating curve. The rating curve is shown in Figure 2.45. Higher and lower Manning's n value for within the culvert were applied in the model and found not to significantly affect results - the results of this analysis are not shown.

The project digital elevation model shows a low point in Gooandra Trail on the eastern bank of the Eucumbene River such that when water levels rise above 1382.2 m AHD, water flows both through the culvert and over the top of the track. This can be seen in see the HEC-RAS cross section immediately upstream of the culvert (Figure 2.46) and is responsible for the increase in flow relative to water surface elevation relative in the ratings curve at this elevation.

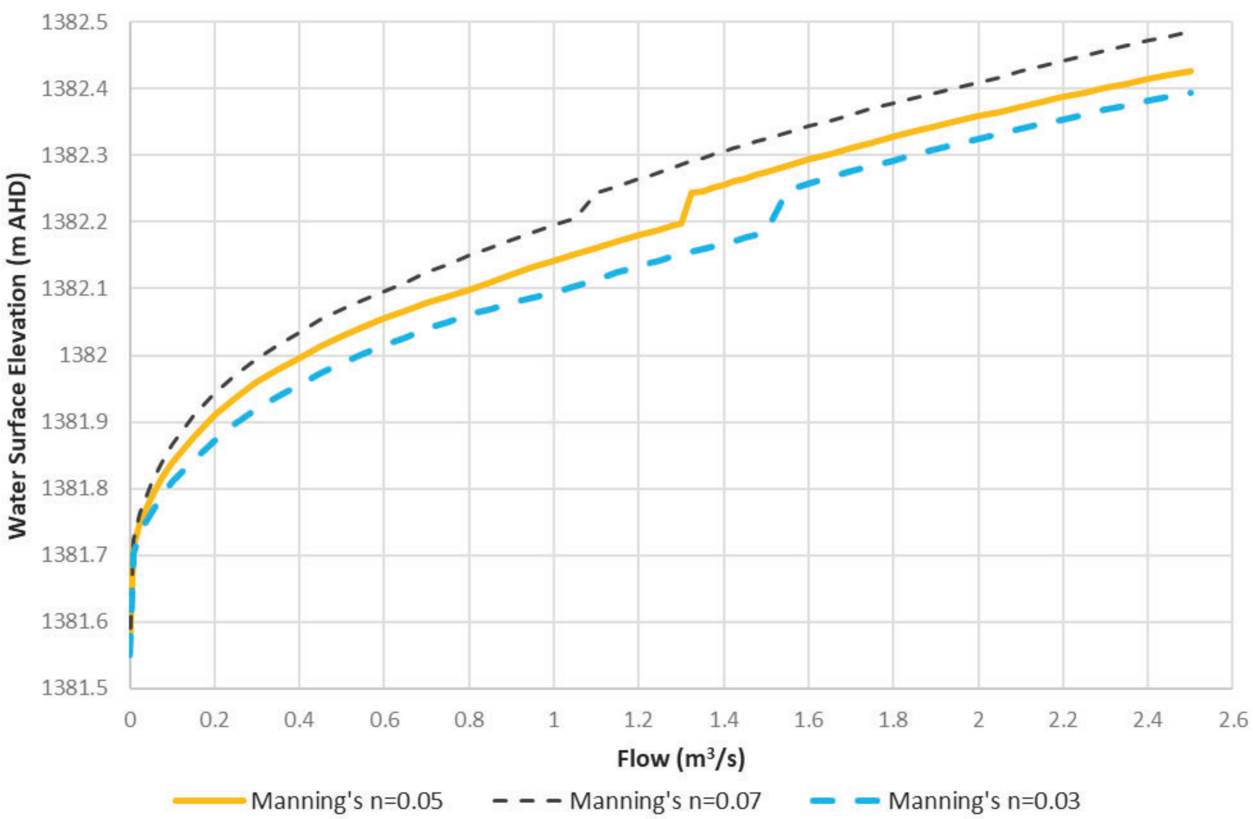


Figure 2.45 Rating curve for Site 11, Eucumbene River (culvert at the Gooandra Trail)

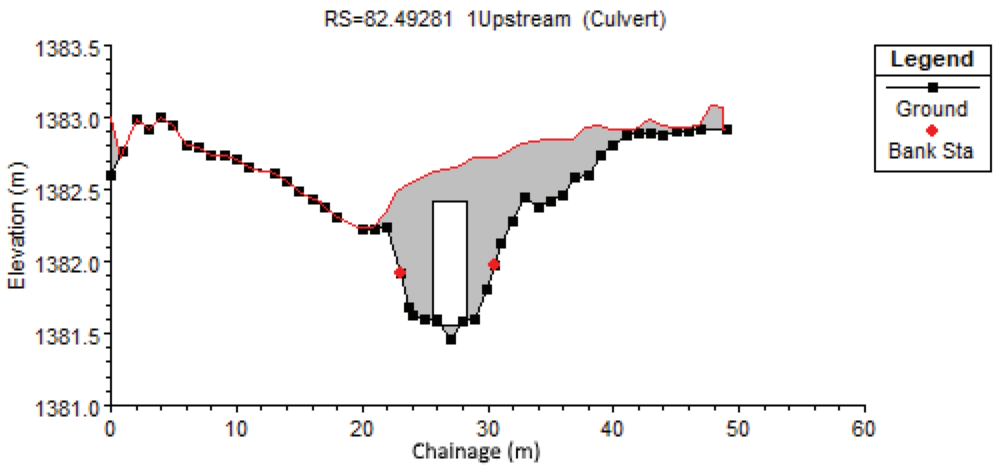


Figure 2.46 HEC-RAS cross section of the Eucumbene River immediately upstream of the Gooandra Trail culvert at Site 11

The estimated streamflow at this location based on the modelled rating curve are presented in Figure 2.47 for the monitoring period (16 April 2019–1 June 2019), together with streamflow estimates from the calibrated catchment model. The flow comparison shows that the model did not predict the peak flow recorded in May or June, but that flow predictions during recession and low flow periods closely matched the recorded data. Daily NSE and RSR statistics showed that the Source model produced a good to very good match to the recorded data (Table 2.10).

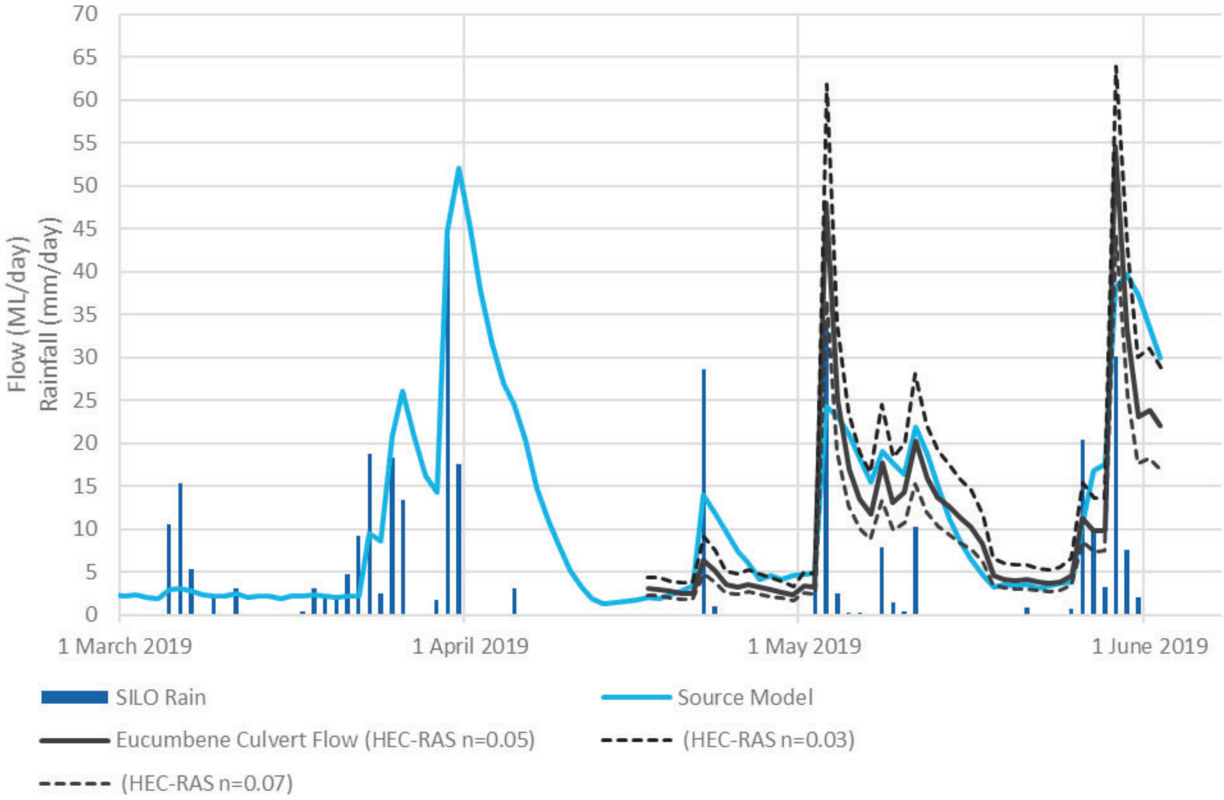


Figure 2.47 Comparison of rainfall data, catchment model flow and flow converted from logger data at Site 11

Table 2.10 Eucumbene River validation statistics

	Calibration Statistic[1]	Interpretation[2]
RSR Daily	53%	Good
NSE Daily	72%	Good
NSE Log Daily	84%	Very Good
NSE Daily and log flow duration	84%	Very Good
Volume Bias	10%	Good

Note: 1. Comparison of Source model with logger data converted to flow using the rating developed with the Hec-Ras model using n=0.05
2. As per Moriasi et al (2007)

2.6.4 Wallaces Creek streamflow gauge

From 1969 to 1999 a streamflow gauge was operated on Wallaces Creek in the ravine area.

The Wallaces Creek gauge recorded lower runoff per square kilometre than the Yarrangobilly River gauge through much of the flow duration curve, and in particular recorded low flows approximately an order of magnitude lower than the Yarrangobilly River gauge. This could be due to the Wallaces Creek catchment being steeper than the remainder of the Yarrangobilly River catchment, such that runoff in Wallaces Creek is 'flashier' with less sustained interflow and baseflow.

A number of difficulties were encountered during calibration when including data from the Wallaces Creek gauge:

- automated calibration procedures preferred unrealistic parameter sets within Wallaces Creek and Stable Creek which resulted in routing all runoff via the groundwater store with no surface runoff; and
- when utilising separate parameter sets in Wallaces Creek and Stable Creek based on calibration of runoff from those catchments to the Wallaces Creek gauge, the calibration statistics at the downstream Yarrangobilly River gauge were poorer.

As the gauge was decommissioned 20 years ago, the condition of the gauge and the accuracy of the gauge during the record period are not known, and it is possible that the calibration problems experienced when using data recorded at this gauge were caused by a rating curve that was poor at representing either low or high flows.

Due to the described calibration difficulties and the possibility of unreliable gauge data, the data from this gauge was excluded from the model calibration.

The Wallaces Creek catchment was modelled using the same parameter set as the Yarrangobilly River, resulting in the model over estimating runoff within this catchment through much of the flow duration curve. Statistics describing the comparison of the gauged and modelled flow (Table 2.11) at this gauge were poorer than the calibration statistics for the downstream Yarrangobilly gauge (cf Table 2.6).

Rainfall contours (Annexure A of the water assessment Figure 4.1) indicate that average yearly precipitation upstream of Wallaces Creek gauge varies from 950 mm/yr near the gauge to 1300 mm/yr at the Wallaces Creek headwaters. The yearly average precipitation provided by the SILO grid data for Wallaces Creek is 1145 mm/yr, providing a good representation of conditions likely to exist at the catchment centroid.

Preliminary tests undertaken during the model validation phase of the project indicated that reducing the rainfall multiplier within the Wallaces and Stable Creek catchments to 90% reduces the Wallaces Creek volume bias to near zero, while maintaining or improving other calibration statistics at the Wallaces Creek gauge. This change has a minor negative influence on Yarrangobilly River gauge calibration statistics that could likely be ameliorated through calibration optimisation. Changing the rainfall multiplier for the Wallaces Creek and Stable Creek catchments and reintroduction of the Wallaces Creek gauge data in the calibration process was not undertaken prior to EIS submission because:

- the SILO data appears to a provide a good representation of precipitation within the catchment (ie there is no immediate justification for altering the precipitation input other than calibration improvement); and
- the groundwater modelling predicted that impacts to streamflow within the Wallaces Creek catchment due to baseflow reduction are likely to be minor or insignificant (see section 2.7.6), and as such inaccuracy in streamflow predictions at the Wallaces Creek gauge are likely to represent a low risk.

If monitoring during construction and operation indicates that larger impacts to baseflow may occur within Wallaces Creek, local recalibration of the catchment model to improve the volume bias will be required before utilising the model to describe the changes to streamflow. The preliminary rainfall reduction test is documented to illustrate that a pathway exists for prediction improvement if monitoring during construction indicates a departure from the model results.

Table 2.11 Wallaces Creek validation statistics

	Calibration Statistic	Interpretation[1]
RSR Monthly	53%	Good
NSE Monthly	72%	Good
NSE Log Daily	72%	Good
NSE Daily and log flow duration	75%	Good
Volume Bias	28%	Unsatisfactory

Note: 1. Moriasi et al (2007)

2.6.5 Q-Lag analysis

The modelled streamflow results were analysed with the Q-Lag method described in 2.3 and compared to the analysis completed with gauge data. Comparison of Q-Lag data relating to the Murrumbidgee gauge (see Figure 2.48) showed that the modelled 90th percentile exceedance streamflow in summer months (January–May) is very similar between modelled and gauged data, indicating that baseflow discharges are well represented in these months.

The modelled 50th percentile exceedance Murrumbidgee streamflow begins to increase during April, while the gauged data begins to increase in May, indicating that the model produces excess runoff in autumn and early winter. In August to October the trend is reversed, with the model producing less runoff for both the 50th and 90th percentile exceedance hydrographs.

One possible explanation for this result is that snowfall in early winter is retained in the catchment, melting several months later and contributing to both quick flow and groundwater recharge. As the model does not model a snow pack, this storage and release process does not occur in the model.

The modelled Yarrangobilly streamflow 50th and 90th exceedance percentiles were generally a good match to the gauged data (Figure 2.49). The reduction in streamflow lag seen in the analysis of Murrumbidgee flow data is not apparent in the Yarrangobilly data. The Yarrangobilly River catchment is lower than the Murrumbidgee catchment, and experiences less snowfall, consistent with the possibility that the departures between measured and modelled data in the Murrumbidgee catchment are driven by snowfall.

The effect of storage of precipitation as snow was investigated, as described in B.5.2, with the conclusion that the predictive power of the trialled model was not improved when simulating a snow pack but that a more complex snow pack model may have produced a different result.

As the impacts of the project on streamflow are primarily limited to summer months (section 2.7.6), the weakness of the catchment model to predict storage of snow through the winter is unlikely to affect impact predictions.

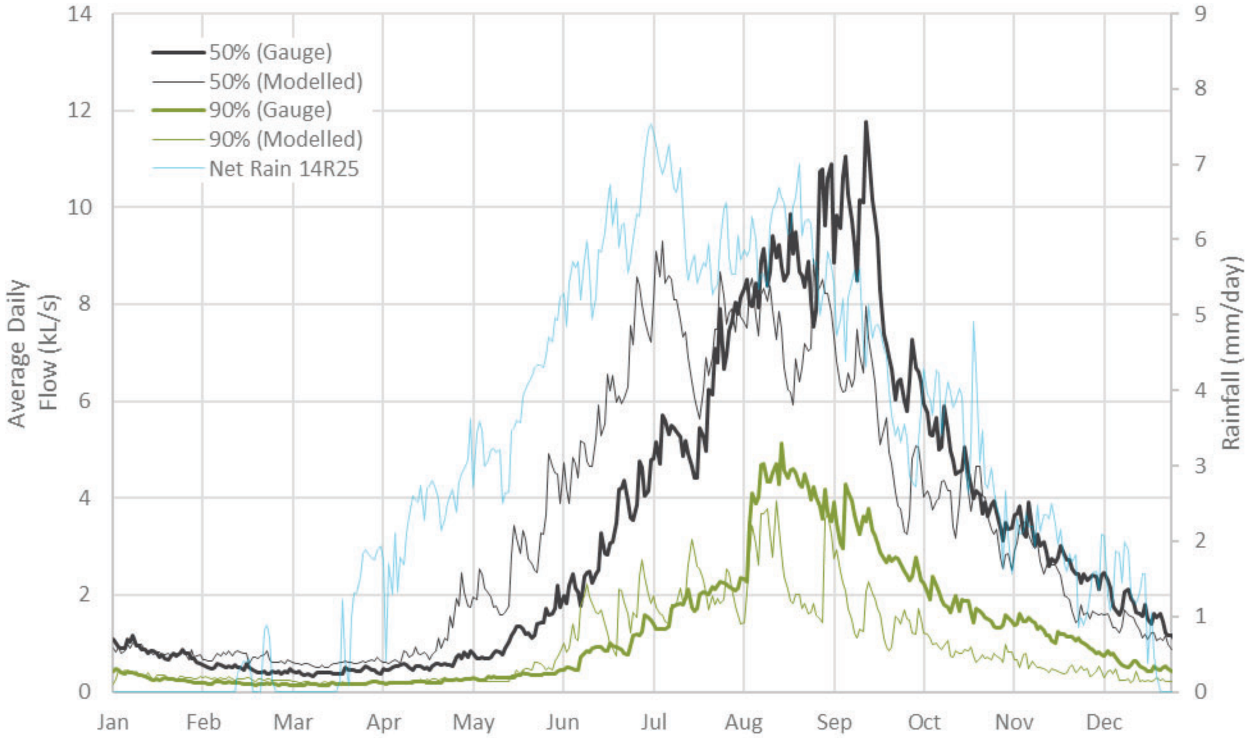


Figure 2.48 Comparison of Murrumbidgee Q-Lag analyses

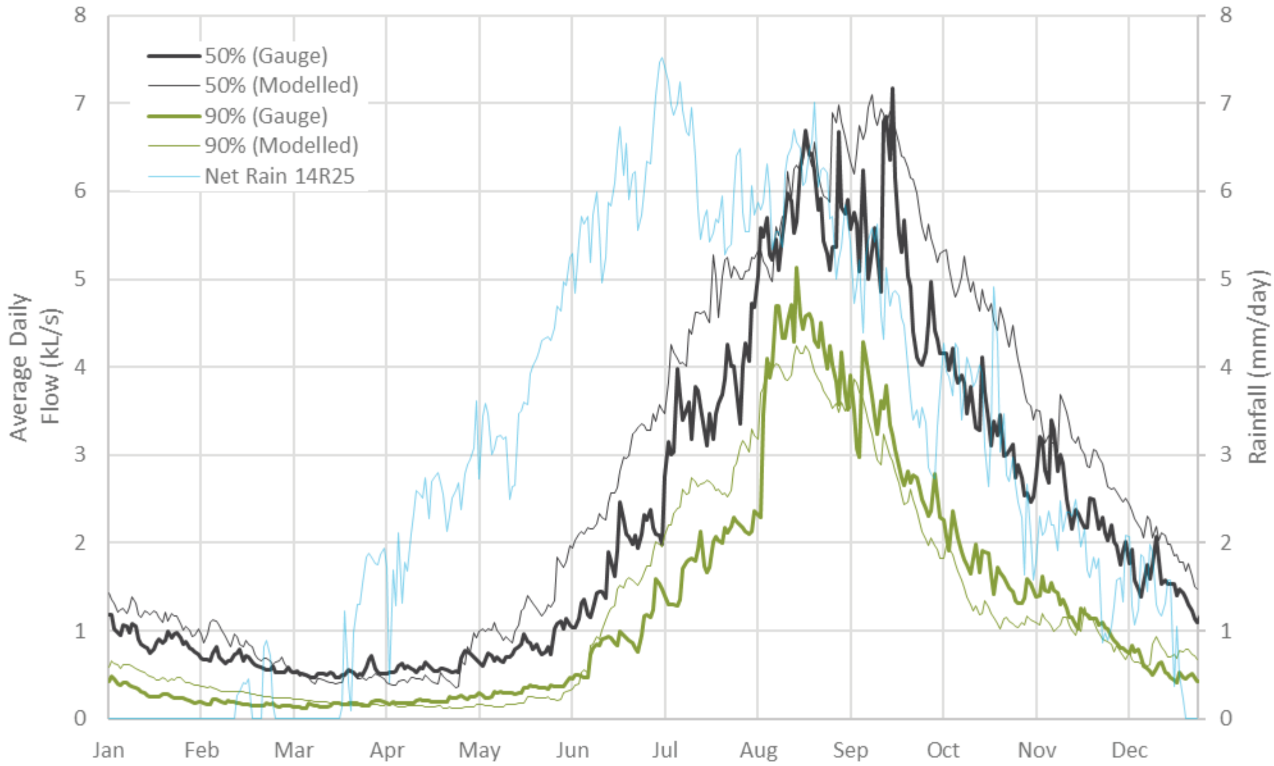


Figure 2.49 Comparison of Yarrangobilly Q-Lag analyses

2.7 Predictive modelling

The calibrated catchment model was used to investigate streamflow regimes for creek and river reaches within Tantangara Creek, Gooandra Creek, Nungar Creek, the Murrumbidgee River, Wallaces Creek, and the Yarrangobilly River at predetermined reporting sites (section 2.7.2).

Streamflow regimes were investigated for the following phases of the project:

- Pre-construction – a pre-construction simulation using the historical climate record from 1 Jun 1970–30 May 2019. This simulation describes the flow regime prior to any project impacts and provides a baseline against which other simulation can be compared;
- Construction – a set of simulations which considered the impacts of tunnel excavation during the 5.5 year construction period using average, wet and dry climate sequences from within the historical record from 1 Jun 1970–30 May 2019. These simulations were developed using transient baseflow discharge results from the groundwater model (section 2.7.5); and
- Operating – a post-construction simulation considering the long-term impact of operating the power waterway. This simulation uses the historical climate record from 1 Jun 1970–30 May 2019 and was developed using steady state baseflow discharge results from the groundwater model (section 2.7.6).

One construction/operation scenario was assessed reflecting the current project construction schedule, and using historical climate data inputs.

The groundwater model run identifiers, catchment model filenames and catchment model run identifiers used to simulate each phase of the project, are recorded in Table 2.12.

Table 2.12 Groundwater model run identifiers and catchment model filenames for each project phase

<table>
<tr><th>Project phase</th><th>Groundwater model run</th><th>Catchment model filename</th><th>Catchment model run</th></tr>
<tr><td>Pre-construction</td><td colspan="3">Model runs without project impacts are given in square brackets underneath corresponding model runs (ie using the same climatic conditions and simulation period)</td></tr>
<tr><td>Construction (average)</td><td>SH4.0_tpred11
[SH4.0_tpred10]</td><td rowspan="3">Snowy 2.0_M05_2019-08-12_Construction.rsproj</td><td>Construction – Average
[Preconstruction – Average]</td></tr>
<tr><td>Construction (wet)</td><td>SH4.0_tpred14
[SH4.0_tpred16]</td><td>Construction – Wet
[Preconstruction – Wet]</td></tr>
<tr><td>Construction (dry)</td><td>SH4.0_tpred15
[SH4.0_tpred17]</td><td>Construction – Dry
[Preconstruction – Dry]</td></tr>
<tr><td>Operating</td><td>SH4.0_sspred11b
[SH4.0_sspred10b]</td><td>Snowy 2.0_M05_2019-08-15_PreConstruction_Operating.rsproj</td><td>Operating
[Preconstruction]</td></tr>
</table>

2.7.1 Method for applying predicted baseflow impacts to the catchment model

In some catchments the groundwater drawdown was predicted to occur (ie reductions in the water table as a result of the project. In areas where streams were present, this also resulted in reductions to the available groundwater for baseflow also being predicted by the groundwater model. These catchments are illustrated in Figure 2.50, with groundwater drawdown seen to occur primarily in the Gooandra and Eucumbene catchments.

The impacts to baseflow predicted by the groundwater model on a quarterly (seasonal) time step were incorporated in the catchment model as a leakage rate from the groundwater store. The leakage rate was applied as a fixed rate through each season in temporal alignment with the groundwater model results. Leakage rates were only applied within model subcatchments substantially affected by groundwater drawdown as illustrated in Figure 2.50. The magnitude of the leakage rate was adjusted until the baseflow reduction achieved in the catchment model matched that predicted in the groundwater model.

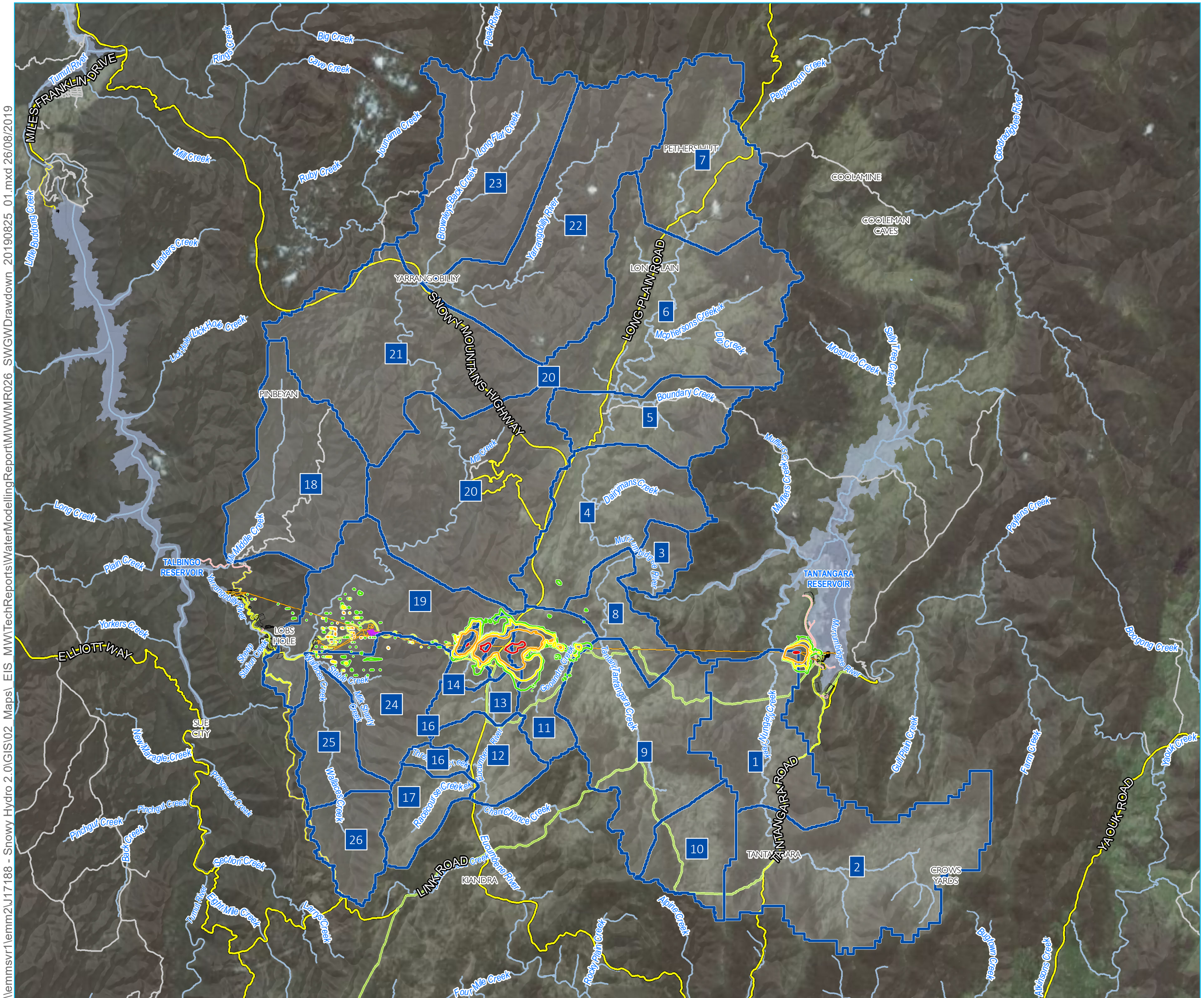
Baseflow reductions predicted by the groundwater model were applied in the catchment model using a 'leakage' term in the Modified SIMHYD rainfall runoff model (see Figure 2.15). This leakage term causes the Modified SIMHYD groundwater store to empty at a faster rate, which results in reduced baseflow.

The leakage rate was varied:

- spatially, so that the impacts to baseflow predicted by the groundwater model are applied within the appropriate sub catchments; and
- seasonally, in accordance with the groundwater model stress periods (construction phase only).

The leakage rate for each season and sub catchment was adjusted iteratively until the baseflow impact in the catchment model matched the baseflow impact predicted by the groundwater model. Where the groundwater model predicted very small reductions in baseflow (<5%); these impacts were not applied in the catchment model due to the levels of uncertainty inherent in the groundwater modelling and because very small reductions in baseflow did not produce measurable reductions in streamflow.

Further discussion of the baseflow loss method is supplied in Attachment B.5.



Source: *EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)*

0 2.5 5 km
GDA 1994 MGA Zone 55

\\emmsvr1\emm2\J17188 - Snowy Hydro 2.0\GIS\02_Maps_EIS_MW\TechReports\WaterModellingReport\MWWMR026_SWGWDrawdown_20190825_01.mxd 26/08/2019

KEY

Modelled drawdown (m)
- 5
- 10
- 20
- 50

Catchments

Snowy 2.0 Main Works operational elements
- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements
- Temporary construction compounds and surface works
- Temporary access road

Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

Surface water model sub-catchments and groundwater model steady state drawdown contours

Snowy 2.0
Modelling Report
Main Works
Figure 2.50

snowy 2.0

EMM creating opportunities

2.7.2 Reporting sites

Sub-catchments in the catchment model were delineated to allow reporting of streamflow results at locations (section 2.4.3):

- which coincided with the downstream end of groundwater model stream reaches;
- where manual flow measurements were taken; and
- at established streamflow gauge sites.

These locations are referred to as reporting sites and are shown in Figure 2.30, with coordinates given for these sites in Table 2.8.

Streamflow results are only presented for reporting sites with >5% reduction in baseflow predicted by the groundwater model. Groundwater modelling showed that key drawdown impacts were in the area within the Gooandra Volcanics, in the western section of the plateau and to a lesser extent in the Kellys Plain Volcanics in the eastern section of the plateau (Figure 2.50). Therefore, based on the groundwater model results, baseflow reductions were applied to sub-catchments in Gooandra Creek and the Eucumbene River and results are presented for reporting sites downstream of these sub catchments. These sites are listed and briefly described in the following sections.

i Gooandra Creek

Gooandra Creek is a located on the plateau in the upper reaches of the Murrumbidgee River catchment and is a tributary to Tantangara Creek. Within the catchment model, Gooandra Creek is represented by one sub catchment to which predicted baseflow reductions were applied.

Streamflow results are shown for the reporting site at the outlet of this sub catchment and for the reporting sites in the river reaches downstream of the Gooandra Creek sub catchment:

- Site 3 Gooandra Creek – upstream of the confluence with Tantangara Creek;
- Site 5 Tantangara Creek – downstream of the confluence with Gooandra Creek;
- Site 6 Tantangara Creek – upstream of the Murrumbidgee River confluence; and
- Murrumbidgee Gauge – on the Murrumbidgee River downstream of the confluence with Tantangara Creek.

ii Eucumbene River

The Eucumbene River is located on the plateau.

Based on results from the groundwater model, particularly drawdown contours produced using the groundwater model results (Figure 2.50), only the headwater catchments of the upper reach of the Eucumbene are predicted to be impacted by the tunnel excavation.

The upper reach of the Eucumbene refers to the river reach above the confluence with Racecourse Creek and is represented in the catchment model by four small sub catchments. Baseflow reductions predicted by the groundwater model were applied to the upstream two of these four sub catchments.

Streamflow results are shown for the reporting sites at the outlet of each of these four sub catchments:

- Site 10 Eucumbene River - upstream of Snowy Mountains Highway. This is a headwater catchment.;
- Site 9 - Unnamed watercourse downstream of Snowy Mountains Highway, upstream of its confluence with the Eucumbene River proper. This is a headwater catchment.;
- Site 11 Eucumbene River Culvert Logger – where the Eucumbene River crosses the Gooandra Trail; and
- Site 2 Eucumbene River – at Garden Gully confluence. This site is downstream of the confluences with Three Mile Creek and Racecourse Creek.

The catchment model domain does not include any reporting sites downstream of the upper reach of the Eucumbene River.

2.7.3 Result types

i No flow threshold

A 'no flow' threshold was applied to aid interpretation of modelled streamflow. Flows below the threshold are presented on hydrographs; however, zero flow was assumed to occur for modelled flows less than 0.1 ML/day (corresponding to approximately 1 L/s) in the calculation of statistics describing the streamflow regime.

The purpose of the no flow threshold is not to state definitively that streams cease to flow below this level, but rather to indicate that flows are very small and to reflect lower confidence in the ability of the catchment model to predict streamflow below this level.

Periods where there is no flow are an important ecological metric. Use of a no flow threshold provides clarity around the assessment and reporting of this metric.

ii Flow categories

River flow objectives are used by the NSW Government in the management of environmental flows and set out aspects of flow considered to be critical for the protection or restoration of river health, ecology and biodiversity. The aim of the objectives is to aid in improving river health by recognising the importance of natural river flow patterns (NSW Department of Environment, Climate Change and Water, 2006). Several flow categories are defined within the descriptions of the river flow objectives. The flow categories used in this analysis are:

- Very low flows: flows below the level naturally exceeded on 95% of all days with flow;
- Low flows: flows below the level naturally exceeded on 80% of all days with flow; and
- High flows: flows that are greater than the level naturally exceeded on 30% of all days with flow.

Flows falling between low flows and high flows are termed "medium flows" for reporting purposes.

For each reporting site, the flow category thresholds were calculated using the modelled pre-construction flow, over the full modelled period.

In addition to the flow categories listed, a "no flow" category was also assessed such that zero flow was assumed to occur for modelled flows less than 0.1 ML/day.

Flow categories relating to river height (eg freshes and floods) have not been used as river height is not a result produced by the surface water model. Freshes and floods are primarily driven by quickflow response to heavy rain, and so the frequency of freshes and floods is not likely to be affected by the predicted changes to baseflow.

iii Flow duration curves

Flow duration curves, also called probability of exceedance curves, are provided for each reporting site. They show the probability that a given streamflow will be exceeded on any given day and, conversely, they show the streamflow corresponding to a given probability of exceedance (ie, median streamflow). It is important to note that statistics relating to streamflow must be treated with caution as they only relate to the modelled (or measured) period and this does not reflect the full range of stream flows that could potentially occur at a location.

Flow duration curves do not have a time dimension. Therefore, seasonal flow duration curves are useful in providing information about the flow regime on a seasonal basis (eg to tie in with temporal ecological requirements).

iv Hydrographs

Daily hydrograph samples are provided for each reporting site to illustrate the impact of the tunnel excavation and operation of the power waterway on streamflow over time.

Through the construction period, hydrographs are shown for the chosen wet, dry and average climate sequences modelled as coinciding with the final two years of construction.

When reporting the impacts of the ongoing operation of the project, hydrographs are shown using 2006 climate data as the lowest yearly flow at the Murrumbidgee gauge was recorded in 2006, and this year thus highlights the impact of baseflow reduction on streamflow.

2.7.4 Pre-construction simulation

i Description

The pre-construction simulation represents the streamflow regime prior to any project impacts, with no changes to baseflow due to the tunnel excavation or operation of the power waterway. This simulation used the calibrated catchment model with no leakage term applied. The modelled period was 1 Jun 1970–30 May 2019, which coincides with the calibration period adjusted to include an equal number of each season.

The pre-construction simulation was used to produce inputs to the groundwater modelling process (Figure 1.2):

- a groundwater recharge dataset for input to the groundwater model; and
- a baseflow discharge dataset which was used to validate the calibration of the groundwater model.

The pre-construction simulation provides a baseline against which the operating and construction simulation were compared.

ii Results

a Gooandra Creek catchment

Annual flows (July to June) for the reporting sites in and downstream of Gooandra Creek are shown in Figure 2.51.

Annual flow varies significantly from year to year; at all sites, 2006 was the lowest flow year and 1974 the highest. Modelled results indicate lower than average flow conditions from 1997 to the present (2019), with only 5 out of 21 years having above average flow.

Site 3 has a modelled average flow of approximately 10 GL/year.

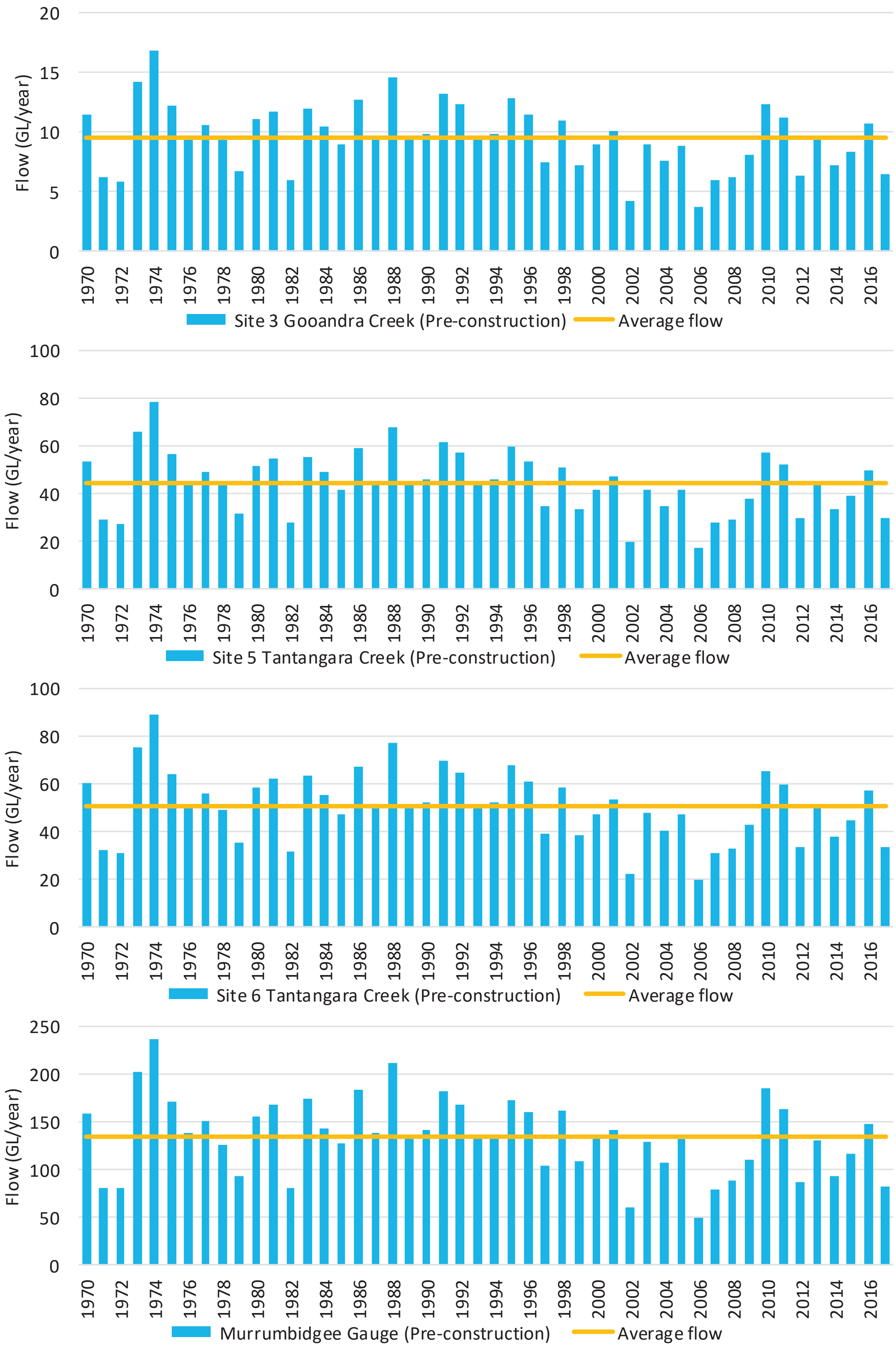


Figure 2.51 Annual stream flows (Gooandra Creek reporting sites)

Site 5 and Site 6 are relatively close together and have modelled average flows 4-5 times higher than those at Site 3 - 45 GL/year and 51 GL/year respectively. These sites are on Tantangara Creek downstream of the confluence with Gooandra Creek and include flows from the upstream Tantangara Creek catchment area.

The Murrumbidgee Gauge has a modelled average annual flow of 135 GL/year, an order of magnitude higher than flows in Gooandra Creek. Flows at this location include Tantangara Creek flows as well as flows from a large catchment area to the north of Tantangara Creek.

Seasonal streamflow are shown in Figure 2.52. For all sites, flows are higher and more variable in winter and spring, when localised precipitation peaks and accumulated snow melts. Flows are lower and less variable in summer and autumn, when climate conditions are drier and baseflows predominate.

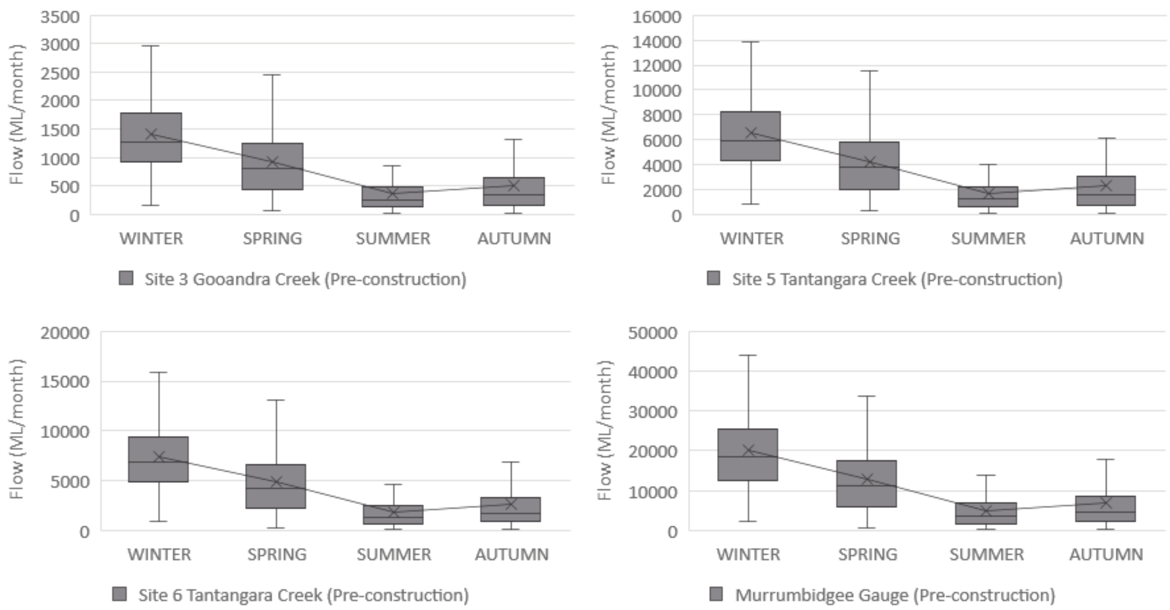


Figure 2.52 Seasonal stream flows (Gooandra Creek reporting sites)

Flow duration curves showing daily flows over the full modelled period for the Gooandra Creek reporting sites are shown in Figure 2.53.

Although Gooandra Creek is characterised as having a perennial flow regime (Annexure A of the water assessment), Figure 2.53 indicates that flows in Gooandra Creek (reporting site 3) fall below the no flow threshold of 0.1 ML/day on approximately 3% of modelled days. This indicates that the flow regime in at Site 3 is vulnerable to reductions in baseflow.

The shape of the flow duration curve is the same for these reporting sites (ie the curves are parallel) because the sub catchments use the same rainfall-runoff model and model parameters and rainfall does not vary significantly between them.

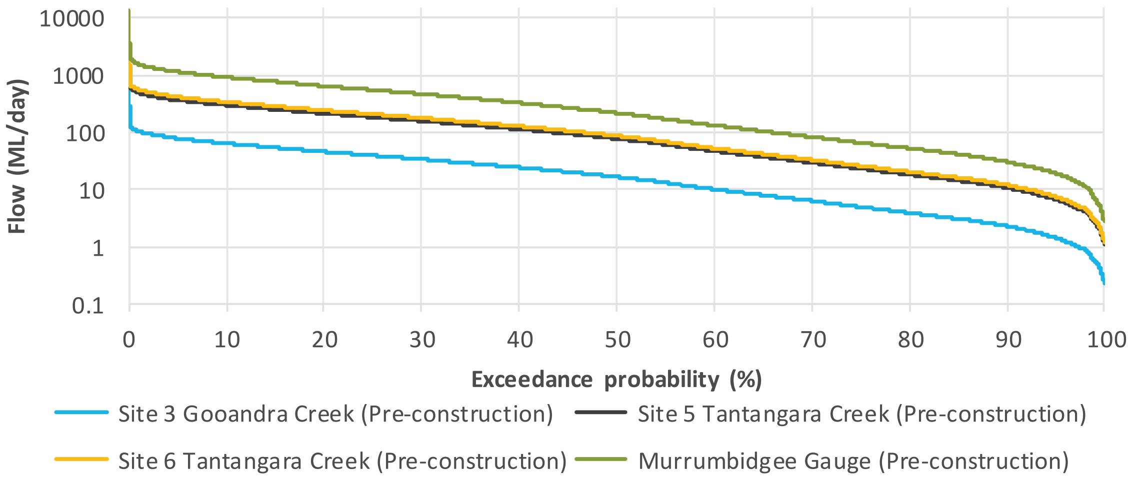


Figure 2.53 Modelled flow duration curves (Gooandra Creek reporting sites)

Flows corresponding to the flow categories described in section 2.7.3ii are given in Table 2.13 for the Gooandra Creek reporting sites.

These were determined using results over the full modelled period and were used to assess changes in the flow regime due to the tunnel excavation and operation of the power waterway.

Table 2.13 Flow categories for Gooandra Creek reporting sites (ML/day)

Flow category	Site 3 Gooandra Creek	Site 5 Tantangara Creek	Site 6 Tantangara Creek	Murrumbidgee Gauge
Very low flows[1]	1.4	6.7	7.6	19.4
Low flows[2]	3.9	18.3	20.7	53.1
High flows[3]	34.1	158.8	180.3	471.1

Note: 1. Flows below the level naturally exceeded on 95% of all days with flow
2. Flows below the level naturally exceeded on 80% of all days with flow
3. Flows that are greater than the level naturally exceeded on 30% of all days with flow

b Eucumbene River catchment

Annual flows (July to June) for the reporting sites in the Eucumbene River are shown in Figure 2.54.

Site 10 and Site 9 have modelled average flows of approximately 3 GL/year and 1.2 GL/year respectfully. These sites are at the outlet of headwater catchments with very small catchment areas (4 km^2 and 1.6 km^2).

Site 11 is on the Eucumbene River where the it crosses the Gooandra Trail. It has a modelled average flow of approximately 8.5 GL/year, which includes flows from Site 10 and Site 9.

Site 2 has a modelled average annual flow of 25 GL/year, including upstream flows in the Eucumbene and from Three Mile Creek and Racecourse Creek.

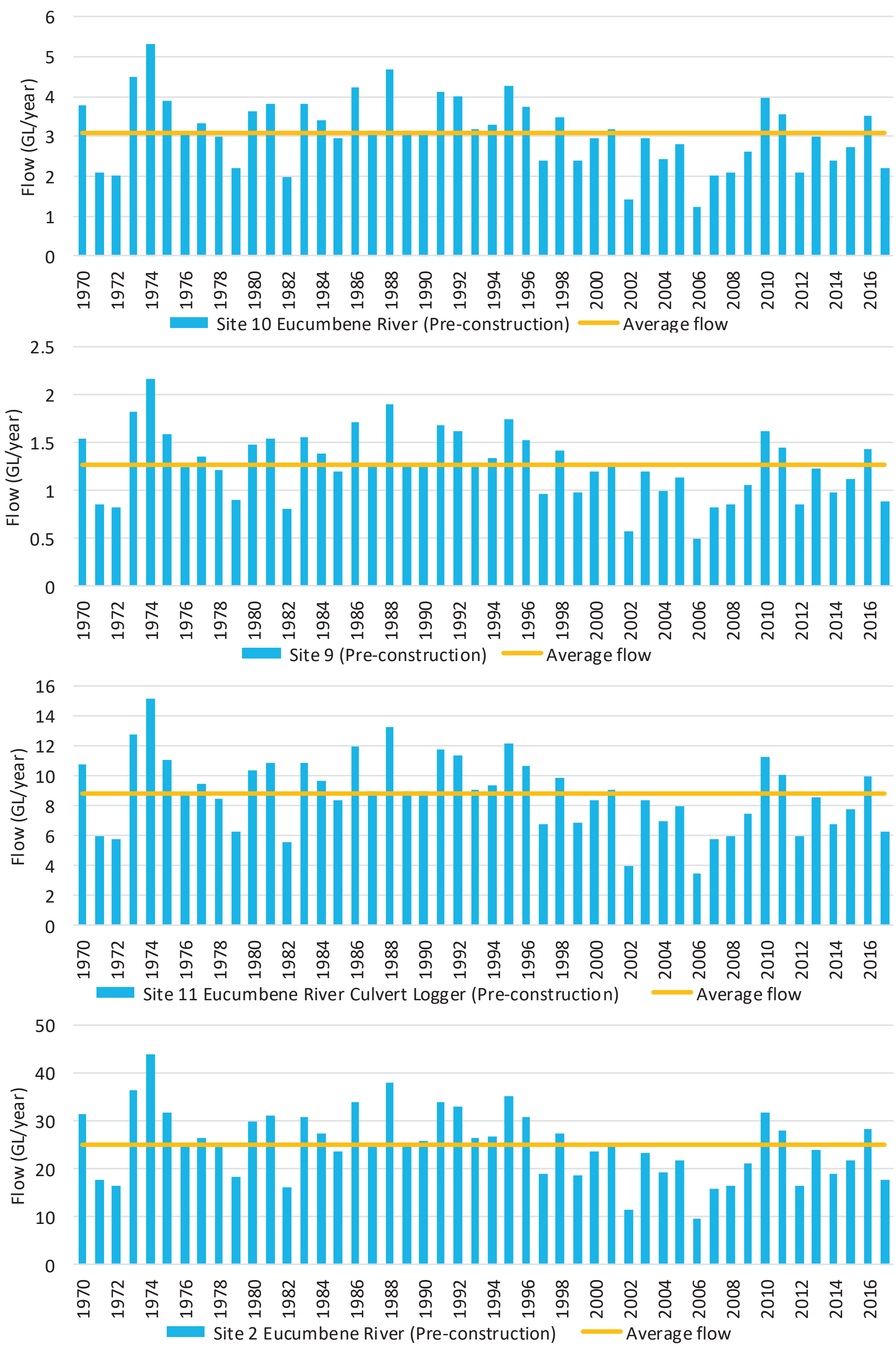


Figure 2.54 Annual stream flows (Eucumbene River reporting sites)

Seasonal streamflow are shown in Figure 2.55. For all sites, modelled flows are higher and more variable in winter and spring, when localised precipitation peaks and accumulated snow melts. Flows are lower and less variable in summer and autumn, when climate conditions are drier and baseflows predominate.

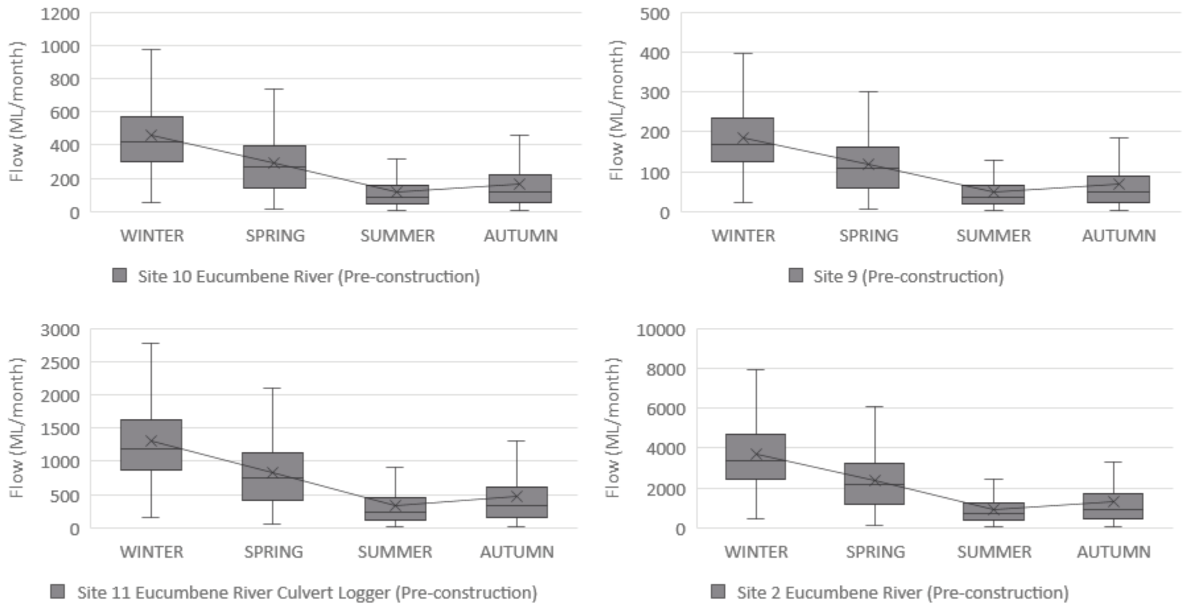


Figure 2.55 Seasonal stream flows (Eucumbene River reporting sites)

Flow duration curves showing daily flows over the full modelled period for the Eucumbene River reporting sites are shown in Figure 2.56.

Creeks in headwater catchments in the Eucumbene River upper reaches, which includes Site 10 and Site 9, are characterised as having a non-perennial flow regime (ie ephemeral). This is validated by the flow duration curves for these sites, which indicate that flows at Site 10 and Site 9 fall below the no flow threshold of 0.1 ML/day on approximately 14% and 32% of modelled days respectively.

Although the main channel of the Eucumbene River is characterised as having a perennial flow regime (Annexure A of the water assessment), Figure 2.56 indicates that modelled flows at Site 11 fall below the no flow threshold of 0.1 ML/day on approximately 3% of modelled days.

Modelled flows at Site 2 do not fall below the no flow threshold.

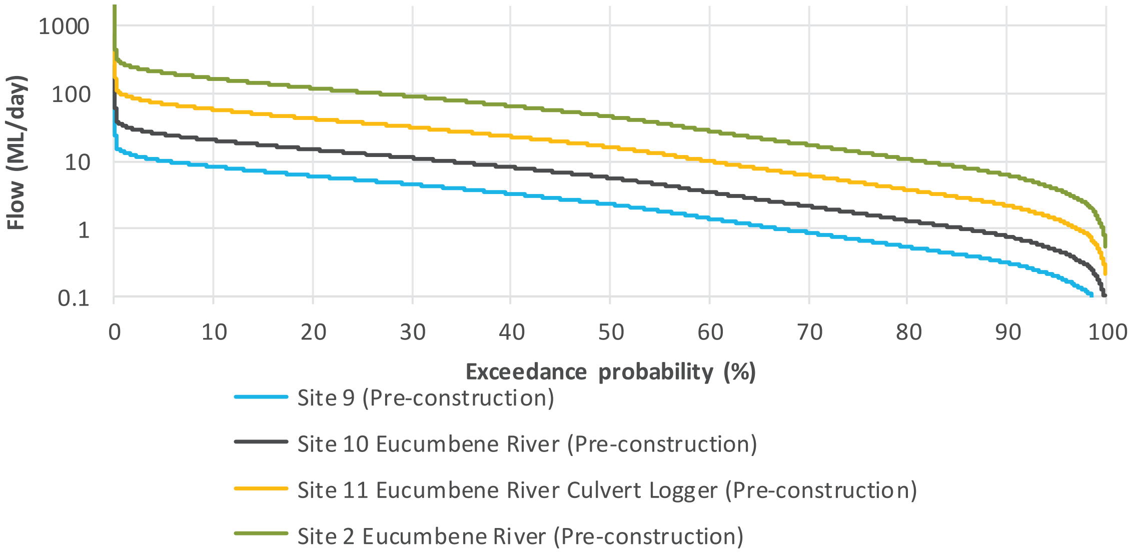


Figure 2.56 Modelled flow duration curves (Eucumbene River reporting sites)

Flows corresponding to the flow categories, described in section 2.7.3ii, are given in Table 2.14 for the Eucumbene River reporting sites.

These were determined using results over the full modelled period and were used to assess changes in the flow regime due to the tunnel excavation and operation of the power waterway.

Table 2.14 Flow categories for Gooandra Creek reporting sites (ML/day)

Flow category	Site 10 Eucumbene River	Site 9	Site 11 Eucumbene River	Site 2 Eucumbene River
Very low flows[1]	0.5	0.2	1.4	3.9
Low flows[2]	1.3	0.6	3.8	10.7
High flows[3]	11.2	4.6	31.9	90.9

Note: 1. Flows below the level naturally exceeded on 95% of all days with flow
2. Flows below the level naturally exceeded on 80% of all days with flow
3. Flows that are greater than the level naturally exceeded on 30% of all days with flow

2.7.5 Streamflow changes during construction

i Description

The power waterway, power station, and associated tunnels and shafts will experience groundwater inflow during construction (section 3.4.4i). As the actual climate that will occur during construction is unknown, possible impacts were assessed with the groundwater and catchment models using wet, average and dry climate sequences. The catchment model utilised the same climate sequences as the groundwater model.

The average, wet and dry climate sequences were chosen through an assessment of streamflow data recorded in the Murrumbidgee River (gauge 410535) (Figure 2.57).

The Victorian Government reports that recorded climate data throughout south-eastern Australia indicates that there may have been a 'climate step-change' around 1997 (Victorian Department of Environment, Land, Water and Planning, 2016, p. 6), and that utilising post-1997 climate data averages is appropriate for planning studies. Through the record period, the average yearly flow recorded at the gauge was 142 GL/year, while the post-1997 average yearly flow was 131 GL/year. The post-1997 average flow was used for this assessment. 'Average' rainfall conditions were simulated using climate data from December 2012 to December 2017. Through this period the average Murrumbidgee River flow was 127 GL/year, close to the post 1997 average of 131 ML/year. During this climate sequence there were high flows in 2015, and lower than average flows through the other years. Other possible 'average' historical climate sequences similarly feature a mixture of wet and dry years (Figure 2.57).

'Wet' rainfall conditions were simulated using climate data from December 1988 to December 1993. Through this period the average Murrumbidgee River flow was 188 GL/year, and each year experienced above average flow. This climate sequence includes 1990, during which year extensive flooding occurred in NSW.

'Dry' climate conditions were simulated using climate data from December 2001 to December 2006. Through this period the average Murrumbidgee River flow was 96 GL/year. Four of these years experienced lower than average streamflow, and one year experienced above average streamflow. This climate sequence includes the driest years of the Millennium Drought.

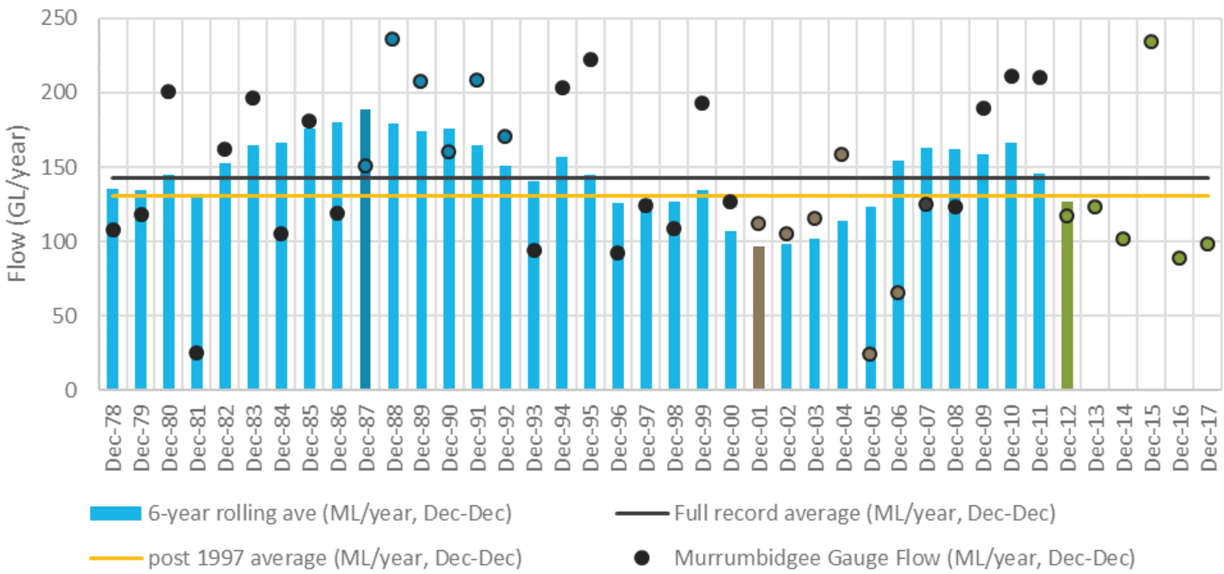


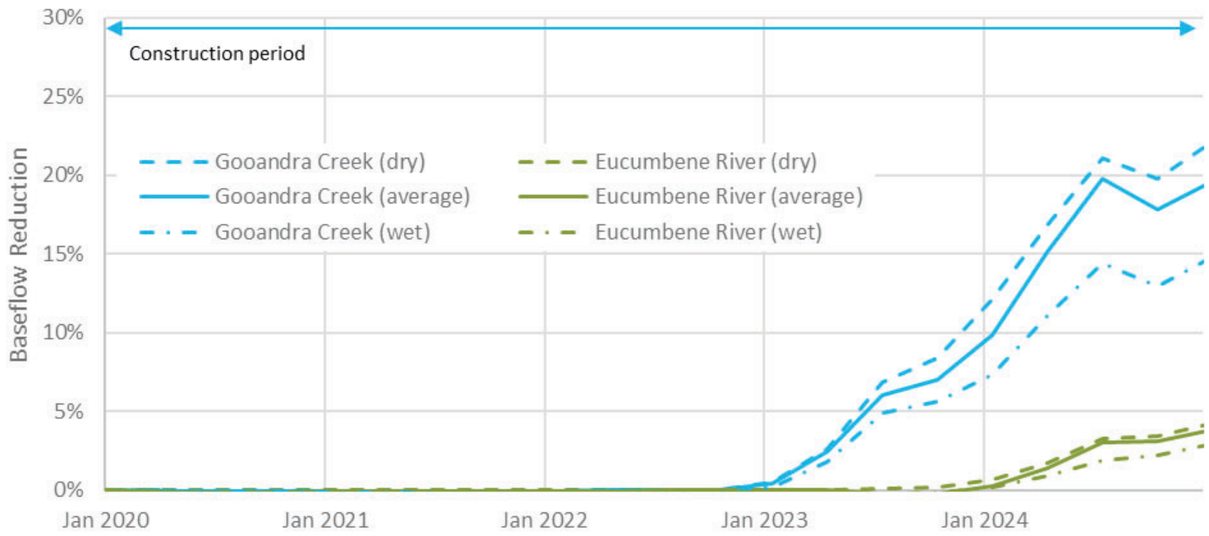
Figure 2.57 Murrumbidgee River (410535) total yearly and average 6 yearly flow (average of following years)

The quarterly (seasonal) baseflow losses predicted by the groundwater model were used to select 'groundwater leakage' rates for each catchment model subcatchment for each quarter. Leakage rates were selected such that the resulting baseflow reduction percent in the catchment model closely matched the baseflow reduction percent predicted by the groundwater model.

The groundwater model predicted that impacts to creek and river baseflow would develop over time, with the largest impacts to stream baseflow seen after construction is complete. Baseflow reduction due to tunnelling and excavation works during the construction period was predicted in Gooandra Creek and the headwaters of the Eucumbene River. The timing of the baseflow reduction will depend on the project schedule, as drawdown impacts are predicted to peak after the tunnel excavation reaches the Gooandra Volcanics, which occur in the vicinity of Gooandra Creek and the Eucumbene River headwaters. If no delays to schedule occur, Gooandra Creek baseflow reduction could begin during year 4 of construction, and Eucumbene River baseflow reductions could begin in year 5 of construction (Figure 2.58).

The catchment model contains several Eucumbene River subcatchments. A groundwater leakage term was applied only within the Eucumbene River head water subcatchments (model sub catchments 14 and 15) as these are located within the extent of predicted groundwater drawdown.

The groundwater model predicted that, during construction, Gooandra Creek baseflow may decline by up to 20%. Baseflow for the portion of the Eucumbene River contained within the model domain was predicted to decline by up to 5%. Impacts were predicted to be still developing at the end of the construction period (Figure 2.58). Long-term (steady state) impacts are presented in section 2.7.6.



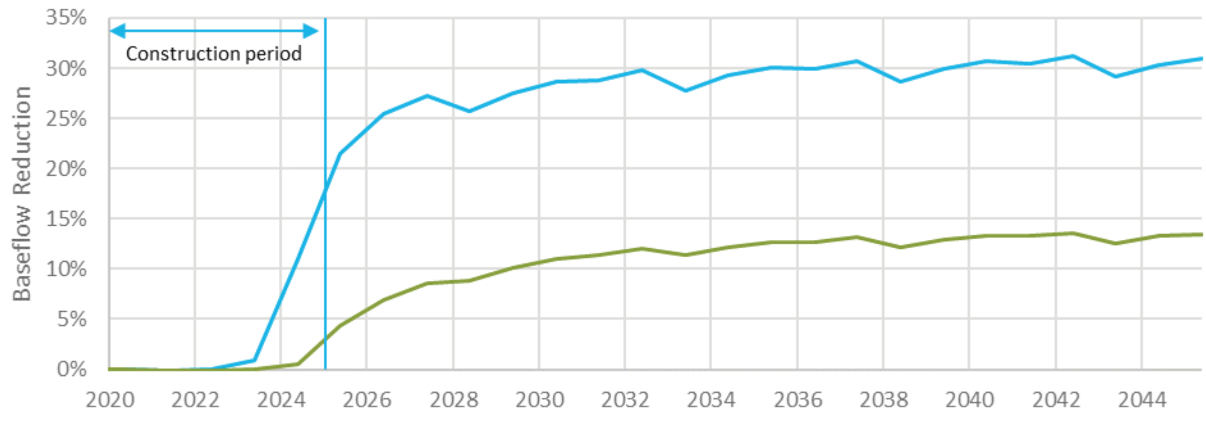


Figure 2.58 Baseflow reduction predicted by the groundwater model during project construction

The predicted declines in baseflow were modelled in the catchment model using the groundwater leakage term, with leakage rates at the end of the construction period approaching 0.08 mm/day in both the Gooandra Creek and Eucumbene River head water catchments (Figure 2.59). A steadily increasing leakage rate was utilised as the impacts of tunnelling works will increase as the excavation progresses.

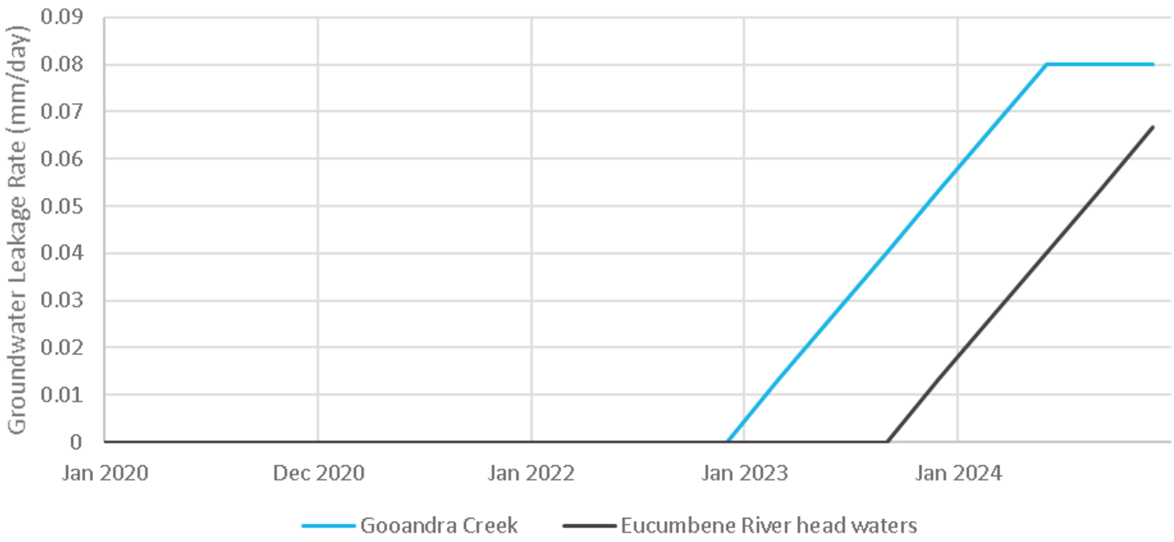


Figure 2.59 Groundwater leakage rate applied during construction years in the catchment model

ii Results

No impacts to baseflow due to tunnel excavation were predicted within creek catchments other than Gooandra Creek and the Eucumbene River north of the Snowy Highway.

The baseflow reduction in Gooandra Creek during the excavation of the power waterway is expected to cause no discernible changes to streamflow through winter months (Figure 2.60 to Figure 2.62). During March–April in the final two years of excavation baseflow reduction may result in cease to flow within the Gooandra Creek catchment if the those construction years coincide with dry climate conditions (Figure 2.62).

Within the Eucumbene River, baseflow reduction during the construction period is expected to cause no discernible changes to streamflow. Streamflow hydrographs for the modelled climate sequences are presented for sites 9, 10, and 11 within the Eucumbene River catchment in Attachment D.

Inflows to the tunnel excavation are predicted to increase markedly during the groundwater model year 2023, rising by approximately 100 L/s when the tunnel encounters the Gooandra Volcanics and then stabilising in 2024 (Figure 3.48). Through the final quarter of construction, the baseflow impacts within the Gooandra and Eucumbene catchments were estimated to be in the order of 40 L/s, significantly less than the tunnel inflows. Impacts to baseflow within the Gooandra Creek catchment and within the Eucumbene River catchment upstream of Gooandra Track were predicted to increase over the final years of the construction period (Figure 2.58), indicating a lag between the greatest tunnel inflow occurring and the greatest baseflow impacts. The peak change in baseflow is expected to occur following completion of the project, discussed in section 2.7.6.

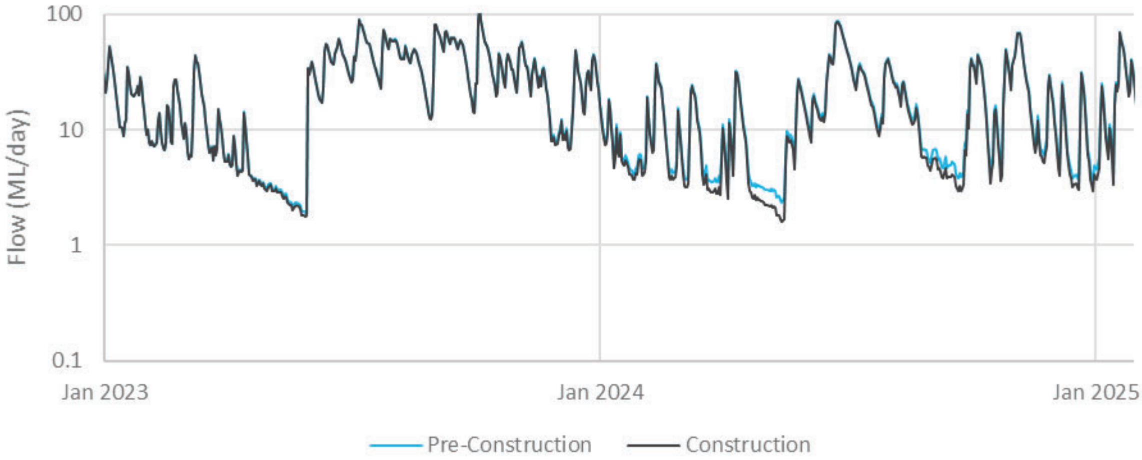


Figure 2.60 Modelled Gooandra Creek flow during the final two years of the construction period using a 'wet' climate sequence

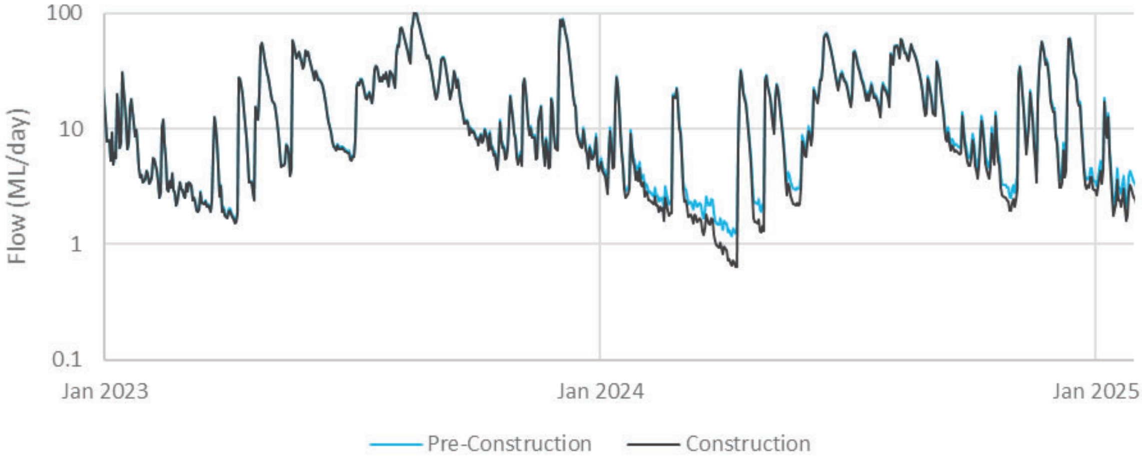


Figure 2.61 Modelled Gooandra Creek flow during the final two years of the construction period using an 'average' climate sequence

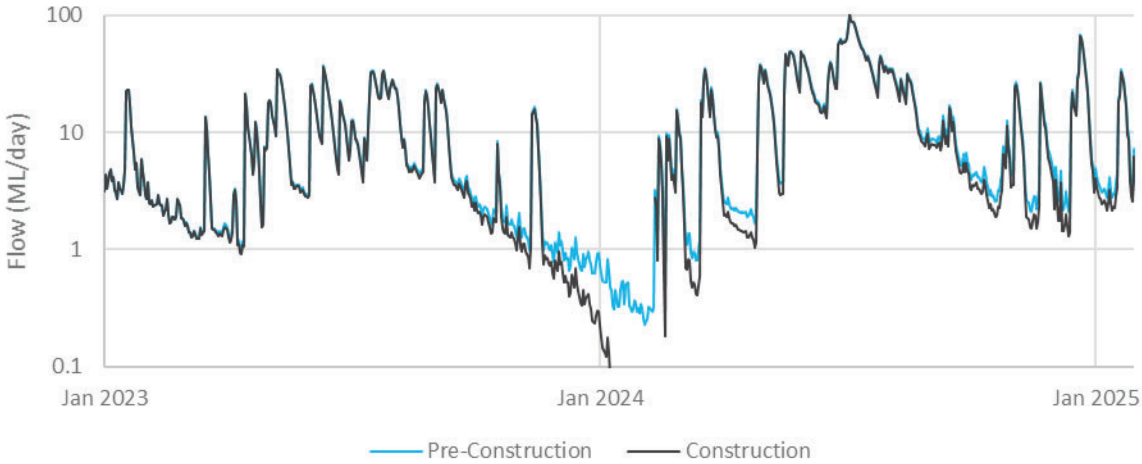


Figure 2.62 Modelled Gooandra Creek flow during the final two years of the construction period using a 'dry' climate sequence

2.7.6 Streamflow changes during operation

i Description

The long-term impact of tunnel excavation and operation of the power waterway was modelled using the results of the steady state groundwater model (groundwater model run: 'SH4.0_sspred11b'). This simulation represents the streamflow regime with permanent reductions to baseflow.

The model period was 1 Jun 1970–30 May 2019, which is the same modelled period as for the pre-construction simulation (to allow for comparison).

Baseflow reductions predicted by the groundwater model for the river reaches named in Figure 2.63 are given in Table 2.15. Reductions of less than 5% were not modelled in the catchment model; therefore, impacts were only applied to Gooandra Creek and Eucumbene River.

Based on inspection of the drawdown contours produced using the groundwater model results (Figure 2.50), only the two headwater catchments of the upper reach of the Eucumbene are predicted to be impacted by the tunnel excavation.

Table 2.15 Baseflow reductions during operation of the power waterway

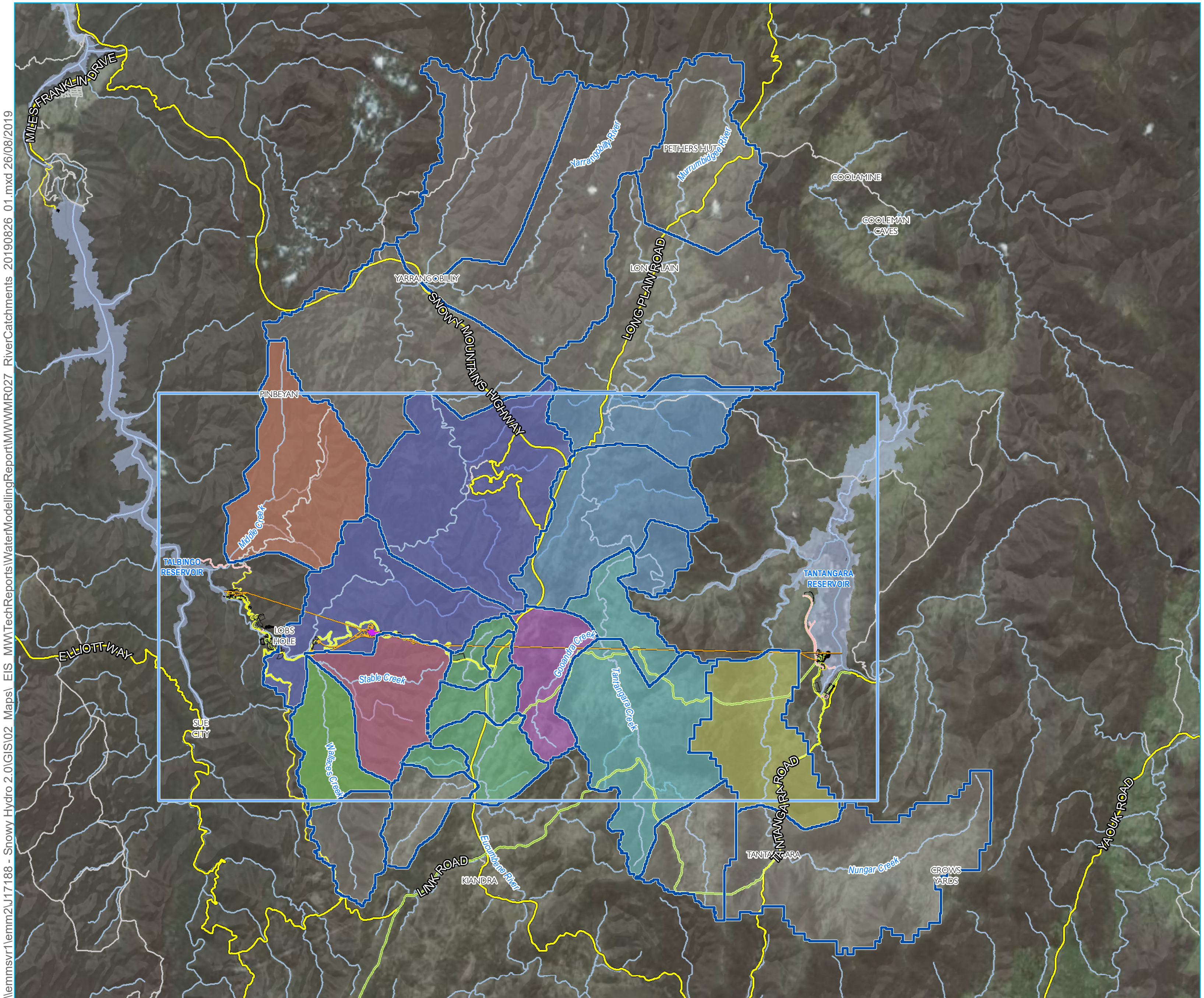
Middle Creek	Yarrangobilly River	Wallaces Creek	Stable Creek	Eucumbene River	Murrumbidgee River	Tantangara Creek	Gooandra Creek	Nungar Creek
0.1%	2.9%	0.5%	2.8%	12.5%	0.3%	1.5%	28.8%	0.9%

A constant rate was used for the leakage rate in each sub-catchment as the groundwater model water budget showed relatively constant rates of flow to the tunnel (Table 3.5).

Leakage rates for each sub catchment were determined by iterative adjustment until the baseflow impact in the catchment model over the modelled period 2007–2012 matched the baseflow impact predicted by the groundwater model for each region. The period 2007–2012 was used because it was the same period as climate inputs used in the steady state groundwater model run. The leakage rates applied are recorded in Table 2.16.

Table 2.16 Leakage rates during operation of the power waterway

	Gooandra Creek	Eucumbene River	
	Upstream of Site 3 Catchment 11	Upstream of Site 9 Catchment 14	Upstream of Site 10 Catchment 15
Leakage rate (mm/day):	0.21	0.46	0.46



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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

Reach
- Eucumbene River
- Gooandra Creek
- Middle Creek
- Murrumbidgee River
- Nungar Creek
- Stable Creek
- Tantangara Creek
- Wallaces Creek
- Yarrangobilly River
- Surface water catchments
- Groundwater model domain

Snowy 2.0 Main Works operational elements
- Tunnels, portals, intakes, shafts
- Power station
- Utilities
- Permanent road

Snowy 2.0 Main Works construction elements
- Temporary construction compounds and surface works
- Temporary access road

Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

River catchments within the groundwater model domain

Snowy 2.0

Modelling Report

Main Works

Figure 2.63

snowy 2.0

EMM creating opportunities

ii Results

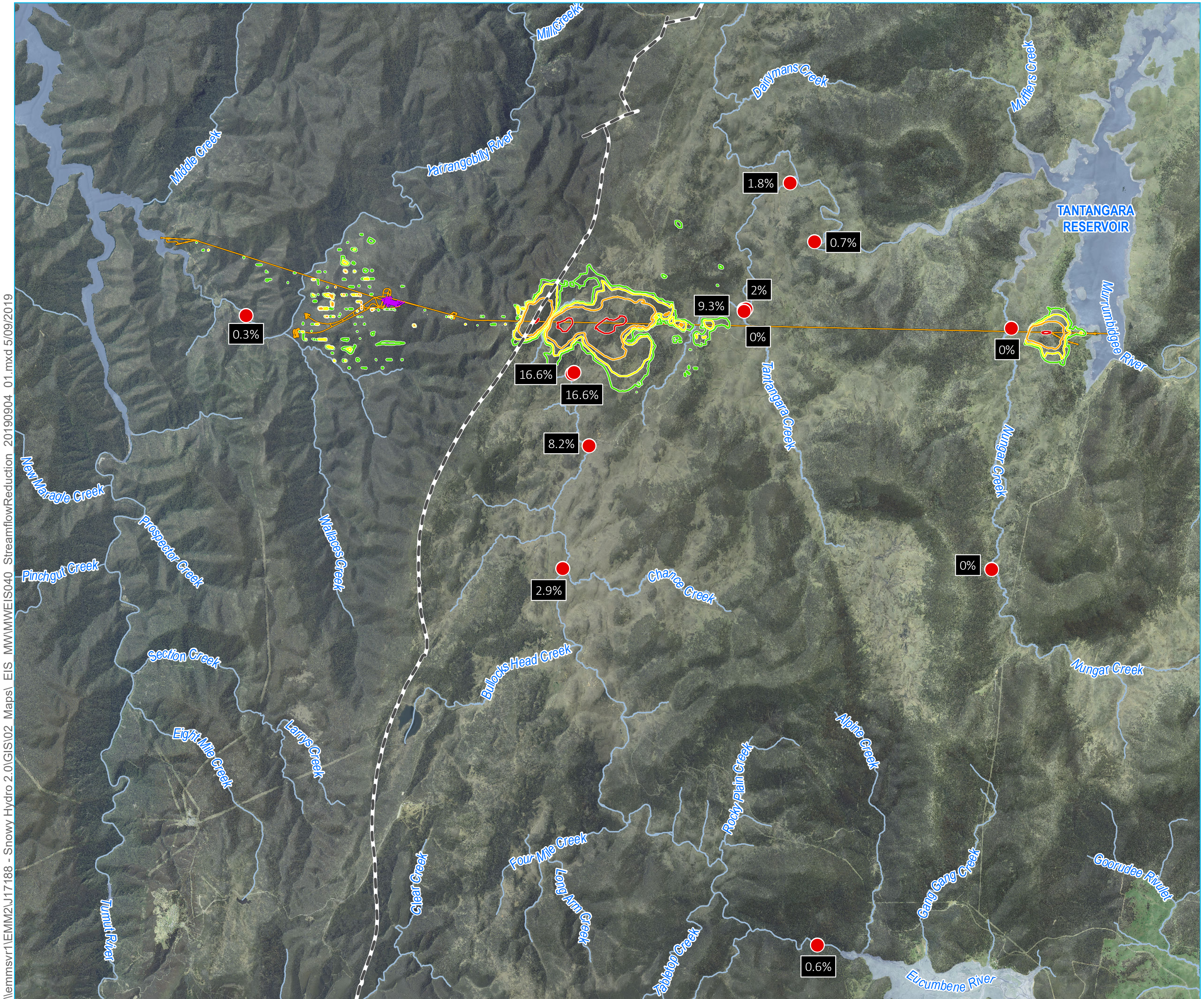
Baseflow reductions caused by the tunnel excavation and operation of the power waterway are expected to have a noticeable impact on the streamflow regime;

- in smaller headwater catchments, as:
  - reduced baseflow may lead to cease-to-flow conditions during dry periods; and
  - these catchments do not benefit from flow from unaffected catchment areas further upstream;
- during summer and autumn, when climate conditions are drier and baseflows are a large part of the total flow.

Predicted reductions in total and seasonal streamflow over the full modelled period (1 Jun 1970–30 May 2019) are given in Table 2.17 for the reporting sites. The average yearly streamflow reductions are illustrated in Figure 2.64. Figure 2.64 also includes the estimated total streamflow reduction at the Eucumbene River gauge 222522 which lies outside the model domain based on the streamflow recorded at that gauge and the magnitude of baseflow loss the models predicted within the catchment upstream.

Table 2.17 Predicted reduction in streamflow (yearly average and by season)

	Gooandra Creek reporting sites				Eucumbene River reporting sites			
	Site 3	**Site 5**	**Site 6**	**Murrumbidgee Gauge**	**Site 10**	**Site 9**	**Site 11**	**Site 2**
Average	-9.3%	-2.0%	-1.8%	-0.7%	-16.6%	-16.6%	-8.2%	-2.9%
Summer	-18.4%	-3.9%	-3.5%	-1.3%	-32.2%	-32.4%	-15.9%	-5.6%
Autumn	-13.3%	-2.9%	-2.5%	-1.0%	-19.6%	-19.6%	-9.7%	-3.4%
Winter	-5.9%	-1.3%	-1.1%	-0.4%	-10.8%	-10.8%	-5.3%	-1.9%
Spring	-8.9%	-1.9%	-1.7%	-0.6%	-17.7%	-17.7%	-8.7%	-3.0%



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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY
- Reporting points

Modelled drawdown (m)
- 5
- 10
- 20
- 50
- Long Plain Fault

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station
- Perennial watercourse
- Scheme storage

Long term total streamflow reduction

Snowy 2.0
Water modelling report
Main Works
Figure 2.64

snowy 2.0

EMM creating opportunities

a Gooandra Creek catchment

Hydrographs for the reporting sites in Gooandra Creek catchment (for 2006, the lowest flow year on record) are shown in Figure 2.65.

Site 3 on Gooandra Creek shows the largest predicted impact on streamflow. Peak flows are reduced, and long periods of “no flow” can be observed in the operating phase hydrograph.

For Site 5 and Site 6 on Tantangara Creek, the predicted impact of the operation and the reduction of baseflows in the upstream Gooandra Creek catchment is much less pronounced and is barely discernible on the hydrograph as the flows from the upstream Tantangara Creek catchment area were not predicted to experience baseflow reduction.

At the Murrumbidgee gauge, the predicted impact is further reduced due to the flows from the large catchment area of the Murrumbidgee to the north. The impact of operation on stream flows is barely discernible on the hydrograph at the Murrumbidgee gauge.

Approximately 4.5 km of Gooandra Creek immediately upstream of the confluence with Tantangara creek is expected to be impacted by baseflow reduction due to groundwater drawdown (Figure 2.50).

Total and seasonal flow duration curves for Gooandra Creek reporting site 3 are show in Figure 2.66 and Figure 2.67. Flow duration curves are not shown for the other reporting sites (Site 5, Site 6 and Murrumbidgee Gauge) because impacts are too small to be visualised in this format (indicating that impacts would be effectively impossible to discern from the measured streamflow data).

The flow duration curves for Site 3 show that the low flow regime is most affected by the reduction in baseflow. Where the curve for the pre-construction case showed a perennial flow regime, the curve for the operating case shows the low flow portion of the curve dropping off sharply, with 10% of modelled days below the no flow threshold. This indicates a shift to a more ephemeral flow regime for this site; particularly in Summer and Autumn. Seasonal flow duration curves for Winter and Spring showed a much less pronounced increase in no flow days.

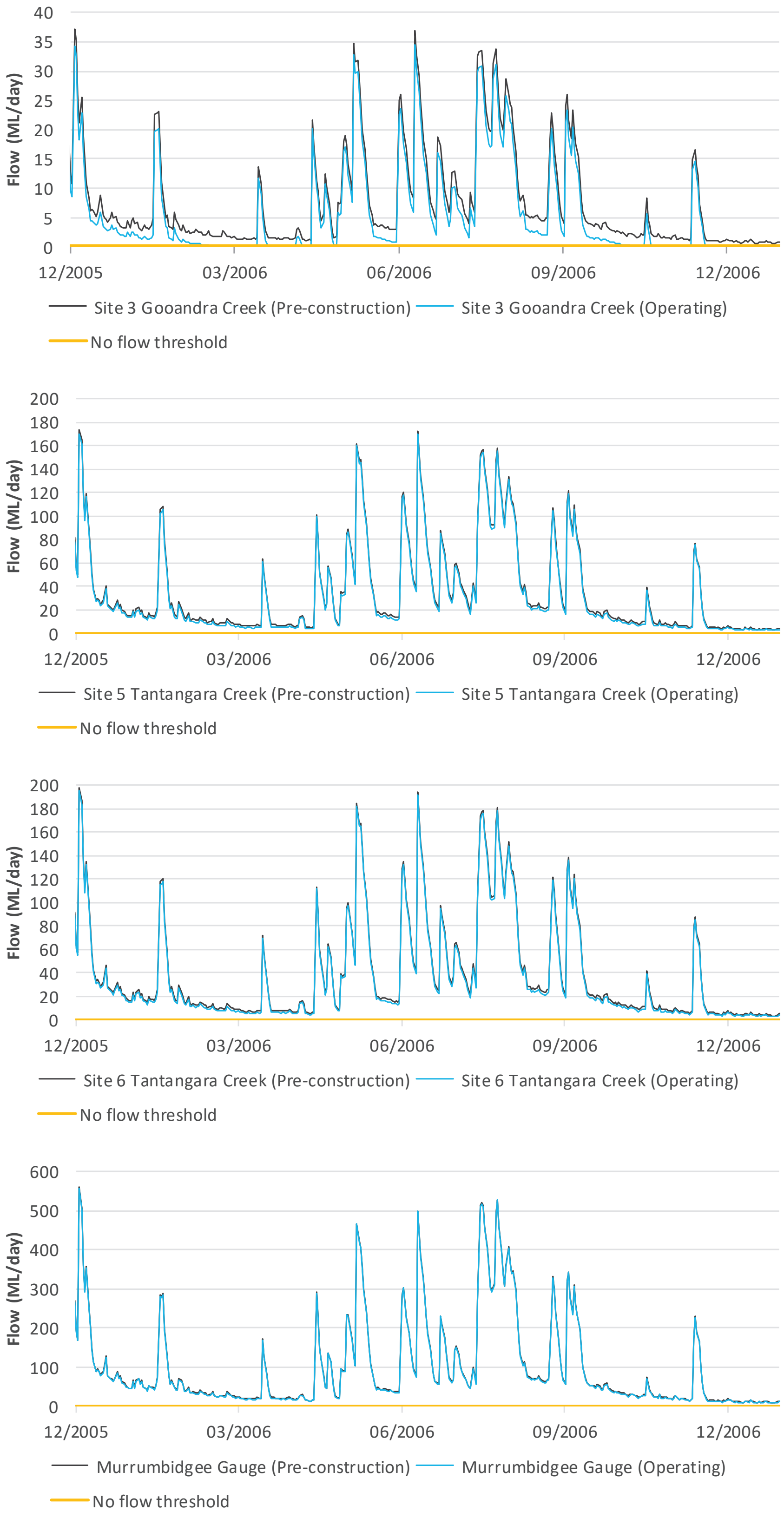


Figure 2.65 Operation phase: hydrographs for the Gooandra Creek reporting sites

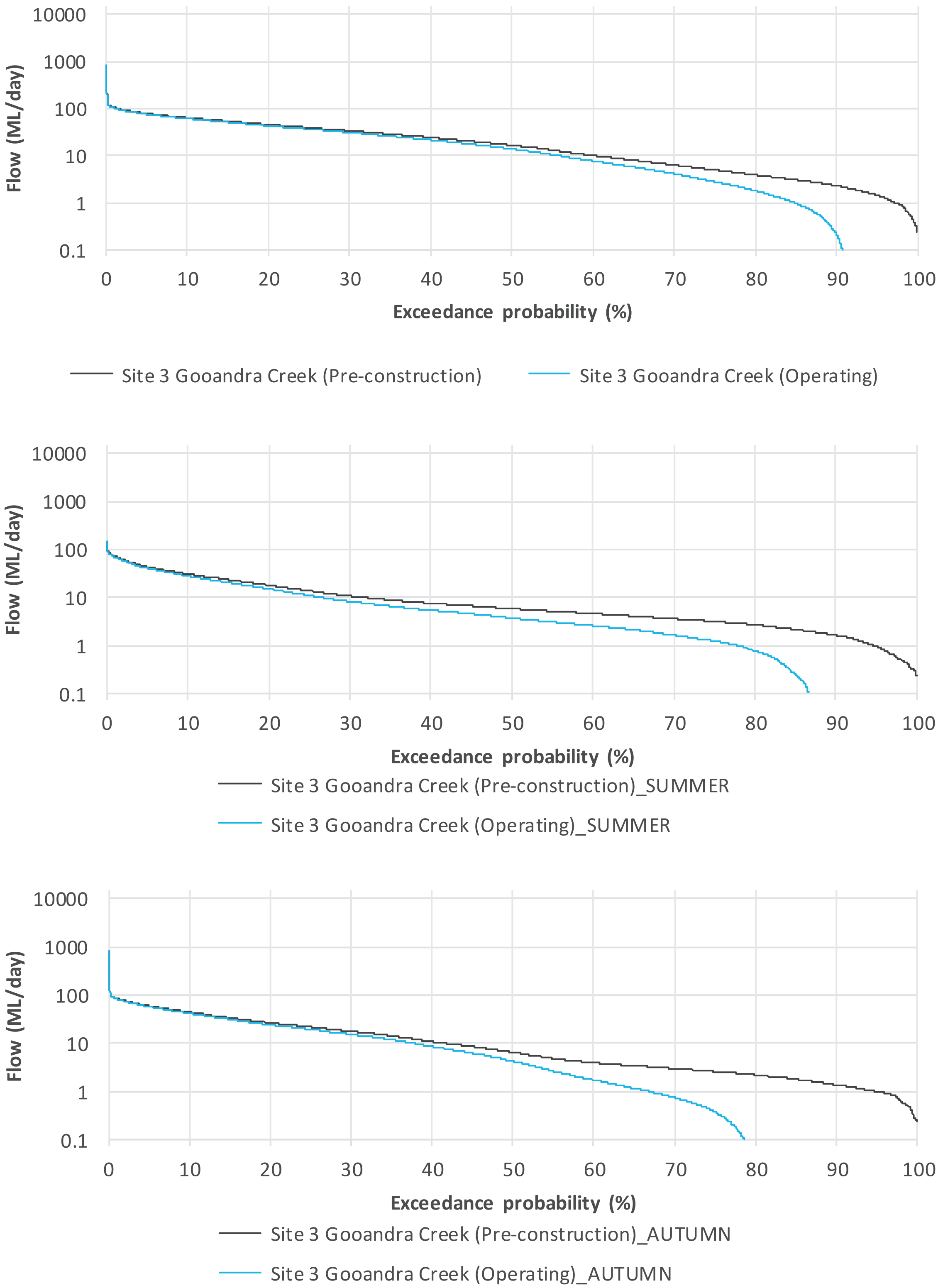
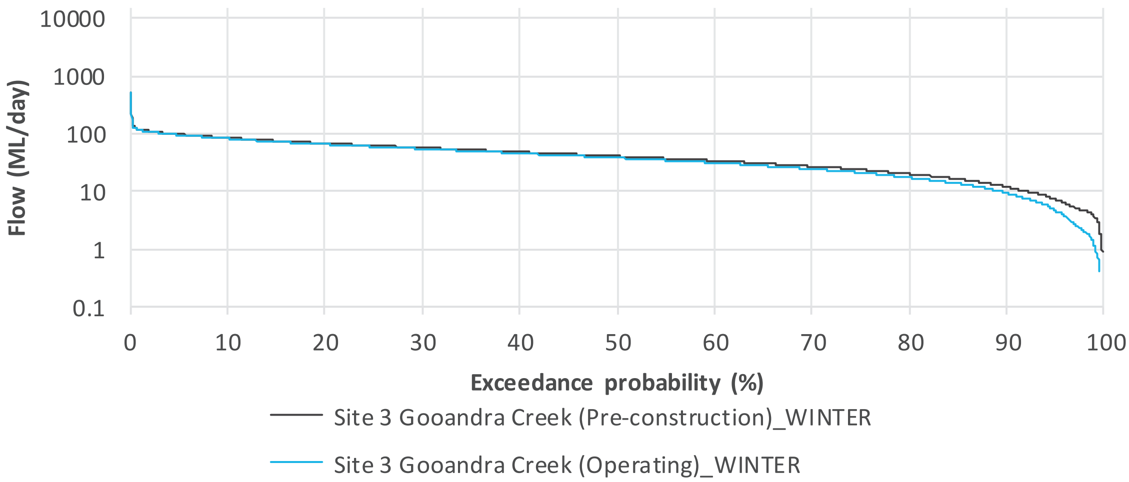


Figure 2.66 **Operation phase: flow duration curves for Gooandra Creek reporting site, Site 3 (Total, Summer and Autumn)**



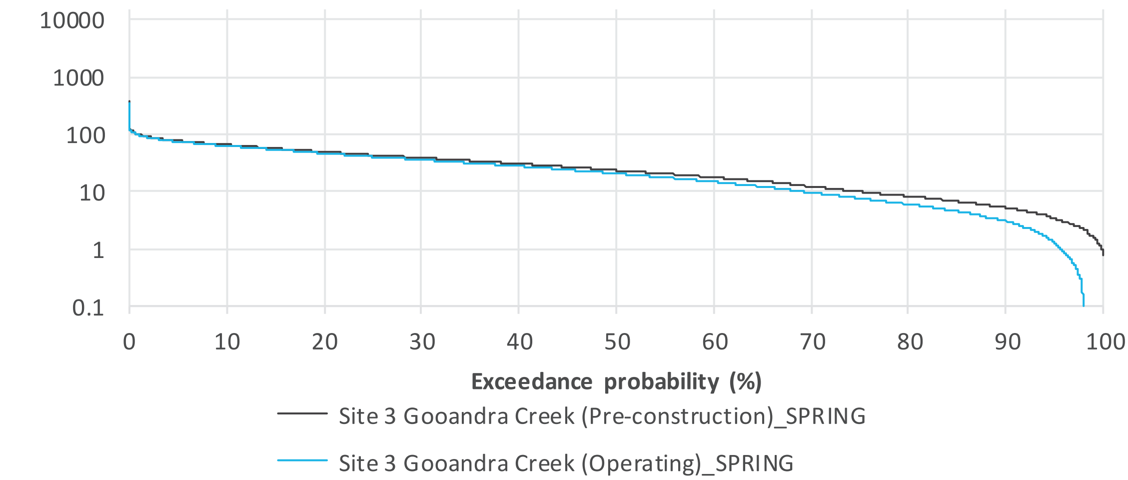


Figure 2.67 Operation phase: flow duration curves for Gooandra Creek reporting site, Site 3 (Winter and Spring)

Using the flow categories determined using the modelled pre-construction flow data for each reporting site (section2.7.4ii), the percentage of modelled days within each flow category was plotted on a histogram to show how the flow regime is expected to change.

For example, at Site 3, 7% of summer flows are “low flows”. During operation of the project, 11% of summer flows are “low flows”.

This analysis was undertaken over the full modelling period for all flows at each reporting site (Figure 2.68) and seasonally at each reporting site (Figure 2.69 to Figure 2.72). This analysis indicates that during operation phase of the project:

- Gooandra Creek will change from having a perennial streamflow regime to being ephemeral (days with ‘no flow’ increase from 0% to 9% at Site 3). This impact does not continue downstream, as flows from Tantangara Creek reduce the impact (days with ‘no flow’ remain at 0% at Site 5, Site 6 and Murrumbidgee Gauge);
- days with no flows and very low flows increase at Site 3, particularly in Summer and Autumn. The number of days with low, medium and high flows decrease correspondingly;
- for Site 5, Site 6 and the Murrumbidgee Gauge, the number of days with very low flows increases, particularly in summer and autumn; and
- in winter and spring, days with medium and high flows predominate and there is little change. Therefore, results are only shown for Site 3 for Winter and Spring.

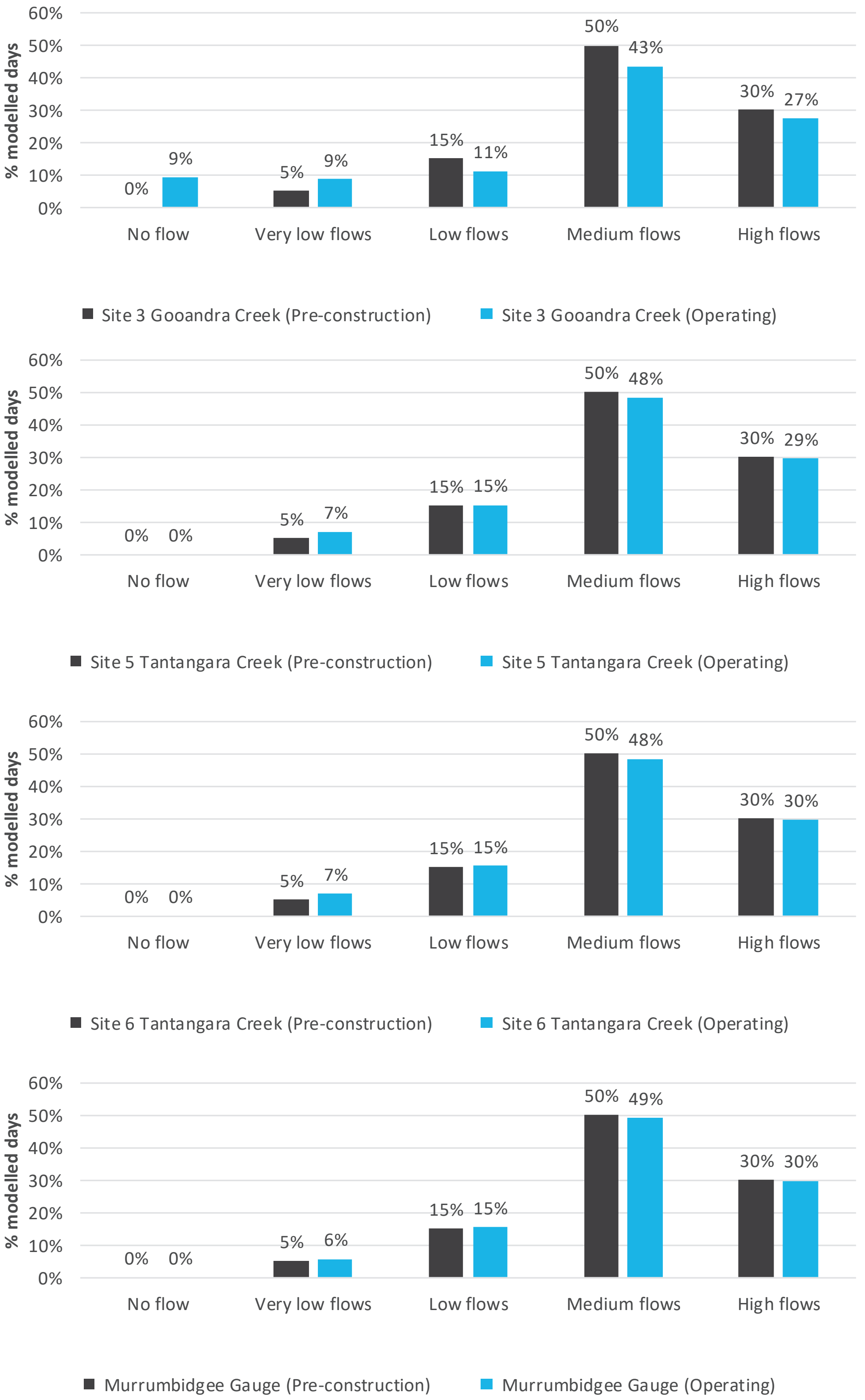


Figure 2.68 Percentage of days in each flow category (Gooandra Creek reporting sites)

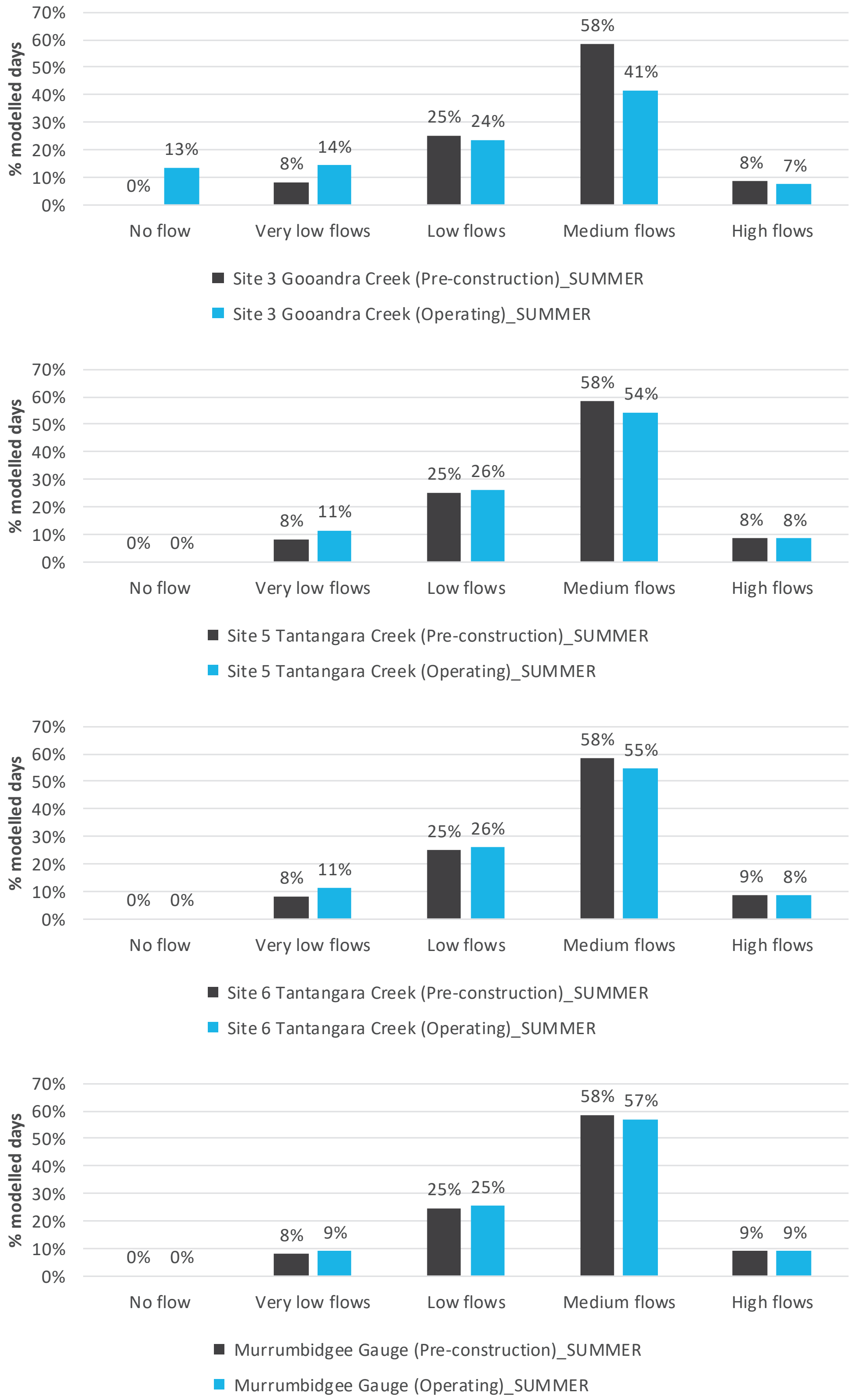


Figure 2.69 Percentage summer days in each flow category (Gooandra Creek reporting sites)

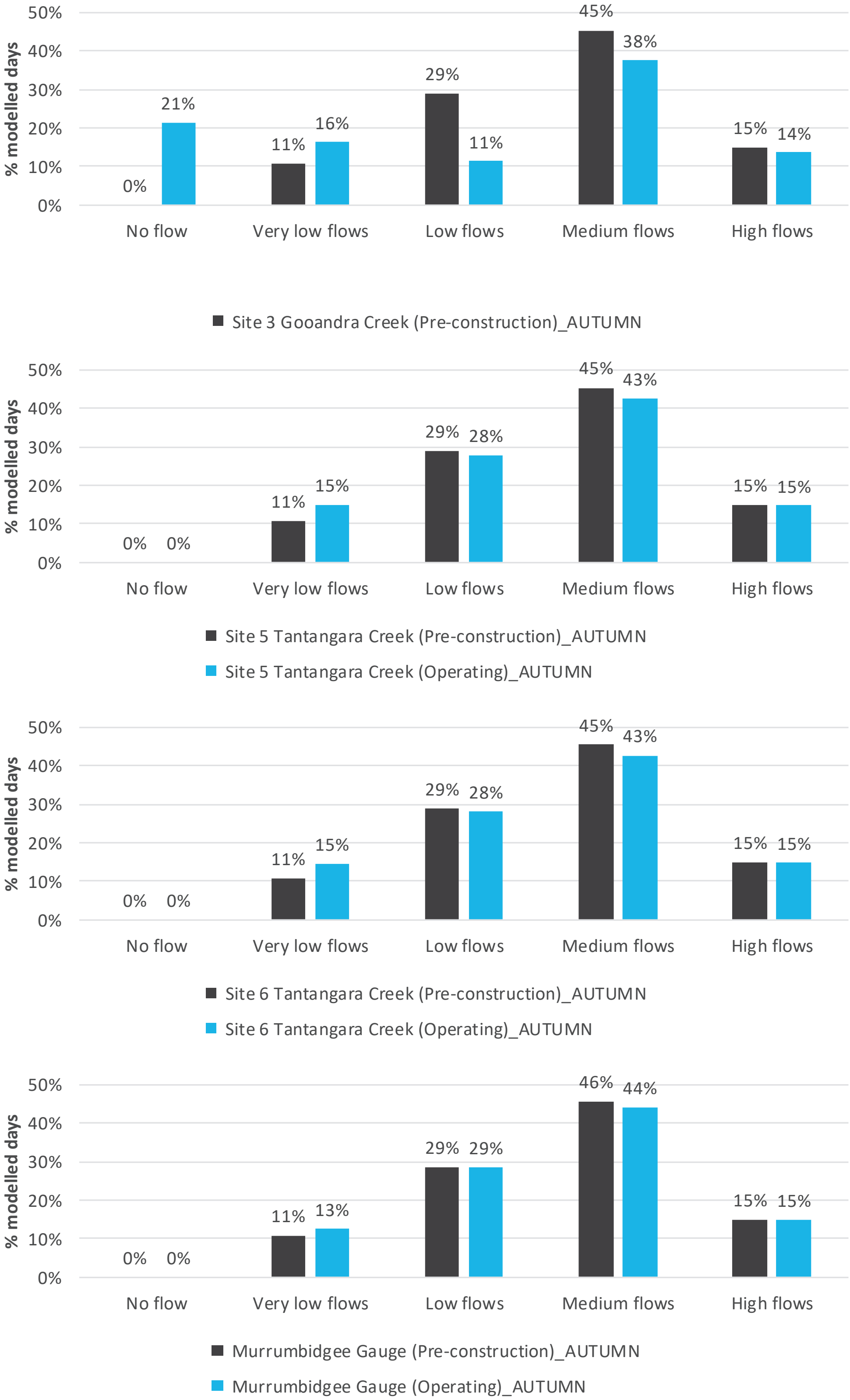


Figure 2.70 Percentage autumn days in each flow category (Gooandra Creek reporting sites)

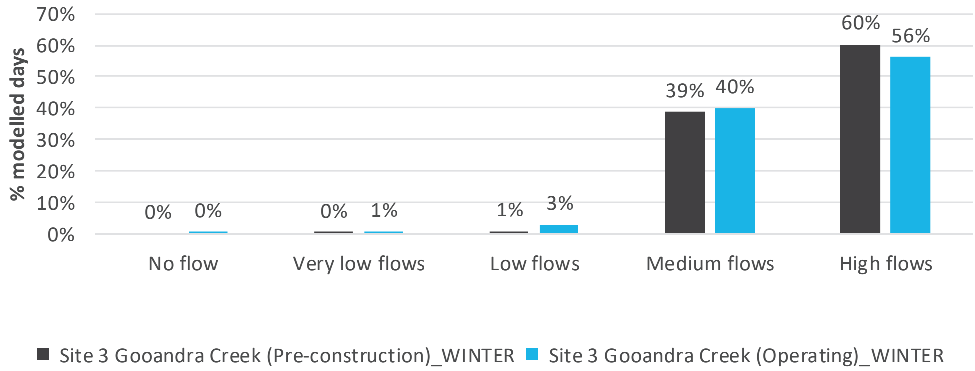


Figure 2.71 Percentage of winter days in each flow category (Site 3)

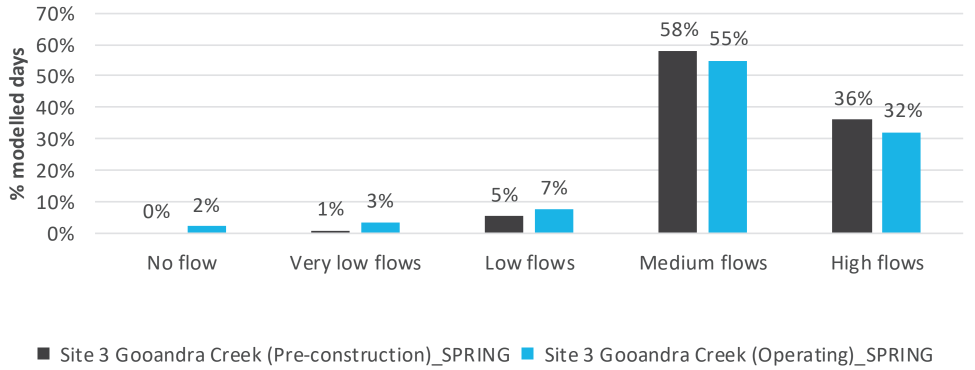


Figure 2.72 Percentage of spring days in each flow category (Site 3)

b Eucumbene River catchment

Hydrographs for the reporting sites in Eucumbene River catchment (for 2006, the lowest flow year on record) are given in Figure 2.73.

There is a significant predicted impact on streamflow for each reporting site in the areas directly overlying the groundwater drawdown contours (ie overlying the tunnel alignment); peak flows are reduced, and long periods of "no flow" can be observed in the operation phase hydrographs.

The uppermost 5 km of the Eucumbene River is expected to be impacted by baseflow reduction due to groundwater drawdown (drawdown shown in Figure 2.50), with baseflow discharges potentially approaching zero in the uppermost 1.5 km of the catchment. Impacts decrease gradually along the length of the river as unaffected catchments incrementally contribute flow to the river.

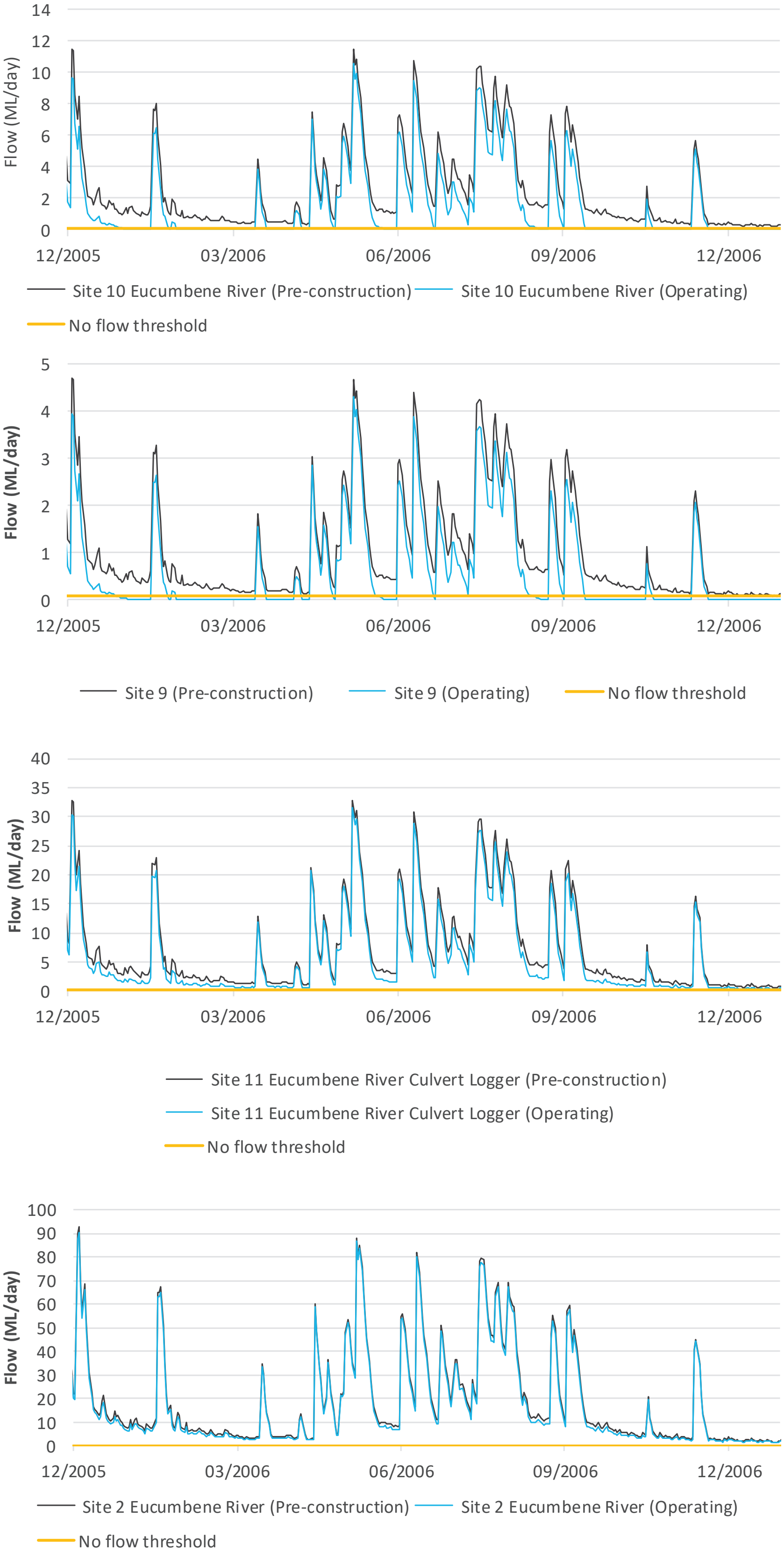


Figure 2.73 Operation phase: hydrographs for the Eucumbene River reporting sites

Total and seasonal flow duration curves for Eucumbene River reporting sites are show in Figure 2.74 to Figure 2.78.

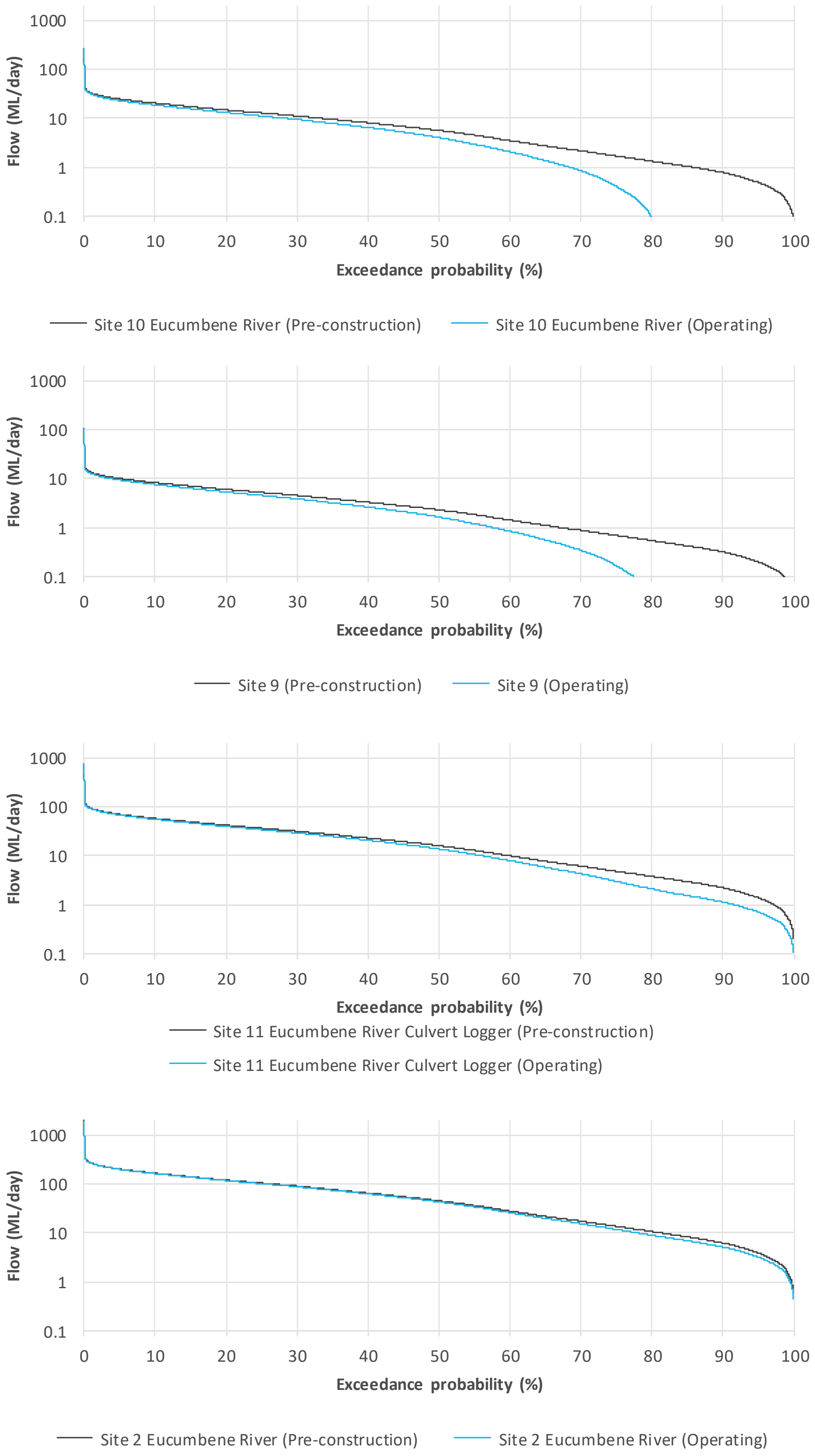


Figure 2.74 Operation phase: flow duration curves for Eucumbene River reporting sites (total)

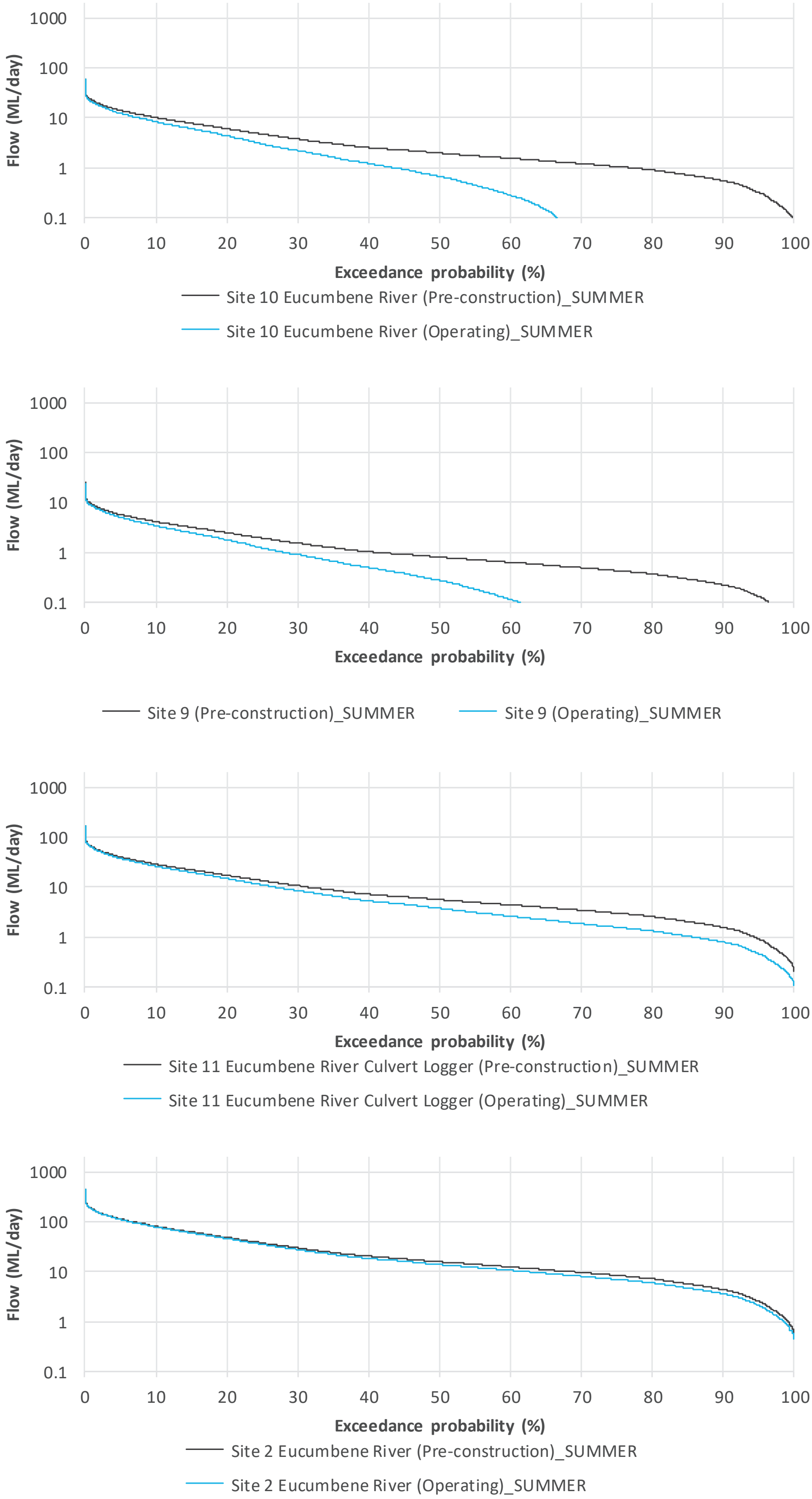


Figure 2.75 Operation phase: flow duration curves for Eucumbene River reporting sites (Summer)

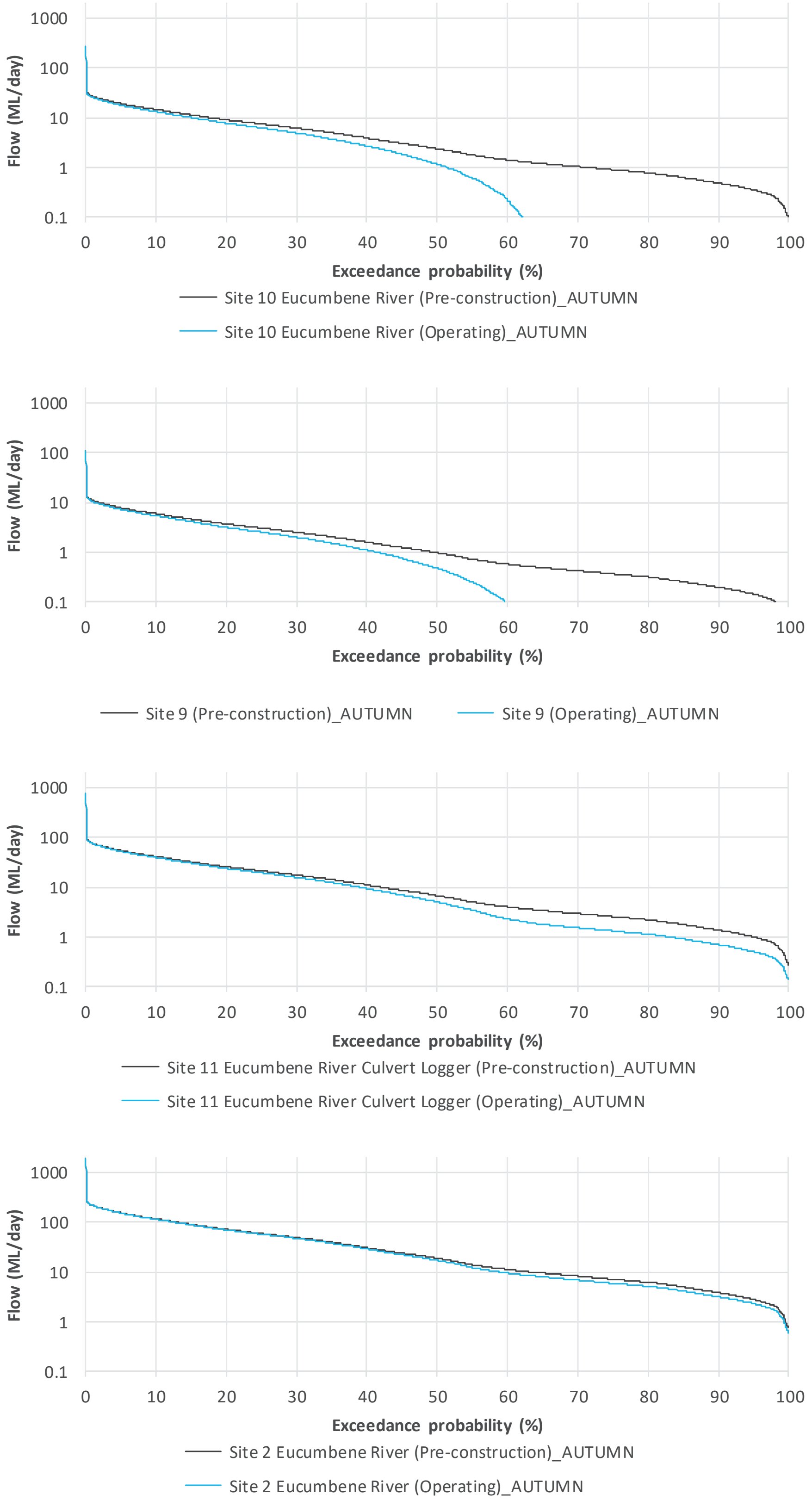


Figure 2.76 Operation phase: flow duration curves for Eucumbene River reporting sites (Autumn)

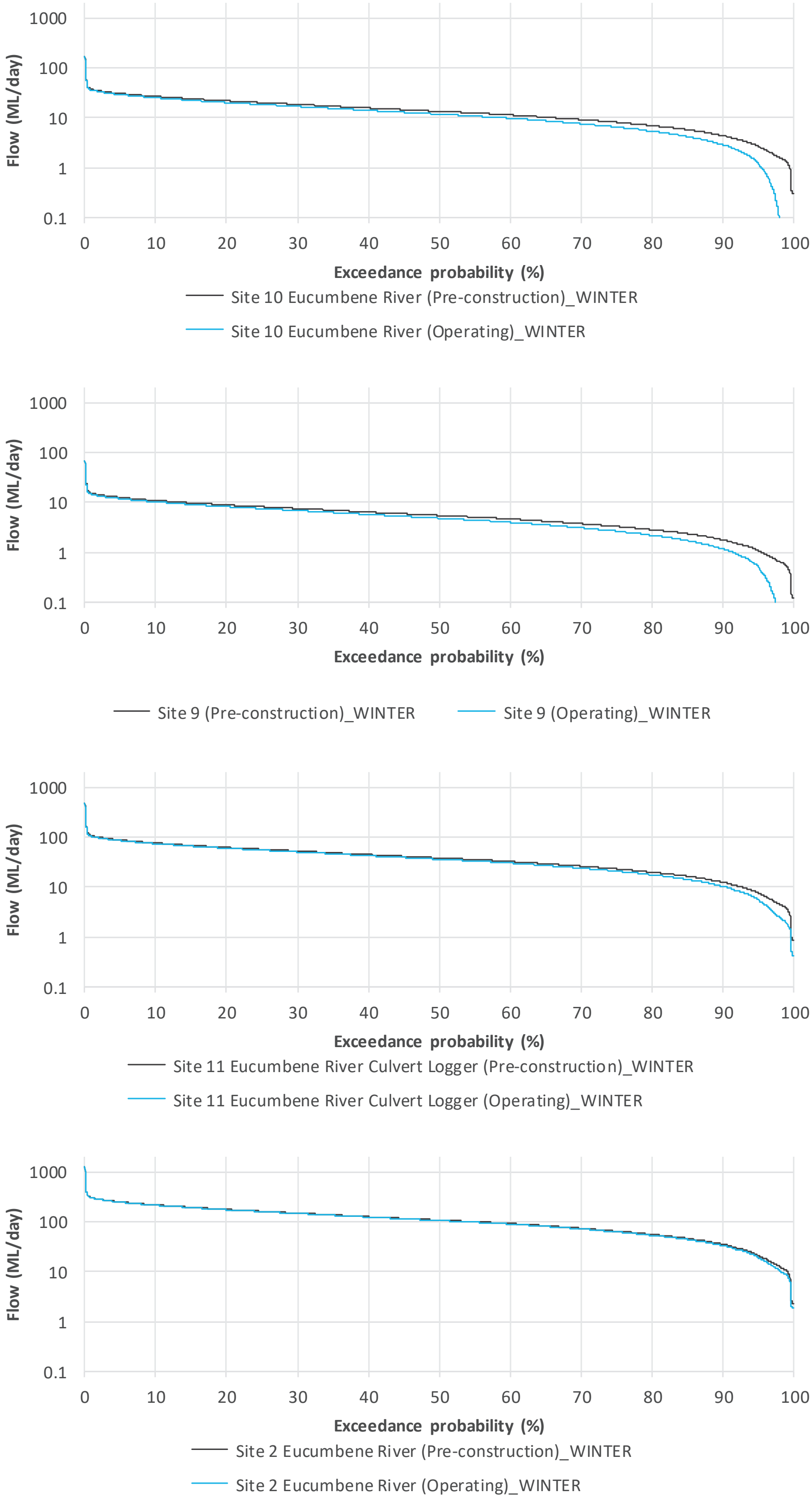


Figure 2.77 Operation phase: flow duration curves for Eucumbene River reporting sites (Winter)

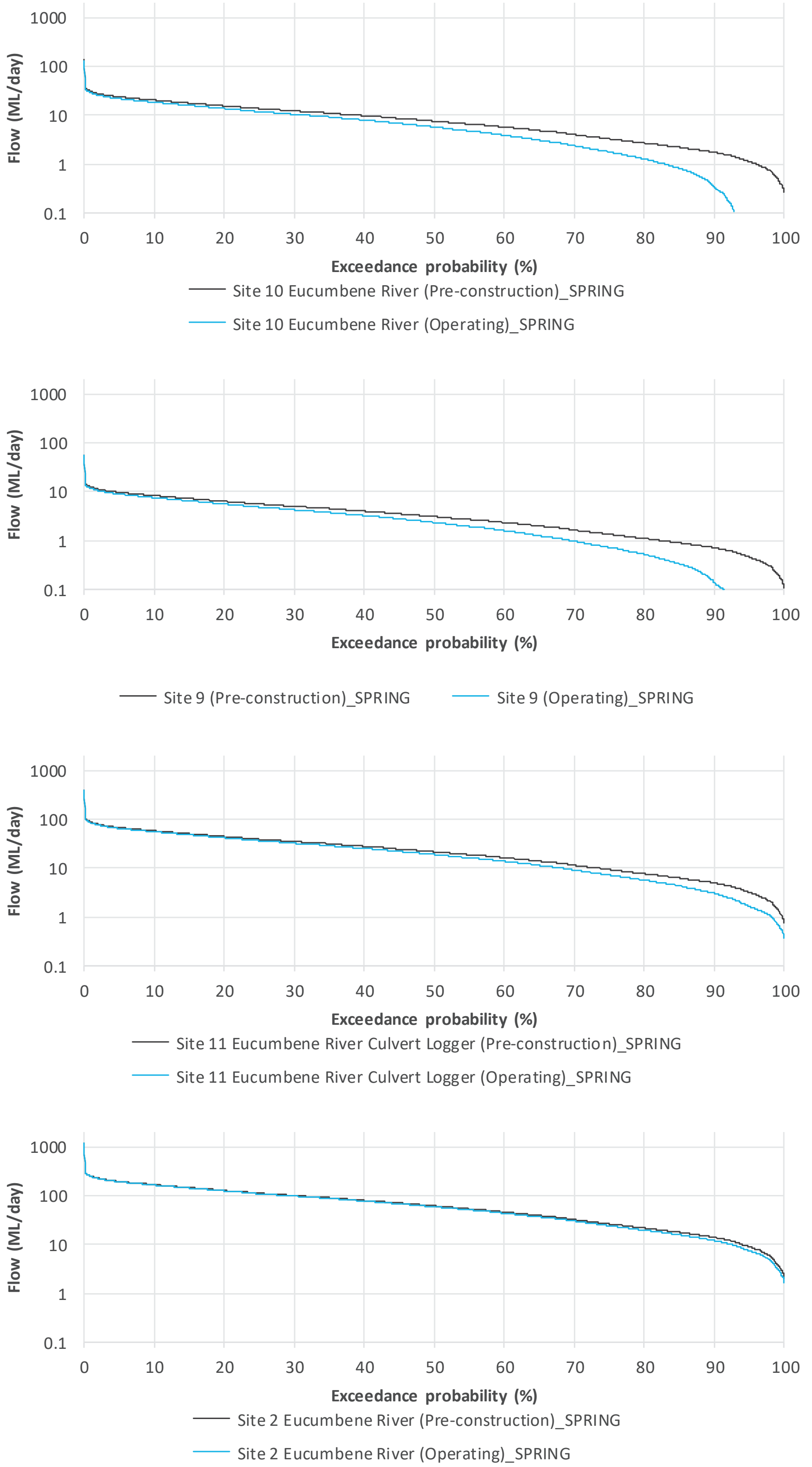


Figure 2.78 Operation phase: flow duration curves for Eucumbene River reporting sites (Spring)

Using the flow categories determined using the pre-construction simulation for each reporting site (section2.7.4ii), the percentage of modelled days within each flow category was plotted on a histogram to show how the flow regime has changed during the operation phase in relation to those categories.

This analysis was done over the full modelling period for all flows at each reporting site and seasonally at each reporting site (Figure 2.79 to Figure 2.83). This analysis indicates that:

- during the operation phase, the headwaters of the Eucumbene River could change from having a perennial streamflow regime to being ephemeral (days with 'no flow' increase from 0% to approximately 20-25% at Site 10 and Site 9). Use of a different 'no flow' threshold could change these results, however, and there could be a flow trickle on these days.

- the impact does not continue downstream past Site 11, as flows from unaffected catchment areas dilute the impact (days with 'no flow' remain at 0% at Site 11 and Site 2);

- days with no flows and very low flows increase at Site 10 and Site 9, particularly in summer and autumn. Days with low, medium and high flows decrease correspondingly; and

- days with very low flows and low flows increase at Site 11 and Site 2, particularly in summer and autumn.

Note that while flow categories relating to river height (eg freshes and floods) have not been assessed; reduced medium and high flows could potentially impact these flow categories.

Figure 2.79 Percentage of days in each flow category (Eucumbene River reporting sites)

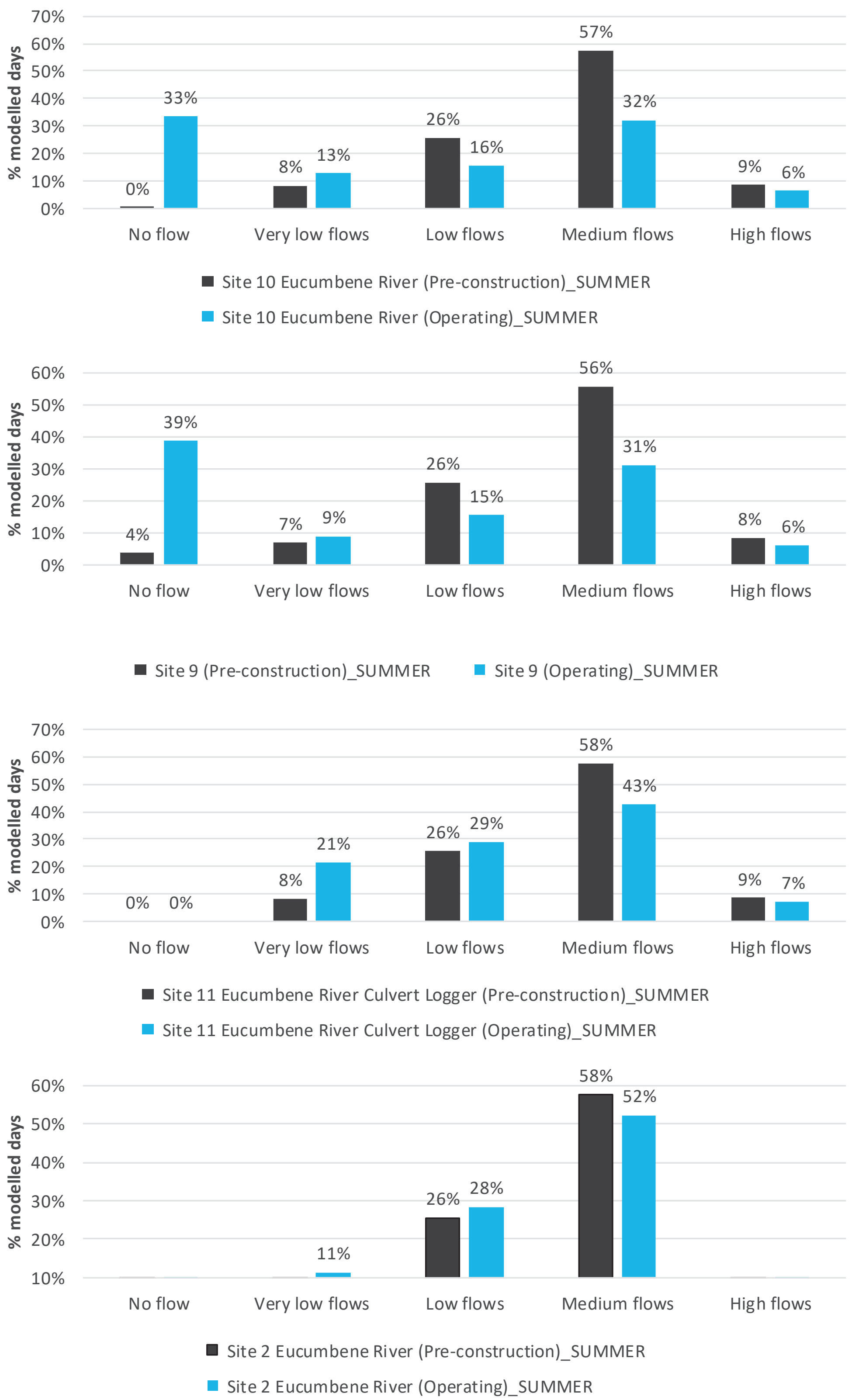


Figure 2.80 Percentage of summer days in each flow category (Eucumbene River reporting sites)

Figure 2.81 Percentage of autumn days in each flow category (Eucumbene River reporting sites)

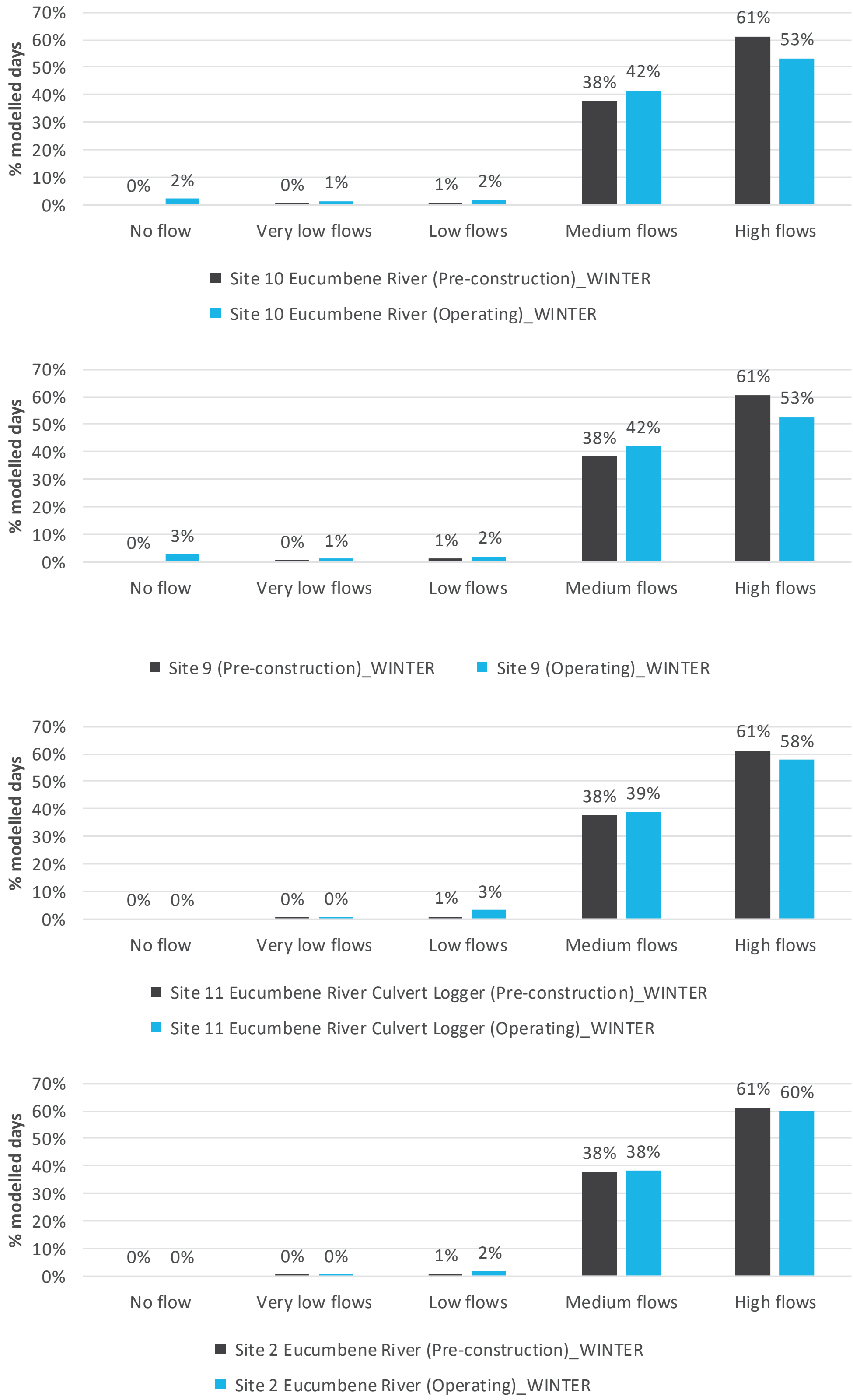


Figure 2.82 Percentage of winter days in each flow category (Eucumbene River reporting sites)

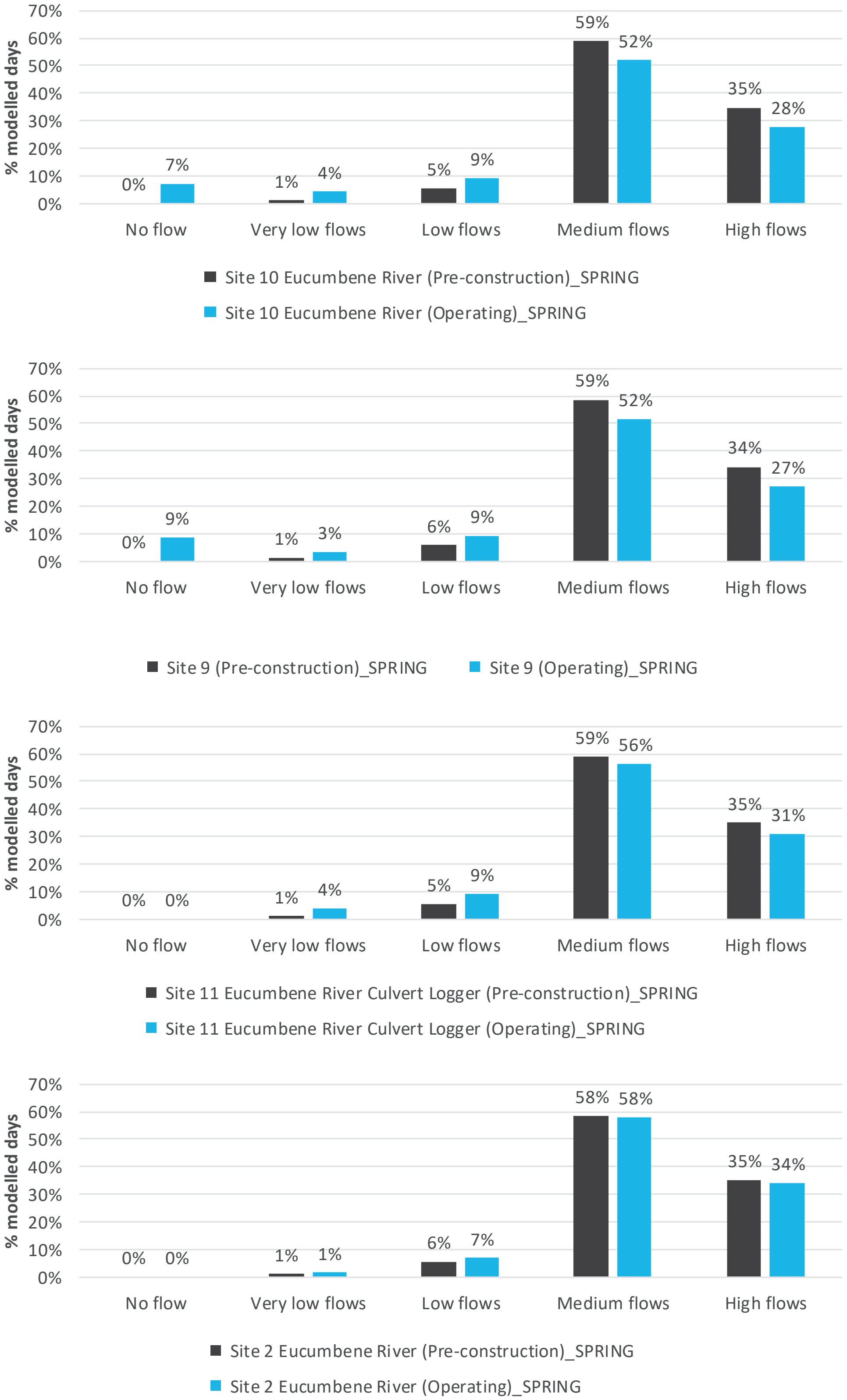


Figure 2.83 Percentage of spring days in each flow category (Eucumbene River reporting sites)

2.7.7 Predictive uncertainty analysis

i Method

The predictive uncertainty associated with model parameterisation was assessed by rerunning the model across a range of alternative parameter sets. Models were run with individual parameters altered as per the upper and lower limits of each parameter as determined via a sensitivity analysis (described in section 2.5.6). All other model parameters were held constant at the calibrated value, as were the groundwater leakage rates. This method is expected to provide a reasonable indication of the range in model results attributable to parameter choices.

The pre-construction and operating phase models were run with each alternative parameter set, and the percentage of days with flow within the 'no flow' and 'very low flow' categories (combined) (see section2.7.4ii for category descriptions) was reported to illustrate the range of the predicted tunnel excavation and power waterway operation impacts. Uncertainty associated with runoff model selection was not assessed as the alternate runoff models discussed in the calibration chapter (section 2.4.5) did not contain methods for modelling loss of groundwater to the tunnel excavation.

ii Uncertainty associated with catchment model parameterisation

Twenty alternative model parameter sets were assessed (Table 2.18). The resulting percentage of modelled days with flow within or less than the 'very low flow' category was recorded for reporting sites 3, 5, 6 and at the Murrumbidgee gauge within the Murrumbidgee catchment (Figure 2.84), and at reporting sites 9, 10, 11 and 2 within the Eucumbene catchment (Figure 2.85).

It was found that, although alternative model parameter sets yield different results for the pre-construction and operating phases, the change due to the operation of the project was relatively consistent across the parameter sets:

- the largest range in the prediction of the impact of the project was seen at Site 3 (Gooandra Creek), where the increase in no and very low flow days ranged from +5% to +16%; and
- at the Murrumbidgee Gauge downstream, the increase in no and very low flow days was a much smaller spread of +0% to +1%.

The relatively tight spreads in the prediction of the impact of the project on increases in very low and no flow days at most sites assessed indicates that the results are relatively insensitive to the exact parameters chosen (within the bounds of the parameter sets that give an adequate calibration). This means that the results presented throughout section 2.7 would likely be very similar if an alternate calibration had been chosen; the results have low uncertainty due to model parameter selection.

Table 2.18 Parameters modified within the uncertainty analysis

Parameter set	Short name	Parameter Factor[1]			
		Plateau Catchments		Ravine Catchments	
		Lower (L)	Upper (U)	Lower (L)	Upper (U)
Parameters for calibrated model	Cal.	1.00			
Rain Multiplier	P1	0.10	2.50	0.50	1.00
ET Multiplier	P2	0.52	2.58	0.97	1.67
Infiltration Exponent SQ	P3	0.20	2.00	0.37	3.70
Soil Moisture Store Capacity	P4	0.80	1.20	1.00	1.00
Recharge Coefficient	P5	0.00	2.50	0.27	1.09
Minimum Saturation	P6	0.76	1.49	0.66	1.97
Interflow Coefficient	P7	0.40	5.00	0.53	1.69
Interception Capacity	P8	0.36	1.87	0.68	1.02
Infiltration Coefficient	P9	0.75	1.10	0.85	1.15
Groundwater Recession	P10	0.98	1.15	0.95	1.02

Note: 1. The parameter ranges tested corresponded to the range of parameters which were found in the sensitivity analysis to produce a calibrated model.

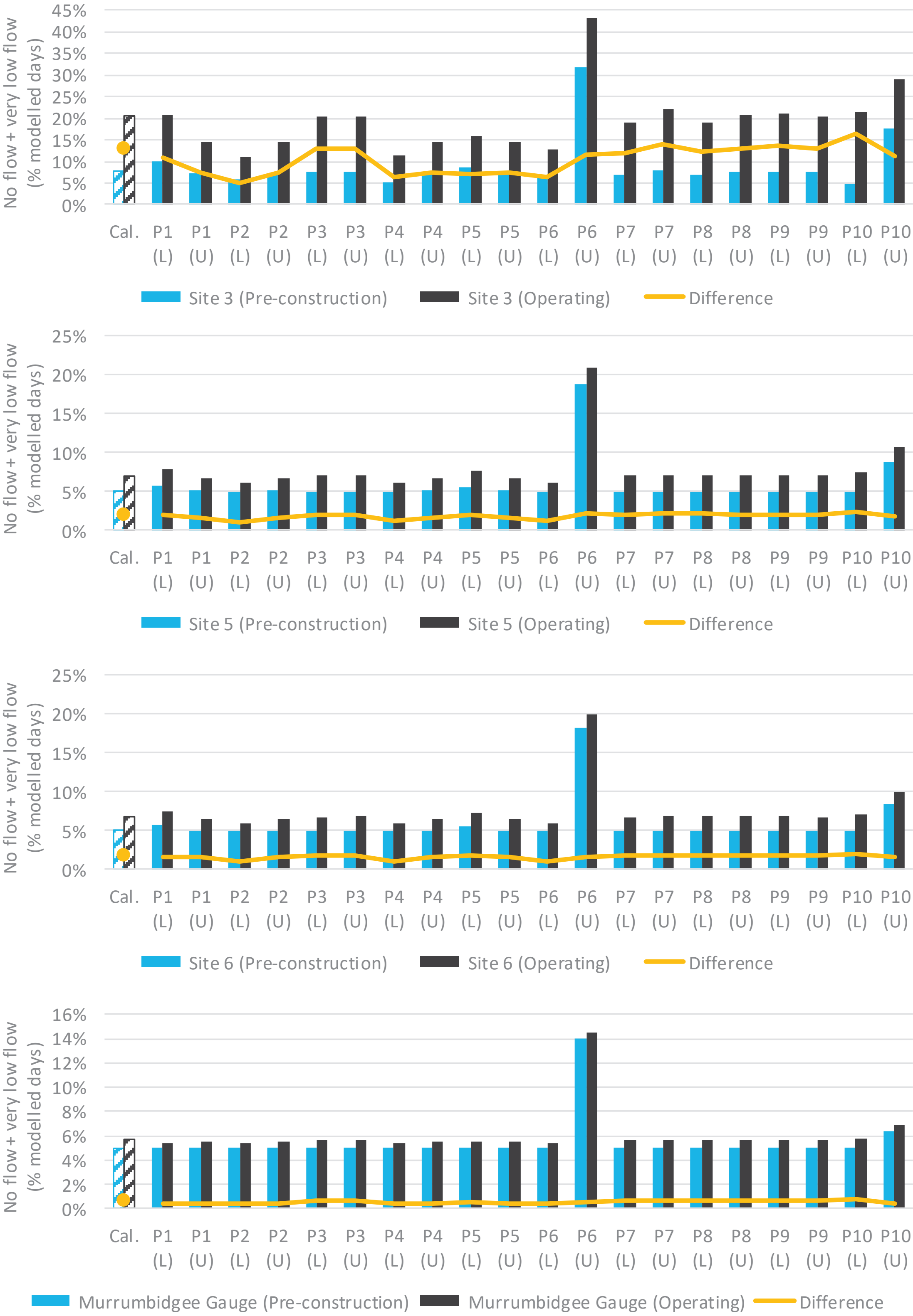


Figure 2.84 Modelled results across alternative model parameter sets (Gooandra Creek reporting sites)

Figure 2.85 Modelled results across alternative model parameter sets (Eucumbene River reporting sites)

iii Uncertainty associated with the magnitude of baseflow reduction predicted by the groundwater model

The change in number of very low and no flow days predicted by the model was tested for baseflow loss rates ranging from 0% to 100% of baseflow within catchments 11, 14, and 15 (Gooandra Creek, and Eucumbene headwater catchments). The percentage of modelled days with low or very low flow over the range of baseflow reduction rates are shown in Figure 2.86 and Figure 2.87 for reporting sites on the Gooandra Creek and Eucumbene River respectively. The long-term (steady state) baseflow reduction rate predicted by the groundwater model during operation of the project using current best estimate parameters is shown on these figures for context (labelled as “predicted impact”).

This analysis shows that for the reporting sites immediately downstream of the affected headwater catchments, the percentage of modelled days no or very low flow increases as the reduction in baseflow increases. For Site 3 (Gooandra Creek) (Figure 2.86):

- when there is no reduction in baseflow (ie currently under ‘normal’ conditions), less than 10% of days have no or very low flow;
- if 100% of baseflow were to be lost, approximately 40% of days would have no or very low flow; and
- the predicted impact (28.8% reduction in baseflow) results in 20% of days with no or very low flow.

Downstream of Gooandra Creek the baseflow reductions modelled within Gooandra Creek have a smaller impact as unaffected sub catchments provide additional baseflow during dry periods. For example, at the Murrumbidgee Gauge:

- when there is no reduction in baseflow within the Gooandra Creek catchment (ie currently under ‘normal’ conditions), on 5% of days there would be very low flow at the Murrumbidgee gauge (as per the very low flow definition);
- if 100% of baseflow were to be lost within the Gooandra Creek catchment, on approximately 6% of days there would be no or very low flow at the Murrumbidgee gauge; and
- the predicted impact (28.8% reduction in baseflow within the Gooandra Creek catchment) results in 6% of days falling within the very low or no flow category; and

At each site downstream of the confluence of Gooandra Creek and Tantangara Creek (sites 5, 6 and Murrumbidgee Gauge), the number of days with very low or no flow does not increase when the baseflow reduction within the Gooandra Creek catchment is increased towards 100%, which suggests that the reduction in baseflow as a result of the project is insignificant to the catchment beyond Gooandra Creek.

A similar pattern of results is seen within the Eucumbene catchments (Figure 2.87):

- if 100% of baseflow were lost upstream of Sites 9 and 10, the number of days with very low or no flow at those reporting points would increase from the current (under ‘normal’ conditions) prediction of 35% and 45% of days to 42% and 52% of days; and
- the number of days with very low or no flow at Site 11 (Gooandra Track) and Site 2 does not increase when the baseflow loss within the upstream catchments increases beyond the predicted 58% reduction which again suggests that the reduction in baseflow as a result of the project is insignificant to the catchment beyond the Upper reaches of the Eucumbene River.

These results indicate that the prediction of the change in number of days with very low or no flow days within Tantangara Creek, the Murrumbidgee River and Eucumbene River downstream of Gooandra Track is insensitive to uncertainty in groundwater model predictions of baseflow loss magnitude within the predicted impact area (Gooandra Creek and Eucumbene River upstream of Sites 9 and 10).

iv Uncertainty associated with the spatial extent of baseflow reduction predicted by the groundwater model

Section 3.4.3 indicates that if the hydraulic conductivity of various rock units that will be encountered by the tunnel boring machines during excavation is higher than indicated by the tests detailed in Table 3.3, then groundwater drawdown may occur across a larger area than the current prediction. The areas most likely to be affected in such a case are Nungar Creek (model sub-catchment 1), Tantangara Creek (subcatchment 9), Stable Creek (model sub-catchment 24) and Yarrangobilly River (sub-catchment 19) (Figure 3.39 to Figure 3.41), and downstream river reaches.

The sensitivity of surface water model results to increased groundwater drawdown extents has not been assessed.

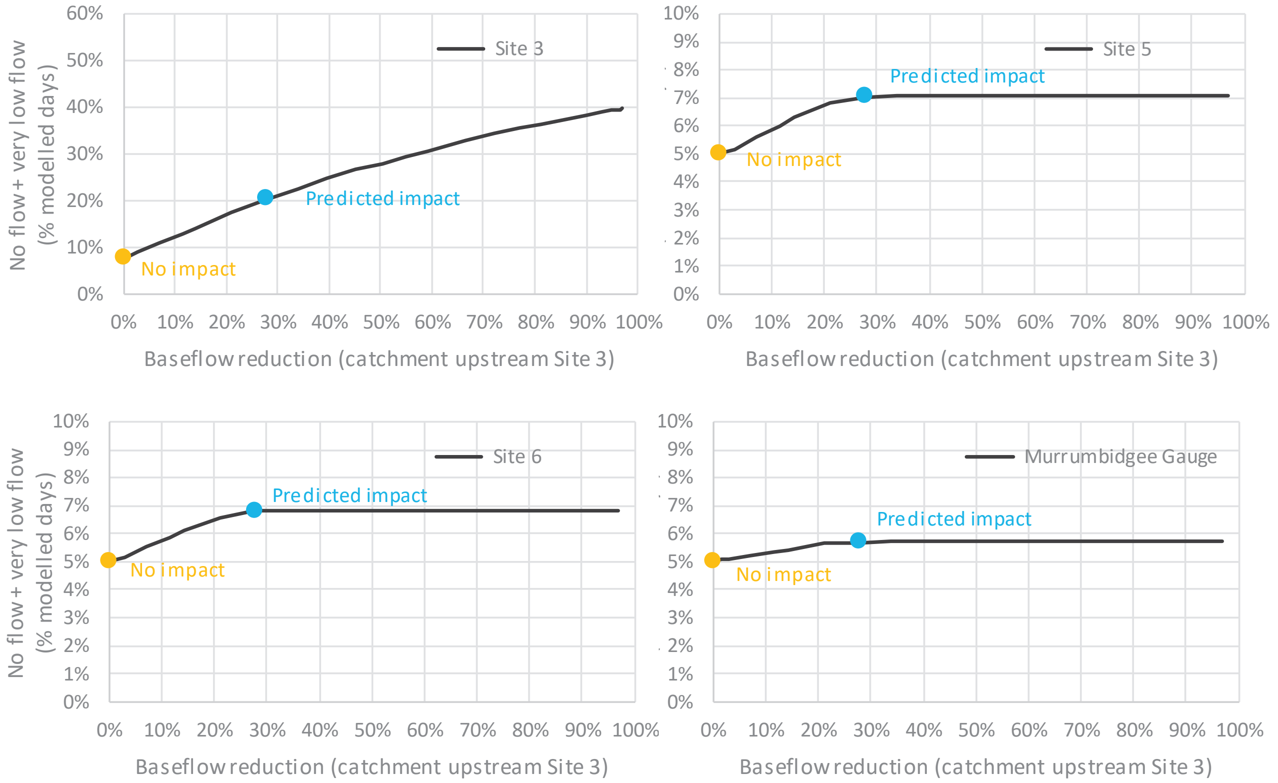


Figure 2.86 Modelled results across a range of baseflow reduction rates (Gooandra Creek reporting sites)

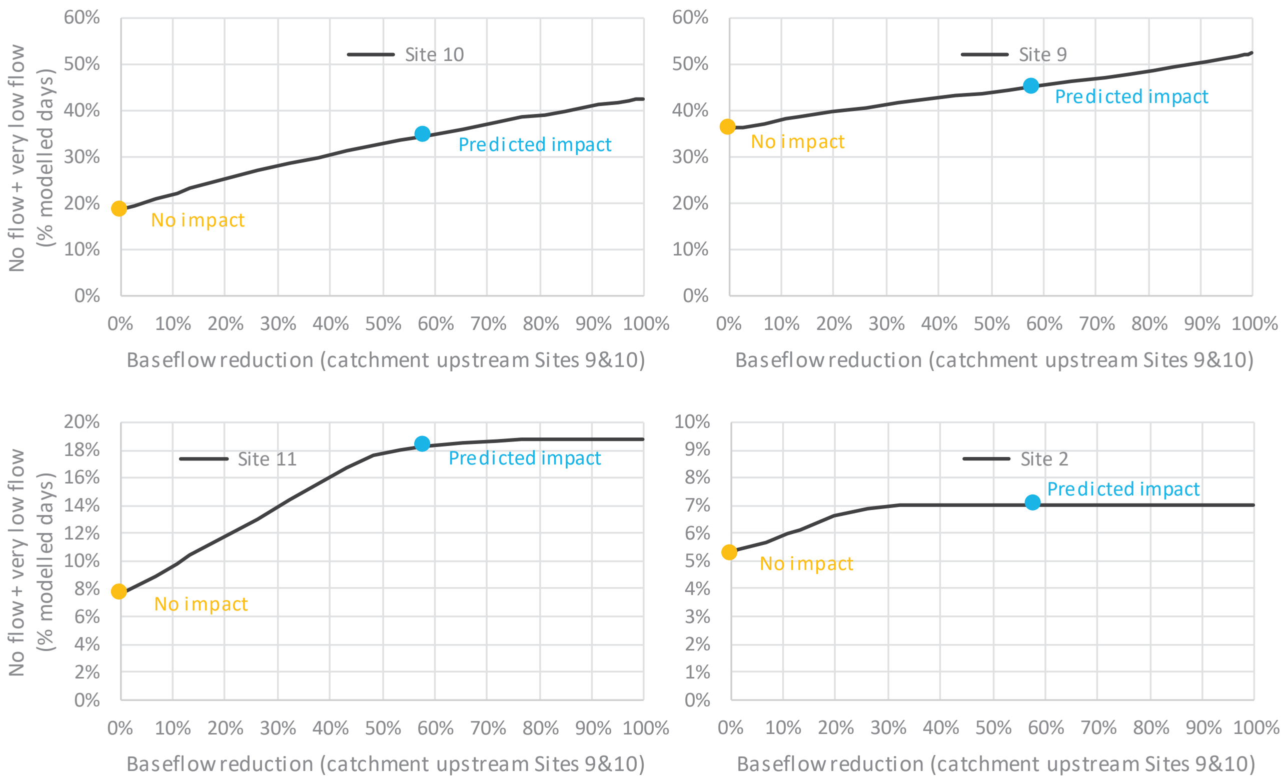


Figure 2.87 Modelled results across a range of baseflow reduction rates (Eucumbene River reporting sites)

2.8 Limitations

The catchment characterisation and impacts predicted in this surface water chapter of the modelling report are dependent on data collected from a number of sources (referenced in the text), a number of assumptions, and the analysis methods. The data, assumptions, and method have been subjected to professional rigour and review typical of work completed for assessing environmental impact. However, no guarantee is expressed or implied that the impacts observed within the described study area will match the model results.

Key aspects to be aware of when interpreting the impacts to surface water described in this report include:

- **Scale**

  The catchment model describes impacts at a sub-catchment scale. Within each sub-catchment there will be a number of tributaries to the main creek represented in the model. Impacts to individual small creeks and tributaries cannot be described separately using the applied method.

  Within some creeks there is a diversity of pools, riffles, bends, and straights. The applied method cannot describe impacts at specific locations (ie micro scale) within sub-catchments and does not include a hydraulic assessment of localised features within creeks.

  The baseflow impact data produced by the groundwater model is assessed on a creek reach basis. This data can be used within the surface water model to discuss impacts at the sub-catchment scale only.

  Both the groundwater model and surface water catchment model were calibrated to regional data sets. As described in the model calibration chapters of this report, the models represent the regional movement of water through the environment with an accuracy typical of modelling projects. However, at any specific location within the domain of either model, environmental conditions may vary from the data included in the models.

  The model scale is considered fit for the purpose of considering the streamflow regime effects of the regional scale project.

- **Catchment modelling approach**

  As described in section 2.4.5, a number of runoff models were tested, each with different sets of equations utilised for predicting the conversion of rainfall to runoff. Each of these runoff models, including the modified SIMHYD model ultimately applied, are extremely simple when compared to the diversity of physical processes at work in the environment. The calibration statistics of the modified SIMHYD model provide an indication that the simplified physical processes represented by model equations may adequately represent the more complex physical processes. Nevertheless, the runoff model utilised is a significant simplification of reality and cannot provide detailed or reliable information about features such as individual bogs, fens, localised baseflow discharge points at bedrock fractures, hill slope springs, or shallow vs deep groundwater flow pathways.

  In particular, the recharge estimation process within the SIMHYD model is a physically based but simple set of equations. Other approaches exist for detailed modelling of the unsaturated soil zone and use of water by vegetation which would likely have resulted in a different groundwater recharge time series.

  The SIMHYD model utilised makes the basic assumption that groundwater flow systems align with surface water catchments. It is expected that some portion of water entering the regional groundwater system on the plateau will flow to the ravine area. If this flow path could be captured in the surface water model, the Wallace Creek and Yarrangobilly River model catchments may have been calibrated with an alternate set of parameters, leading to an alternate set of impacts predicted. However, minor differences in groundwater flow systems would not significantly affect the overall model results.

- **Catchment model calibration**

  While the catchment model has good calibration statistics over the duration of records utilised (section 0), the model represents flow on some days better than on other days. The rainfall records used in the model are not a perfect representation of the rainfall that the catchment experienced, and so each rain event the model predicts more or less streamflow than actually occurred.

  When flows are very low in summer following periods of no rain, the model also predicts low flows. However, small magnitude errors when applied to small flows can result in a large percentage error. It is typical of surface water models to be poor at matching gauged low flows, and it is also typical of gauges to be poor at recording low flows. As many of the impacts presented in this EIS relate to low flows, the uncertainty relating to gauged low flows and modelled low flows result in uncertainty around the magnitude and frequency of impacts to low flows. For this reason, absolute flow rates should not be taken from the model when considering low flows. Relative impacts obtained through comparison of the modelled pre-construction case and the modelled construction/operation case will be less affected by gauge and model uncertainty than absolute impacts.

  Prediction of 'typical' flows (within the 20^{th} flow percentile to 80^{th} flow percentile) are usually well recorded at gauges, and are well represented in the model.

- **Groundwater model approach**

  The groundwater model assumptions and limitations result in uncertainty relating to the impact predictions. These uncertainties are directly passed into the surface water model and the uncertainty associated with analysis of surface water impacts.

  The hydraulic conductivity of the rock to be excavated by the project has been estimated using appropriate hydrogeological techniques and pumping test methods. However, fracture flow is not uniform and local scale and overall tunnel groundwater inflow will only be known once the project commences and groundwater flows into the tunnel are measured. Until that time, the groundwater drawdown and baseflow reduction predictions of the groundwater model will carry a degree of uncertainty.

  The groundwater model uses conservative assumptions of hydraulic conductivity and does not model mitigation and management measures (ie grouting). However, should the hydraulic conductivity of the rock be higher than modelled (ie there are more fractures encountered than anticipated), then impacts to creeks at the surface may be larger than estimated. This could take the form of more severe impacts within creeks already predicted to be impacted, or it could take the form of impacts to creeks previously estimated to be unaffected by the project. Conversely, if fewer fractures are encountered, or if these fractures are not regionally connected, or if mitigation measures are applied (which is planned) then the estimated tunnel inflows may be significantly reduced, and then reduction to baseflow in creeks would be lower.

- **Catchment runoff characteristic changes over time**

  It is possible that vegetation coverage or type may change over time due to climate change, project impacts, or natural effects such as bushfire. This could lead to changes to runoff and infiltration relationships and decalibration of the models.

- **Data utilised in the surface water model**

  The SILO rainfall data used is expected to represent rainfall within the catchment reasonably well. However, it is likely that some of the spatial variability that occurs within storm rainfall patterns is not represented in the SILO rainfall grid. This is a typical problem faced when modelling catchments, and means that in some rainfall events the model will over predict runoff, and in some events it will under predict.

  There are differences between the SILO data (developed from Bureau of Meteorology climate station data) and precipitation data collected throughout the project region by Snowy Hydro.

  Morton's potential evapotranspiration data varies from other sources of evaporation data such as the Bureau of Meteorology Class A pan evaporation data and such as remote sensing estimates of regional evapotranspiration. Calibration and prediction using alternate evaporation datasets was not investigated. Nathan and McMahon (2017) note that choice of evapotranspiration data source typically has little impact on model predictive power, so long as the same dataset is used for prediction as was used for model calibration.

3 Groundwater

3.1 Groundwater modelling overview

The model was prepared in accordance with the *Australian groundwater modelling guidelines* (AGMG) (Barnett, et al., 2012), and in accordance with the requirements of the Aquifer Interference Policy (DPI Water, 2012). The model and associated predictions meet many of the criteria outlined in the AGMG for a Class 2 model, with the remaining criteria conforming to Class 1. The primary limitations of the modelling relate to the water level dataset, which is largely two-dimensional, and length of monitoring available to inform the conceptualisation and calibration. Additionally, geological and hydrogeological mapping and property testing is largely two-dimensional, along the project alignment. The model used outputs from the catchment model (Chapter 2.5.5) to inform rainfall-derived recharge as well as to provide soft history matching/validation targets for baseflow.

3.1.1 Groundwater modelling objectives

A regional numerical groundwater flow model, referred to as SH4.0, was developed for the Snowy 2.0 Main Works groundwater assessment. The model is based on the SH1.0 model, developed for the Exploratory Works groundwater assessment (EMM Consulting, 2018), but is informed by datasets that have expanded, both spatially and temporally, since the Exploratory Works modelling, enabling greater conceptual understanding of the groundwater system and its interaction with surface environments. Key expanded datasets include groundwater and surface water monitoring, hydraulic and geophysical testing. The focus of the modelling was expanded to Main Works rather than focussing only on the Exploratory Works, necessitating structural alterations to the model.

The modelling objectives were to quantify potential regional-scale impacts on the groundwater system resulting from construction and operation of Snowy 2.0. Specifically, the outcomes required are predictions of:

- watertable drawdown;
- groundwater inflows to excavations; and
- changes to the groundwater water balance.

The SH4.0 numerical groundwater flow model was not designed to explicitly simulate soil water, surface water or perched groundwater nor water quality/solute transport.

3.1.2 Australian Groundwater Modelling Guidelines

The Australian Groundwater Modelling Guidelines, National Water Commission (NWC) (Barnett, et al., 2012) provide a consistent and sound approach for the development of groundwater flow models in Australia. The guidelines ‘propose a point of reference and not a rigid standard’ and provide direction on scope and approaches while acknowledging that techniques are continually evolving and innovation is to be encouraged. The guidelines provide a confidence-based classification schema to set the context for identifying where more effort may be required on data acquisition and/or sensitivity and uncertainty analysis. The schema defines three different classes of model:

- Class 1 – low confidence in model predictions, suitable for use in low value resource or low risk developments;
- Class 2 – medium confidence in model predictions, suitable for use in projects with medium to high risk developments; and

- Class 3 – high confidence in model predictions, suitable for use in high value resources and projects such as regional sustainable yield assessments.

The guidelines provide information on the data requirements for each model class, such as spatial distribution of bores and temporal groundwater level data. Ideally, groundwater resource assessments at major development sites would warrant the use of a class 2 or 3 model. The onerous data requirements to achieve a class 3 model (ie reliable metered extraction and the duration of the prediction to be not more than three times the calibration data period) mean that for most major projects in NSW a full class 3 model is practically unattainable.

The numerical groundwater model developed to predict potential impacts of the project is best described as a class 2 model, with some criteria conforming to a class 1 model, and a few to class 3 criteria. Considerable effort was applied to investigate surface and groundwater interactions and to apply a coupled modelling methodology, thereby addressing non-uniqueness by constraining the calibration to fluxes as well as heads. Where assumptions were required, a conservative approach was applied that would tend to over-estimate impacts, sensitivity and uncertainty analyses were conducted, and the model capabilities and limitations are carefully described.

The New South Wales Department of Planning, Industry and Environment (DPIE) were consulted during the development of the numerical groundwater model.

3.1.3 Peer review

The numerical model has been prepared in accordance with the Australian Groundwater Modelling Guidelines and peer reviewed using the structure of the 'review checklist'. A pre-eminent hydrogeologist, Hugh Middlemis, was engaged to peer review the numerical model.

The model was deemed by the peer reviewer to be fit for purpose and, in several aspects, conservative. The peer review report (Middlemis, August 2019) is included in Attachment A.

3.2 Model design

3.2.1 Software

The SH4.0 model was built using the Groundwater Vistas 7 (Environmental Simulations Incorporated, 2017) graphical user interface (GUI) because of its highly flexible input, output and data processing options when compared with other commercially available GUIs. The model runs in the MODFLOW-USG (Panday, Langevin, Niswonger, Ibaraki, & Hughes, 2017) numerical groundwater flow modelling code, using the recently released USG-Transport version of the code. MODFLOW-USG enables use of an "unstructured grid" rather than the regular rectangular grid of rows, columns and layers required by previous versions of MODFLOW. This flexibility enables greater representation of complex geometry associated with hydrostratigraphy or other hydrogeological features such as rivers and excavations. Additional spatial refinement can be employed around features warranting it, without the requirement for additional rows, columns or layers to be continued across the whole model domain.

3.2.2 Model extent

The south-west corner of the model domain has coordinates of 621,500 m East, 6,032,000 m North (MGA Zone 55), and the domain extends 30 km to the east and 17 km to the north, creating a north-south aligned rectangle. The model domain, presented in Figure 3.3, is sufficiently large to encompass all underground excavations of the Snowy 2.0 project, Yarrangobilly Caves, all major rivers and creeks as well as all project-related groundwater monitoring sites.

3.2.3 Spatial discretisation

Because the majority of geological units in the model domain are aligned almost vertically, model layers were predominantly defined to align with, and provide appropriate discretisation around, the geometry of the project design components rather than hydrostratigraphic units. As a result, some hydrostratigraphic units span many model layers.

In total, forty-two model layers are used to represent the hydrostratigraphy, excavations and anticipated hydraulic gradients. A west-east cross section through the model domain is presented in Figure 3.1 to illustrate the geometrical structure and discretisation of the model.

The uppermost layer represented the more permeable weathered geology, tertiary basalt, alluvium and colluvium. A LiDAR derived digital elevation model was used to define the top of model. The layer was given a thickness of 6 m.

Below model layer one the majority of model layers are primarily horizontal with a nominal 100 m thickness. Where layers intersected an overlying model layer surface they were thinned and/or pinched out.

Five model layers were used to provide spatial detail above and below the Head Race Tunnel (HRT). Of these, the middle layer was used to represent the tunnel. These layers were 12.5 m thick, enabling representation of the pressure profile immediately around the tunnel. Figure 3.2 illustrates the horizontal and vertical spatial discretisation employed around the HRT. Similarly, the 12.5 m thick model layers used to discretise the area around the Tail Race Tunnel (TRT), underground power station components and associated tunnels and adits in the ravine area.

The spatial grid employed to discretise the model domain is shown in Figure 3.4. The model has a nominal regional cell size of 200 m by 200 m. Quadtree refinement was used to split regional model cells into smaller cells along modelled rivers and creeks and around the edges of Talbingo and Tantangara Reservoirs, reducing cell sizes around these features to 25 m by 25 m. Along the alignment of the power waterway and associated excavations, refinement cells were reduced to 12.5 m by 12.5 m, enabling representation of the anticipated large depressurisation gradients into the rock mass moving away from the excavation walls.

The 42 model layers, regional and quadtree meshes yield a total of 8,194,032 cells. Pinching out of discontinuous model layers reduced this to 2,726,923 active cells.

3.2.4 Temporal discretisation

Both the transient history matching calibration period and transient prediction model runs employ four seasonally aligned stress periods per year. This enabled simulation of climate seasonality, which was the only stress on the groundwater system during the groundwater monitoring record and therefore the only stress to which history matching could be conducted. Quarterly stress periods were also considered appropriate temporal discretisation to represent the progress of excavation and construction during the construction stage of the project.

Each quarterly stress period was divided into 20 time steps with a time step multiplier of 1.2. This resulted in the first time step of each stress period being on the order of 0.5 days long and the last, and longest, time step in each stress period on the order of 15 days long (with variability depending on the number of days, 90, 91 or 92, in a given season).

3.2.5 Numerical solution

The MODFLOW-USG SMS solver was employed to solve the series of differential equations generated by the model. Head closure criteria of 0.25 m and 0.05 m were employed for outer iterations (HCLOSE) and inner iterations (HICLOSE) respectively. Whilst larger than often employed in numerical groundwater flow models, these yielded water balance errors of 0.00% both cumulatively and at individual time steps during simulations. Smaller head closure criteria were trialled but proved problematic.

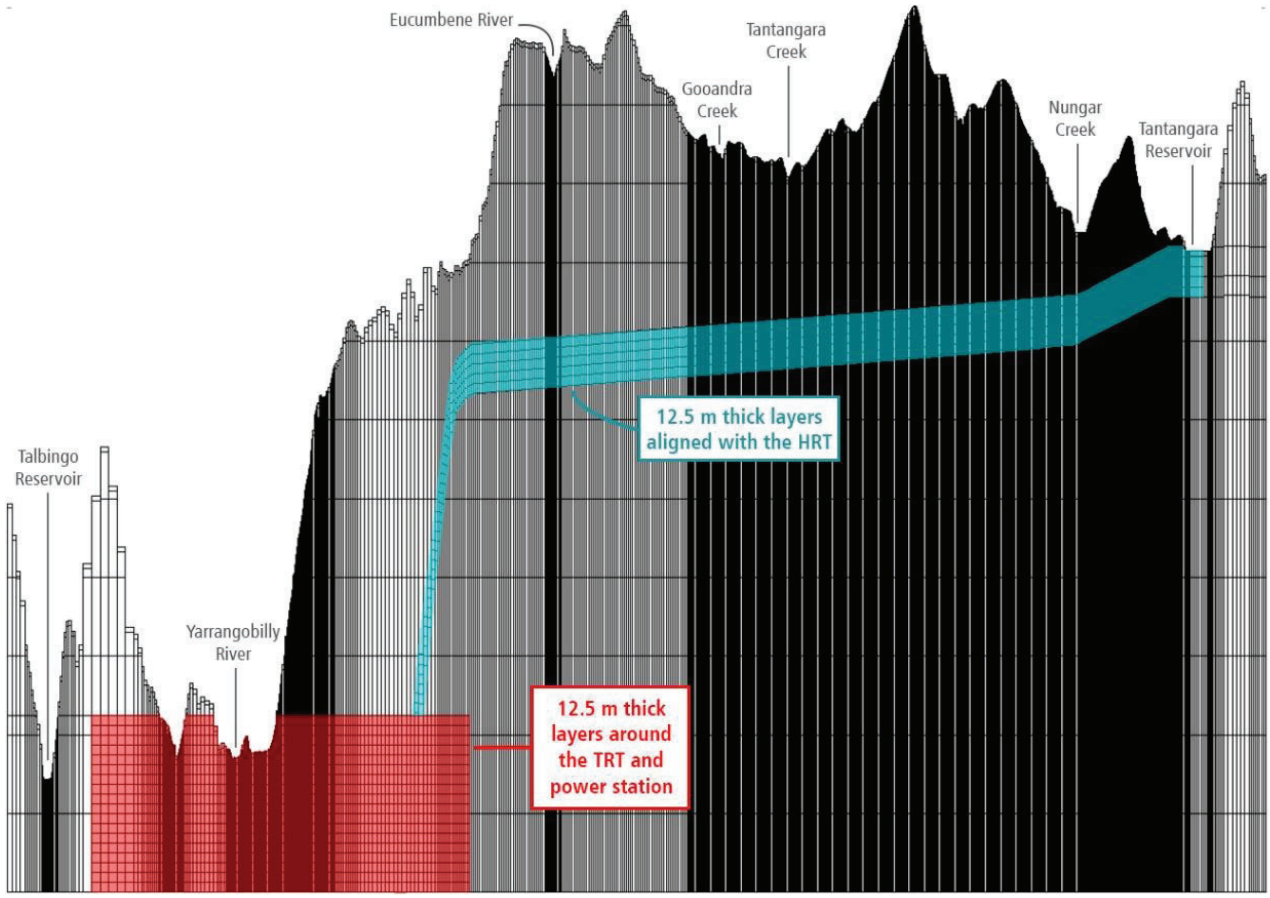


Figure 3.1 West-east cross section through model layers at 6,038,100 m N

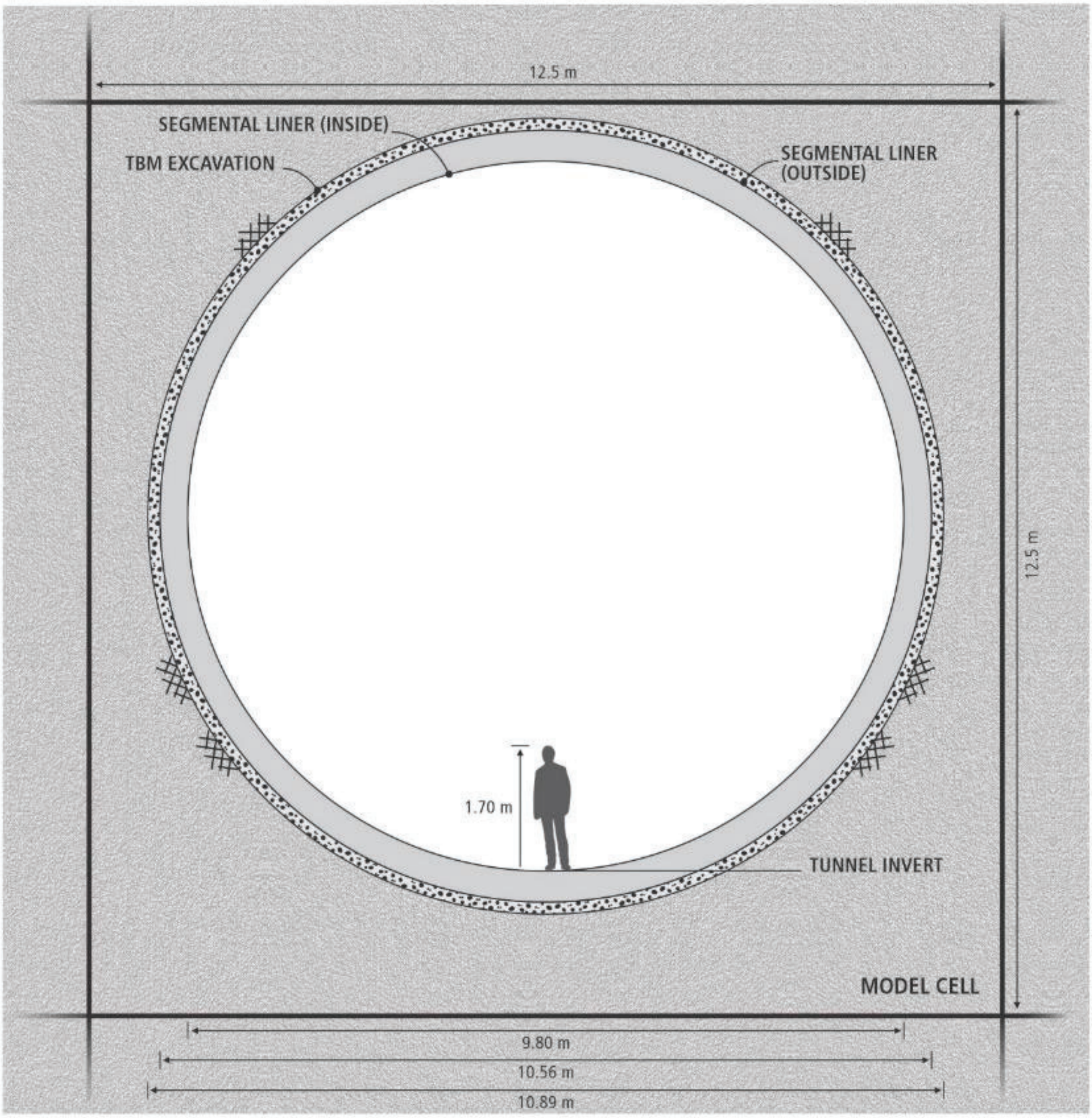
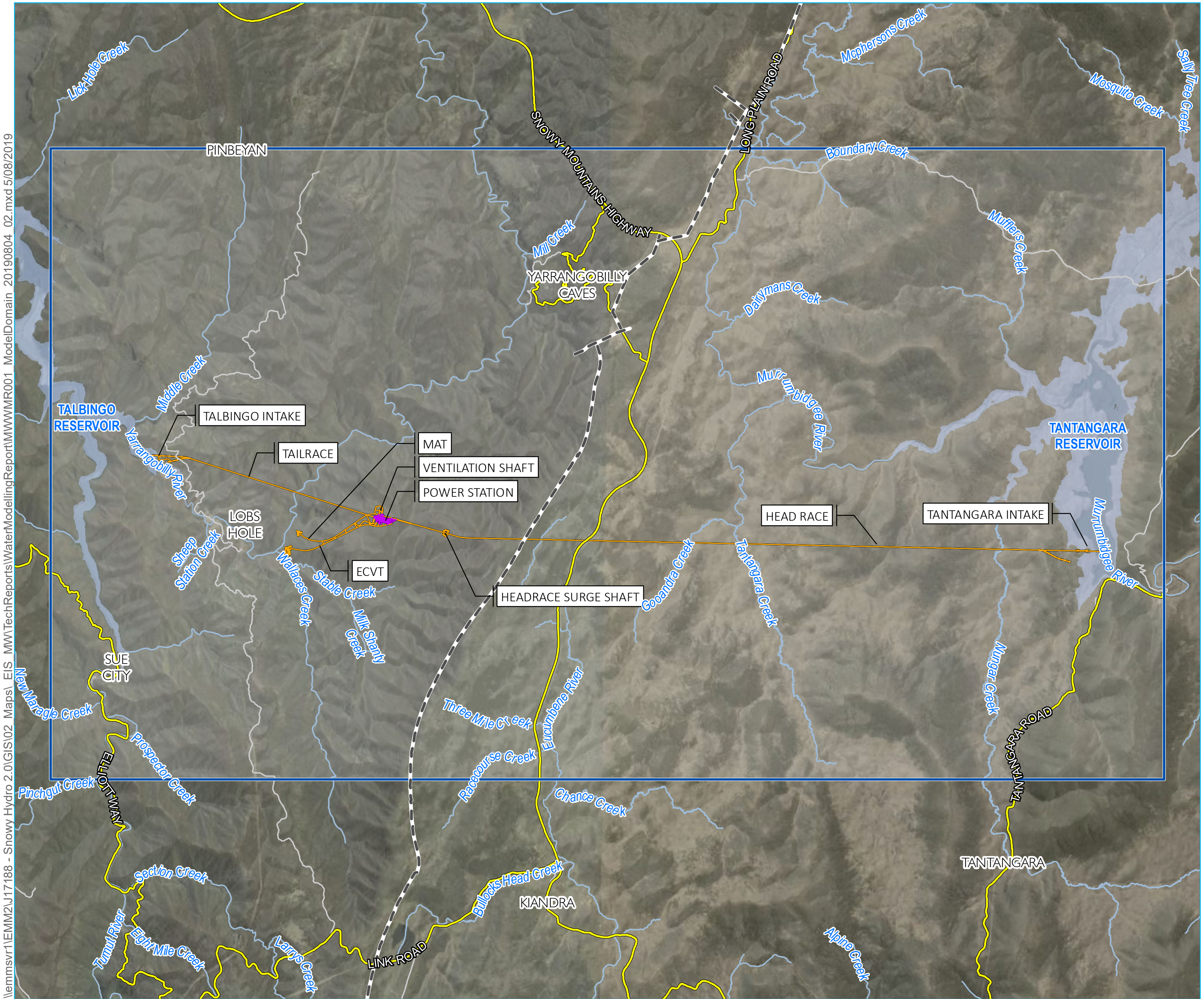


Figure 3.2 Spatial discretisation of the Head Race Tunnel



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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KEY
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

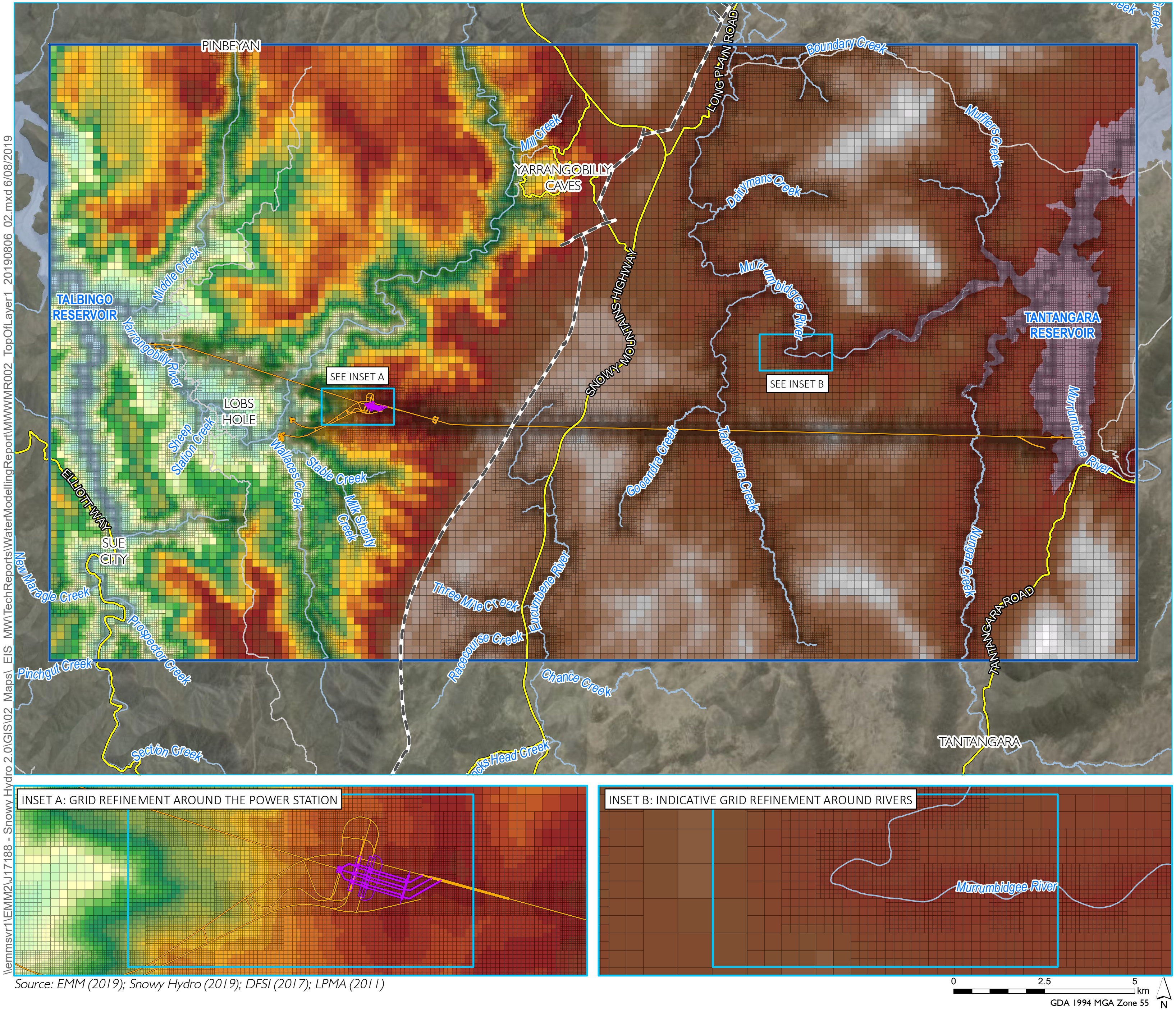
Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

SH4.0 model domain and major features

Snowy 2.0
Modelling Report
Main Works
Figure 3.3

snowy2.0

EMM creating opportunities



KEY

- Long Plain Fault
- Model domain
- Model grid

Snowy 2.0 operational elements

- Tunnels, portals, intakes, shafts
- Power station

Existing environment

- Main road
- Local road
- Perennial watercourse
- Scheme storage

Top of layer 1

High : 1700m

Low : 540m

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

SH4.0 grid and top of layer 1 (topography)

Snowy 2.0
Modelling Report
Main Works
Figure 3.4

3.2.6 Boundary conditions

Regional hydraulic head data, beyond the monitoring bores recently constructed for Snowy 2.0, were not available to suitably inform hydraulic heads or gradients near the model edges. Hence, a conservative approach of assigning no flow boundary conditions around the model domain in all layers was adopted. In this way drawdown induced by depressurisation of the excavations during construction is not incorrectly buffered by model-edge boundary conditions.

i Surface water features

The MODFLOW river (RIV) package was used to represent the Talbingo Reservoir, Tantangara Reservoir and selected rivers and creeks. Initially only perennial surface water features were modelled but, during the calibration process, it became apparent that ephemeral creeks and drainage lines may cumulatively receive a significant volume of baseflow and, hence, a number of these features were subsequently added to the model. It was not practical to model the entire network of draining lines. However, it should be noted that where smaller springs and drainage lines were not represented explicitly in the model with river boundary conditions, modelled evapotranspiration (see next section) removes groundwater in regions where the modelled watertable is near ground surface.

All modelled surface water features were simulated with steady state boundary conditions.

River stage was set at 541 m AHD for Talbingo and 1,215 m AHD for Tantangara, based on analysis of long-term records of reservoir levels. For each reservoir the “river” bottom elevation was set 5 m below stage.

Stage for modelled rivers and creeks was sourced from a 12.5 m by 12.5 m grid of the original 1 m by 1 m LiDAR digital elevation model, with stage then set 1 m below the gridded value. Where model cells were larger than 12.5 m by 12.5 m the lowest elevation data point within the footprint of the model cell was adopted to reduce smearing of topography associated with valleys with hillsides. River bottom elevation was set 1 m below stage for the Murrumbidgee River and Yarrangobilly River. In smaller perennial features (eg Eucumbene River) river bottom was set 0.1 m below stage. River bottom was set equal to stage at ephemeral creeks. In this way the ephemeral creeks can receive baseflow at times when the watertable rises above river stage but the modelled river boundary conditions cannot incorrectly leak water to the groundwater system at times when a creek is dry.

Conductance values assigned to river boundary conditions vary depending on the geometry of the surface water feature and the typical model cell sizes used to represent it. The conductance term used by the MODFLOW river package is:

$$C = K L W / D$$

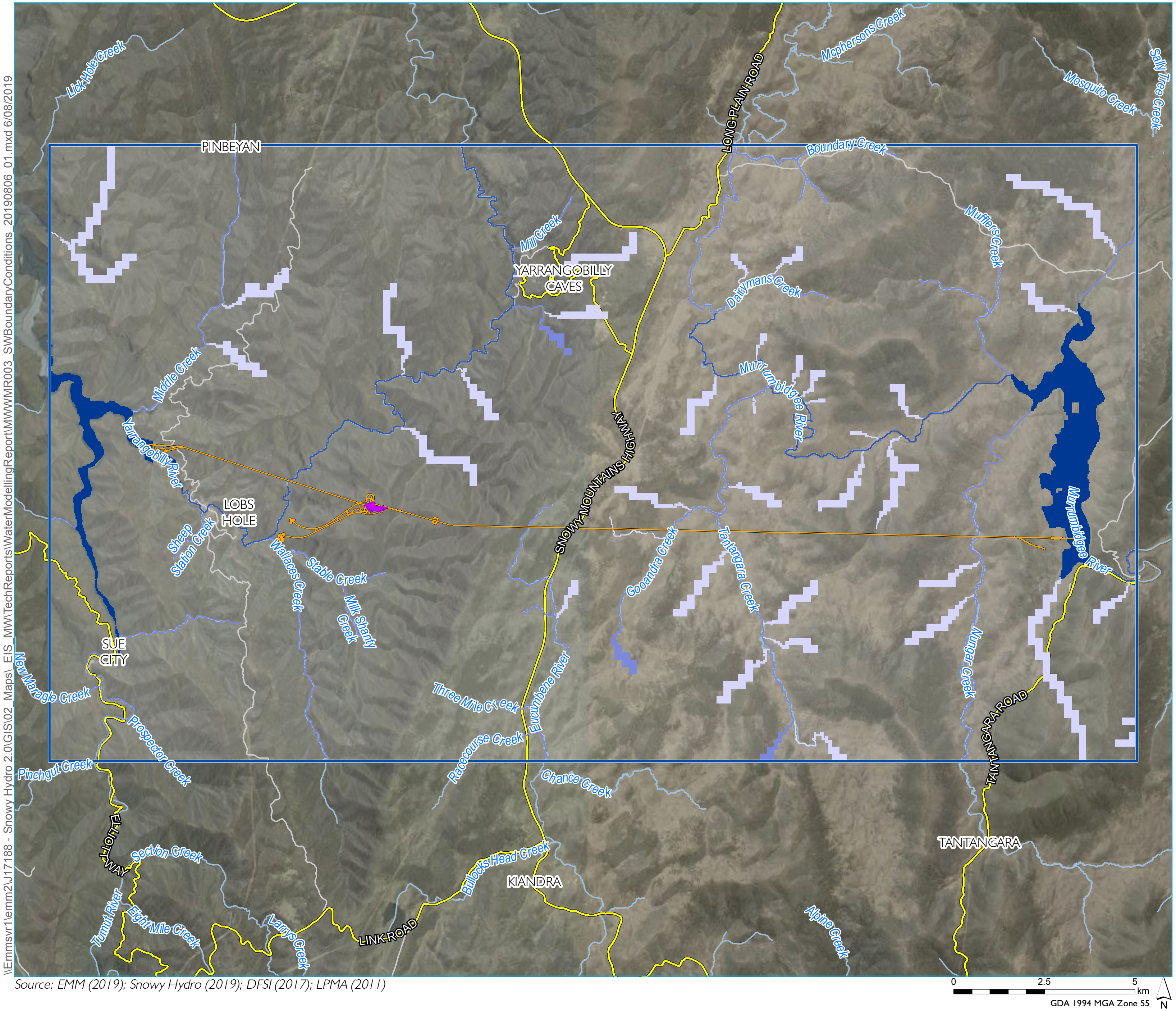
where: K = hydraulic conductivity of the river bed, L = length of the river in the cell, W = width of the river and D = thickness of the river bed material.

No direct measurements of river bed hydraulic conductivity were available. However, some features (eg Gooandra Creek) were observed to flow directly across rock, with no alluvium or eroded material. In the absence of direct data, a value of 0.5 m/d was adopted, consistent with the horizontal and vertical conductivity assigned to the uppermost model layer. The length term was determined from the model cells used to represent surface water features. River width was identified from field observations and aerial imagery. Drive point piezometers were installed at a number of locations and these typically reached refusal around a depth of 1 m. Hence, this value was uniformly adopted for river bed thickness within the conductance equation.

Three values of river bed conductance were assigned:

- Talbingo Reservoir and Tantangara Reservoir: C = 0.5 m/d x 200 m x 200 m / 1 m = 20,000 m^2/d;
- Murrumbidgee River and Yarrangobilly River: C = 0.5 m/d x 25 m x 10 m / 1 m = 125 m^2/d; and
- smaller rivers and creeks: C = 0.5 m/d x 25 m x 1 m / 1 m = 12.5 m^2/d.

Modelled surface water boundary conditions and modelled river conductance are illustrated in Figure 3.5.



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

River boundary conditions
- River stage - river bottom = 5 m, C= 20000 m^2/d
- River stage - river bottom = 1 m, C = 125 m^2/d
- River stage - river bottom = 0.1 m, C = 12.5 m^2/d
- River stage - river bottom = 0 m, C = 12.5 m^2/d
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

Existing environment
- Main road
- Local road
- Perennial watercourse

Surface water boundary conditions

Snowy 2.0
Modelling Report
Main Works
Figure 3.5

ii Rainfall recharge

The model domain spans two distinct areas separated by the Long Plain Fault and topographic high which is oriented approximately 20 degrees clockwise of north. The ravine area lies to the west and the plateau area to the east.

The ravine area is characterised by steeply dipping topography and incised drainage lines, mostly has elevation between around 550 m AHD and around 1,200 m AHD and is largely covered with trees.

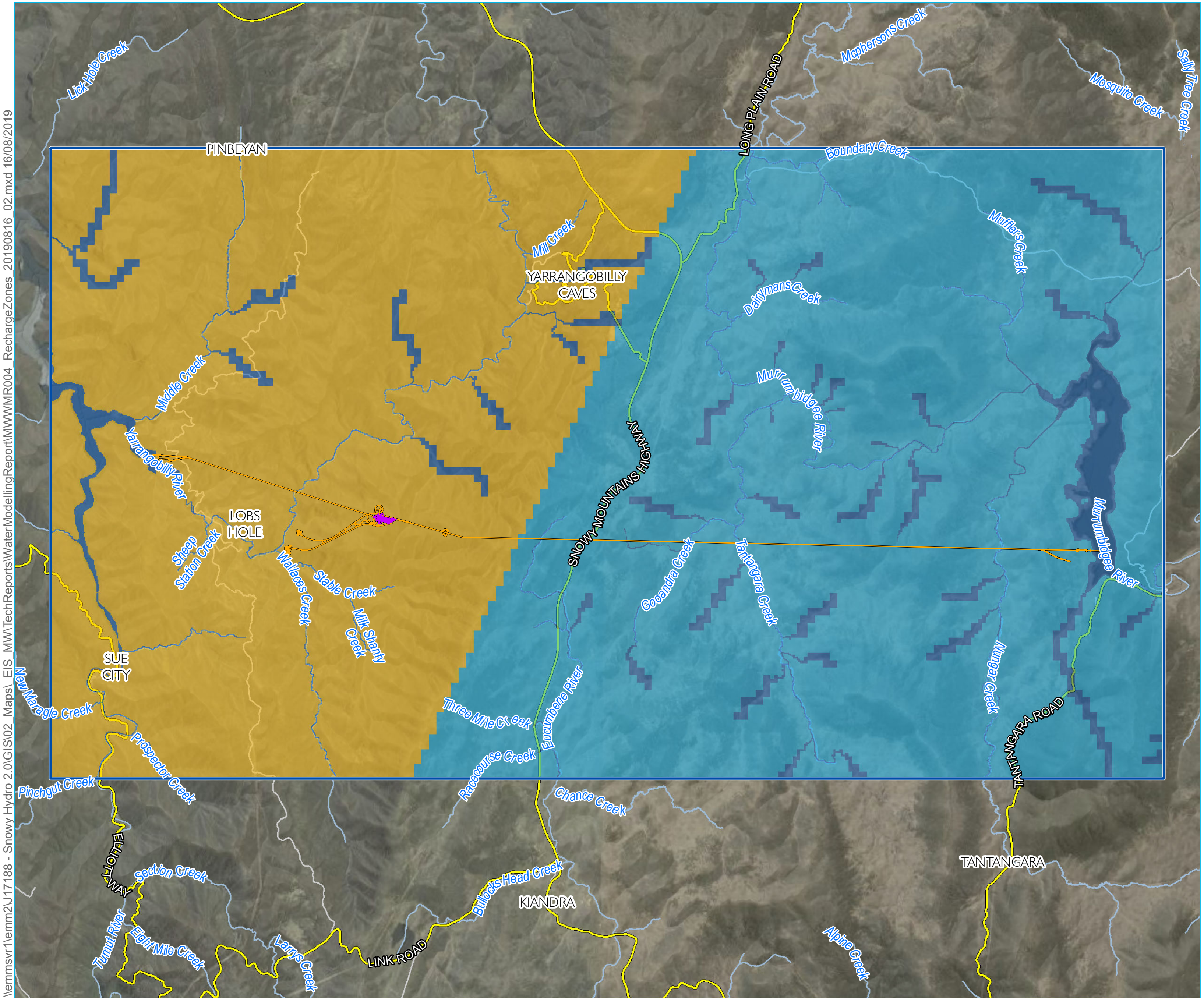
The plateau area is characterised by low relief, mostly has elevation between around 1,200 m AHD and 1,700 m AHD and is largely covered with grasses, marshes and only small stands of tree coverage. As a result of its higher elevation the plateau area is colder than the ravine area and therefore receives more frequent and greater snowfall.

The MODFLOW recharge (RCH) package was used to incorporate the groundwater recharge data provided by the catchment model.

Three zones were used to distribute recharge. The ravine and plateau areas were used to define the two major climatic zones, and a third zone was used to define zero rainfall-derived recharge and zero diffuse baseflow exfiltration for model cells where river boundary conditions were assigned. The modelled recharge and evapotranspiration zones are illustrated in Figure 3.6.

Time series recharge rates to individual catchments simulated by the Source model were aerially aggregated across the ravine and plateau zones simulated by the groundwater model to provide recharge time series for those two zones (see Figure 2.18).

All simulations commence with an initial steady state stress period to generate stable, internally consistent, hydraulic heads prior to subsequent transient stress periods. A five year "average climate" period, spanning 1 December 2007–1 December 2012, was identified as providing a period of relatively stable climate during which the groundwater system may have reached relatively stable conditions. The average recharge rates over this time adopted as steady state climate inputs are shown in Figure 2.18. For reference, the adopted ravine and plateau steady state recharge rates represent approximately 9% and 21% of the mean annual precipitation recorded at the Bureau of Meteorology weather station at Cabramurra SMHEA AWS (station 072161).



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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KEY

Modelled rainfall recharge
Average from Dec 2007 - Dec 2012

- Modelled surface water: recharge = 0 mm/yr
- Ravine: recharge = 101 mm/yr
- Plateau: recharge = 251 mm/yr
- Model domain

Snowy 2.0 operational elements

- Tunnels, portals, intakes, shafts
- Power station

Existing environment

- Main road
- Local road
- Perennial watercourse

Modelled rainfall recharge zones

Snowy 2.0
Modelling Report
Main Works
Figure 3.6

snowy 2.0

EMM creating opportunities

iii Evapotranspiration (diffuse baseflow discharge)

Water supplied to vegetation from a surface water source (including direct rainfall, runoff, interflow, and creek bank seepage) was modelled in the catchment model, and not the groundwater model.

The MODFLOW evapotranspiration (EVT) package was used to simulate diffuse baseflow exfiltration at locations where groundwater reached the surface at a distance from the specified river boundaries without the need to include all the minor creeks and drainage lines, which would require significant model grid refinement that would slow down run times.

In earlier versions of the model that were not linked to a catchment model, the groundwater model utilised different recharge assumptions, and simulated evapotranspiration.

Similar parameters were used within the EVT package as would be used if evapotranspiration were simulated. Extinction depths of 2 m on the plateau and 5 m on in the ravine were used, along with maximum extraction rates similar to daily evapotranspiration data. These parameters ensured model stability, and calibration statistics indicate that the mass balance achieved was acceptable.

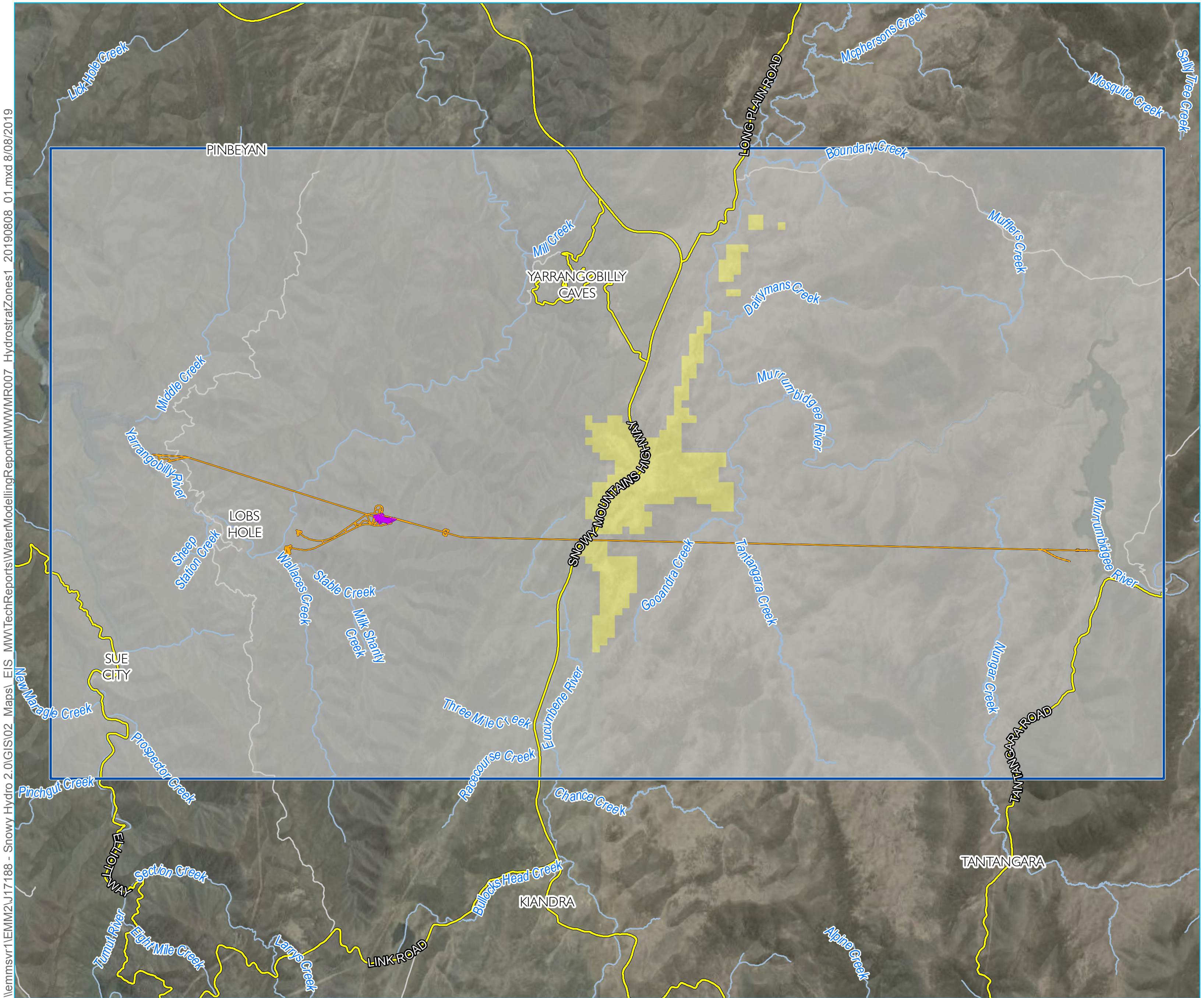
3.2.7 Hydrostratigraphy

Hydrostratigraphic units were assigned to the model for each of the geological units mapped by drilling and geophysical surveys along the project alignment. These data were essentially two-dimensional, following the proposed alignment of the project excavations. Within the model domain, much of the geology has been tipped such that it dips at an angle of around eighty degrees and the units are aligned with the Long Plain Fault. This geometry leant itself to a simple extrapolation at an angle of 20 degrees clockwise of north to delineate hydrostratigraphic units across the model domain. The generated geological surfaces were used to map hydrostratigraphic units to intercepted model layers for model layers 2 to 42.

In addition to the process above, the 6 m thick model layer 1 was assigned to represent weathered material, alluvium and Tertiary Basalt. The presence of Tertiary Basalt was taken from surface geology mapping. Elsewhere the weathered/alluvium unit was assigned.

Modelled hydrostratigraphic units are presented in Figure 3.7 for layer 1 and Figure 3.8 for layer 2. West-east cross sections through the modelled hydrostratigraphic units are presented in Figure 3.9. Model results throughout this chapter on occasion refer to the hydrostratigraphic units using short names, as per the key provided in Figure 3.9.

Available groundwater bore data is focussed around the proposed power waterway alignment, and does not define the extent of the Yarrangobilly Limestone associated with the Yarrangobilly Caves. For this reason the Yarrangobilly Caves located approximately 8 km north of the project alignment are not explicitly represented in the groundwater model. If present at the project alignment, this limestone unit would occur beneath the Ravine Beds and below the proposed project excavations. Given the relatively low hydraulic conductivity of the Ravine Beds it is unlikely that drawdown from project excavations would reach the Yarrangobilly Limestone or propagated at sufficient levels to impact the Yarrangobilly Caves.



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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KEY

Hydrostratigraphic unit

- Weathered/Alluvium
- Tertiary Basalt
- Model domain

Snowy 2.0 operational elements

- Tunnels, portals, intakes, shafts
- Power station

Existing environment

- Main road
- Local road
- Perennial watercourse

Modelled hydrostratigraphic units in layer 1

Snowy 2.0
Modelling Report
Main Works
Figure 3.7

snowy2.0

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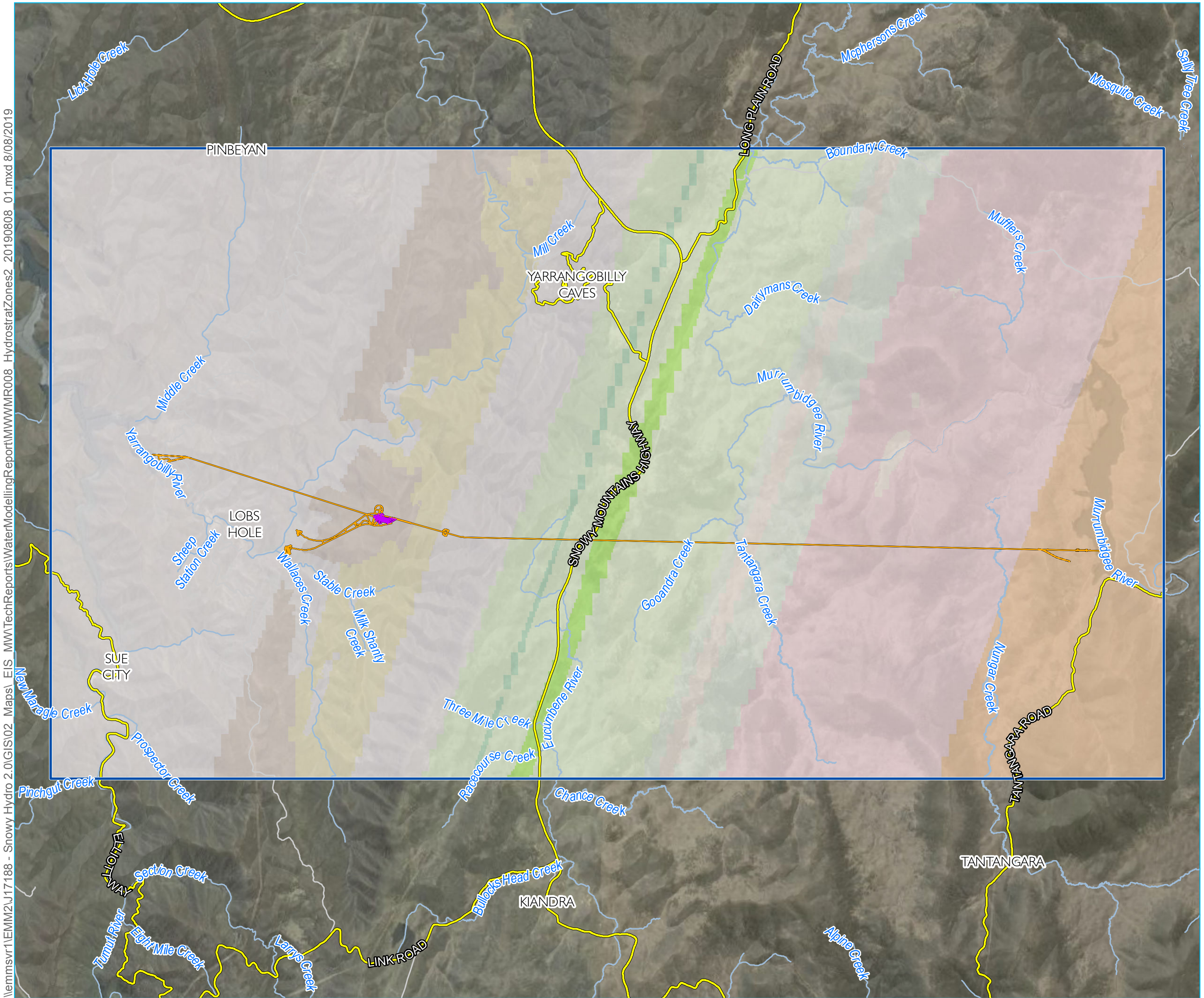


Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

Hydrostratigraphic unit
- Ravine Beds West
- Byron Range Group
- Boraig Group
- Ravine Beds East
- Gooandra Volcanics
- Shaw Hill Gabbro
- Gooandra Volcanics Fractured Zone
- Temperance Formation
- Boggy Plains Suite
- Tantangara Formation
- Granite/Basement
- Kellys Plain Volcanics
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

Existing environment
- Main road
- Local road
- Perennial watercourse

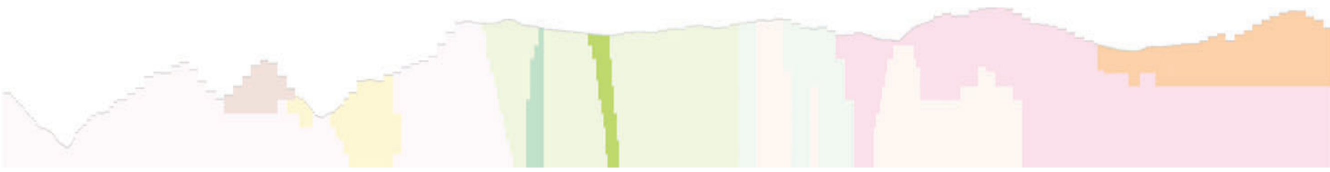
Modelled hydrostratigraphic units in layer 2

Snowy 2.0
Modelling Report
Main Works
Figure 3.8

6043100 m N, ~ 5 km north of project alignment:

6038100 m N, central to project alignment:

6033100 m N, ~ 5km south of project alignment:



West East

KEY

Weathered/Alluvium (WEATH)	Tertiary Basalt (TBAS)	Ravine Beds West (RBW)	Byron Range Group (BRG)	Boraig Group (BOR)
Ravine Beds East (RBE)	Gooandra Volcanics (GOV)	Shaw Hill Gabbro (SHG)	Gooandra Volcanics Fractured Zone (GOVF)	Temperance Formation (TPF)
Boggy Plains Suite (BPS)	Tantangara Formation (TTF)	Granite/Basement (BAS)	Kellys Plain Volcanics (KPV)	

Figure 3.9 West-east cross sections through modelled hydrostratigraphic units

3.3 Calibration and sensitivity analysis

3.3.1 Calibration method and data

The project is located within Kosciuszko National Park and therefore no existing groundwater monitoring network or third party groundwater supply wells exist. Therefore, no groundwater monitoring data were available within or near the model domain prior to proposal of Snowy 2.0.

As part of the water assessment for the project a network of bores was drilled, largely along the project alignment, to conduct hydraulic and geotechnical testing and to monitor and sample groundwater. The network was designed in accordance with the NSW Guidelines for Monitoring and Modelling Plans (DPI Water, 2014) to ensure the requirements of the NSW Aquifer Interference Policy (DPI Water, 2012) would be adequately addressed in the monitoring network and the groundwater model for the project.

Some bores were drilled as dedicated groundwater bores and some were repurposed for groundwater monitoring after geotechnical investigations were conducted. Of the groundwater monitoring locations, some were fitted with vibrating wire piezometers (VWPs) at varying depths within a hole, some were constructed as open hole production wells and others were installed as traditional screened piezometers. For the open hole production wells and piezometers manual depth to water measurements were made to validate logger records. The combination of VWPs, production wells and screened piezometers provides a spatial dataset of hydraulic head monitoring that spans the entire project alignment and provides information on vertical heads gradients down to the elevation of the power waterway.

The earliest groundwater monitoring data date from September 2017 and therefore the guideline value of two years of baseline monitoring data is almost achieved for the project. Baseline data collection is ongoing. Although some bores have almost two years of baseline data, many of the monitoring sites have significantly shorter records as the monitoring network continues to be expanded. Whilst the data do span a full set of seasons, the monitoring of seasonality of groundwater behaviour is limited and the response to prolonged wet or dry periods is not available to inform calibration of the model. Further, the magnitude of stresses involved in dewatering excavations proposed for the project are significantly greater than those induced by climate variability in the monitoring record.

Loggers providing hydraulic head data were typically set to record at frequencies providing more than one measurement per day (often four measurements per day). At a frequency of four measurements per day approximately 365 measurements would be recorded per quarterly model stress period. Given that climate stresses were averaged across each seasonal quarter, and that analysis of measured data indicated negligible response on a sub-daily timescale, measurements were averaged over a day to reduce the dataset to a maximum of one measurement per day per monitoring location.

A number of monitoring sites, mostly those with VWPs installed, have data records with hydraulic head data that either cannot be explained by climate records and/or are significantly different from data recorded at nearby monitoring locations. Several of the VWP sites display a drift, some spanning many months, in measured hydraulic head. The project groundwater team concluded that it is likely these are approaching equilibrium with the surrounding groundwater environment but that the selection of grout may have led to a prolonged time period for this to occur. At sites/times where data were clearly still equilibrating from installation the data were excluded from the calibration dataset. Attachment E displays the excluded data for all sites at which all or part of the data records were excluded. Following exclusion of those data a total of 25,766 transient hydraulic head measurements were collated to provide a transient calibration data set.

Given the apparent ongoing equilibration at some monitoring sites, and the relatively minor influence of seasonality on groundwater (less than 10 m over the monitoring period) when compared with the range in hydraulic head across the monitoring sites, the most recent measurement at each site was adopted as a steady state calibration target. This produced a total of 106 steady state hydraulic head measurements for steady state calibration.

Diffuse baseflow discharge (using the EVT package) and baseflow discharge directly to creeks (using the RIV package) were compared to the baseflow estimates obtained from the catchment model, to confirm that the two models were mass consistent.

Hydraulic testing through constant rate pumping tests (CRTs), constant head pumping tests (CHTs), slug tests, drill stem tests (DSTs) and packer tests provided guidance on hydraulic conductivity and storage properties of most hydrostratigraphic units.

The combination of hydraulic head measurements, baseflow calculations and hydraulic property testing were used to inform calibration of the model in both steady state and transient modes.

The history matching calibration model was designed such that it would commence following a period of relatively uniform climate, using average rainfall recharge and potential evapotranspiration from the period 1 December 2007–1 December 2012. A steady state stress period was defined at the beginning of the model using these climate inputs to a) provide a means for steady state calibration and b) to generate stable, internally consistent, initial hydraulic heads for the subsequent transient stress periods. Twenty six transient quarterly stress periods, aligned with the seasons, were then simulated spanning the period 1 December 2012–1 June 2019. This provided almost five years of transient simulation, or "warm-up" prior to the first available groundwater monitoring data for history matching, in late November 2017.

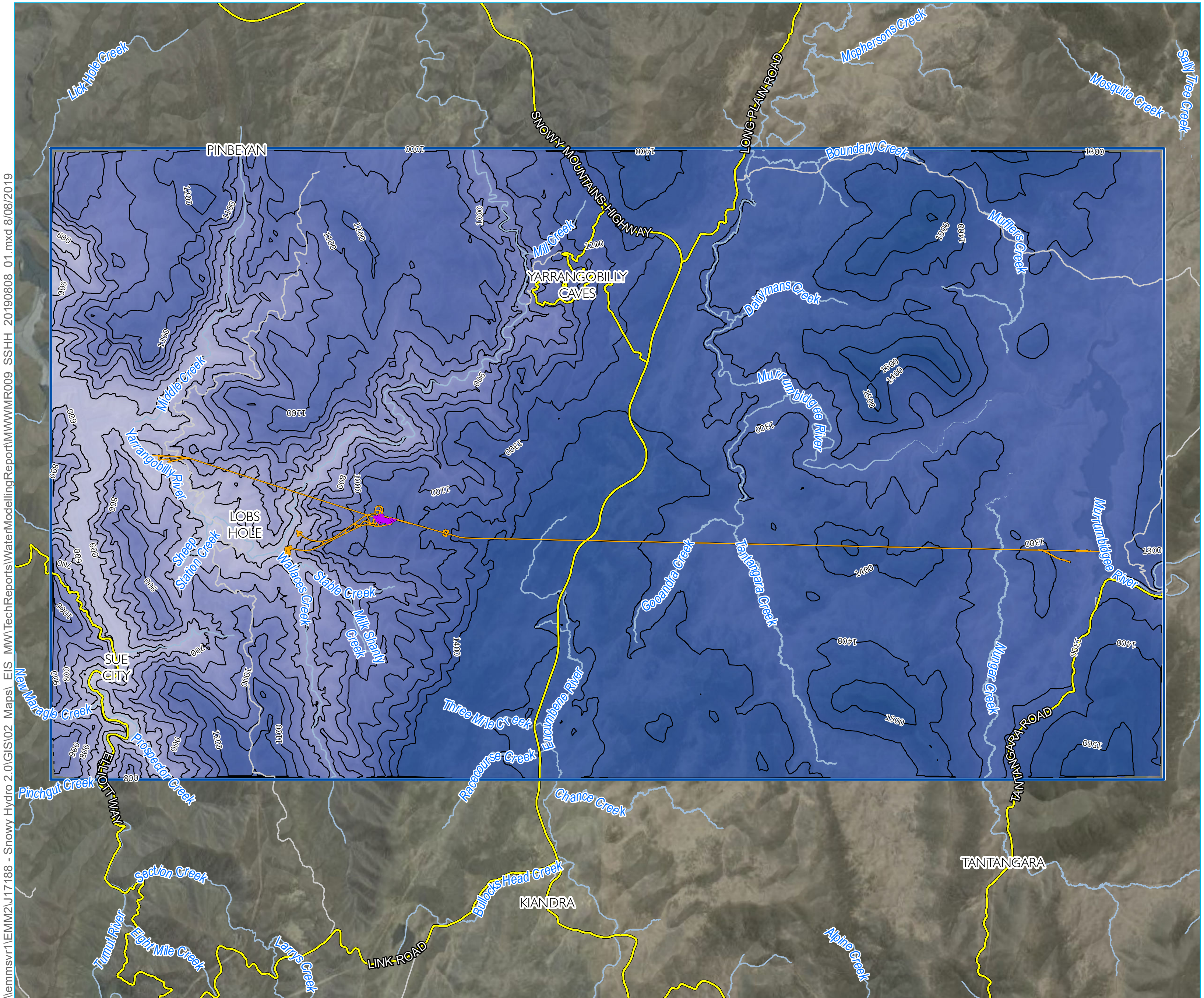
Due to the computational duration of model runs, automated calibration software was not employed. A manual calibration and sensitivity analysis process, constrained by the conceptual model, was undertaken to identify appropriate parameter values and bounds for predictive modelling.

3.3.2 Hydraulic head

Modelled steady state (December 2012–December 2017 climate) watertable elevation is presented in Figure 3.10. The modelled watertable generally mimics topography. Two distinct regions are evident, with steeply dipping watertable elevation around the hills and incised valleys of the ravine area contrasting with the undulating watertable in the plateau area.

Modelled watertable elevation ranges from 540 m AHD1,613 m AHD. A groundwater divide extends into the model domain from the southern boundary, roughly in line with the Snowy Mountains Highway and Long Plain Fault, with groundwater flowing west towards Talbingo Reservoir and east towards Tantangara Reservoir. The divide is coincident with the Gooandra Volcanics, Gooandra Volcanics Fractured Zone and Shaw Hill Gabbro hydrostratigraphic units. It ends where the lowlands associated with the Murrumbidgee River, upstream of Tantangara Reservoir, extend further west.

In addition to the two reservoirs and the major rivers, there are smaller rivers, creeks, ephemeral watercourses and drainage lines that also provide groundwater discharge points and topographic constraints for the watertable.



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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

0 2.5 5 km

GDA 1994 MGA Zone 55

N

KEY

Steady state hydraulic head contour (100m)

Steady state hydraulic head (m)

1610

540

Model

Snowy 2.0 operational elements

Tunnels, portals, intakes, shafts

Power

Existing environment

Main

Local

Perennial watercourse

Modelled hydrostratigraphic units in layer 2

Snowy 2.0

Modelling Report

Main Works

Figure 3.10

snowy2.0

EMM creating opportunities

3.3.3 Water balance

The modelled steady state (December 2007–December 2012) water balance is presented in Figure 3.11. Inflow to the groundwater system is almost entirely from rainfall recharge (87,546 ML/yr). Leakage from rivers is almost negligible at 788 ML/yr, which equates to 0.9% of the total water balance.

Groundwater was removed from the model by baseflow direct to surface water features (22,090 ML/yr) and diffuse baseflow discharge (66,244 ML/yr).

It should be noted that, although not simulated in the model, there will be some groundwater flow across the edges of the model domain. However, given the location of the reservoirs, that act as regional groundwater discharge/low points, at the western and eastern edges of the model, there is likely only minor flow across these boundaries. Similarly, the northern and southern model boundaries likely have minimal flow across them because the primary flow directions in the model domain are west and east, away from the groundwater divide associated with the Long Plain Fault, towards the two reservoirs.

The modelled water balance, averaged for each quarterly stress period, over the transient history matching period is presented in Figure 3.12. The large variation in modelled recharge between seasons is partly balanced by movement of water into storage during wet seasons and out of storage during dry seasons. Baseflow discharging directly to surface features remained relatively constant through the model period, consistent with observations that rivers and creeks in the project area continue to flow through summer. Diffuse baseflow discharge varied seasonally, with a peak discharges occurring with a two stress period (6 month) lag after peak recharge (cf the 2–3 month lag seen in the Q-Lag analysis; section 2.6.5).

Numerical error in the modelled water balance for both steady state and transient modes is 0.00%.

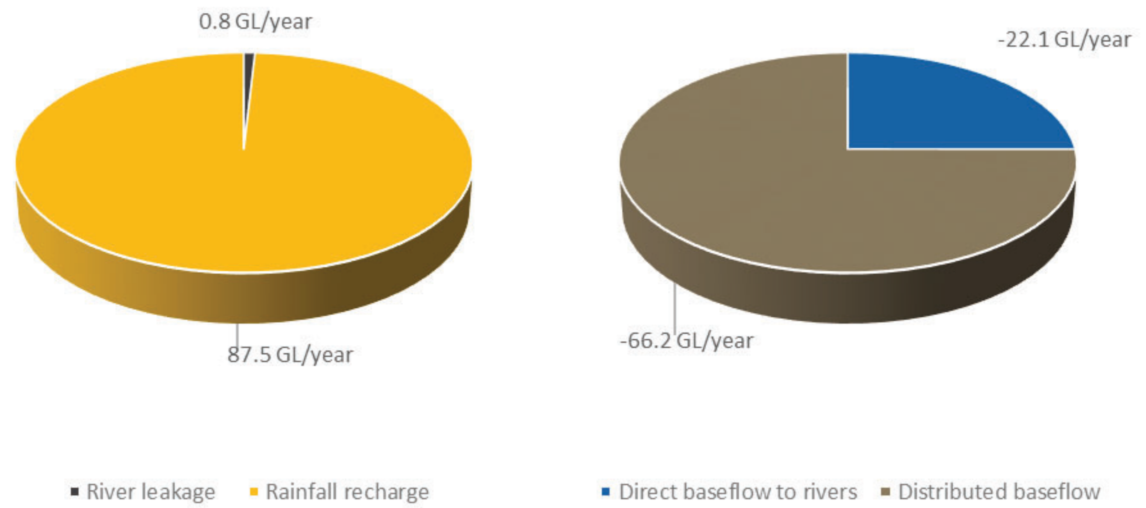


Figure 3.11 Modelled steady state water balance (ML/year) (Dec 2007-Dec 2012 climate)

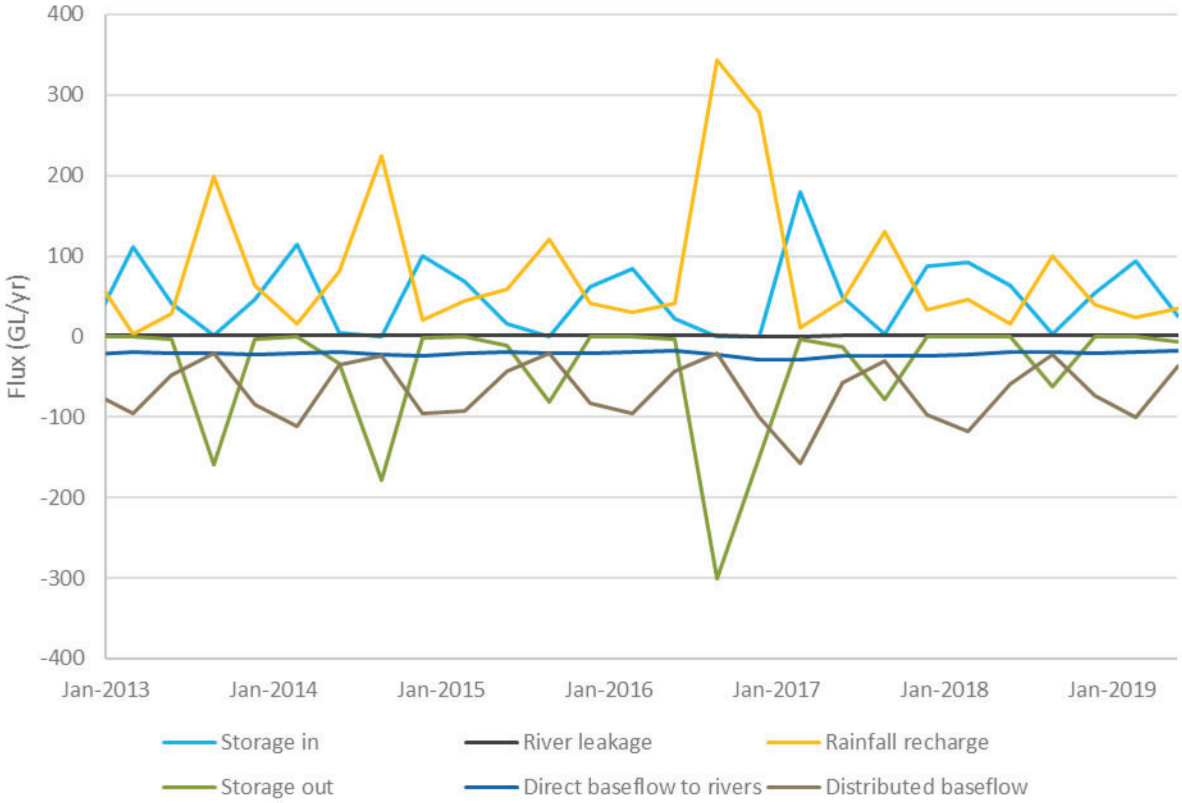


Figure 3.12 Modelled transient history matching period (calibration) water balance

3.3.4 Calibration performance

Calibration performance was assessed in several ways, including statistical measures, temporal trends and comparison baseflow discharges modelled in the catchment model.

Statistical measures of "error" between measured and modelled hydraulic head were employed to quantify the model's ability to match historical observations both in steady state and transient modes. Table 3.1 presents calibration statistics for the adopted base case "calibrated" parameter values. Statistics for steady state and transient modes are very similar due to the relatively small degree of seasonality in hydraulic head records relative to the variability in hydraulic head between monitoring locations. Over the short period of monitoring available, hydraulic head varies on the order of centimetres near surface water bodies, up to around 5 m in mid slope areas and up to almost 10 m at recharge locations relatively removed from surface water and topographic constraints. By comparison, hydraulic head between monitoring locations varies more than 900 m, from 561 m AHD at PB05 in the ravine area to a high of 1479 m AHD at MB11A in the Gooandra Volcanics around the groundwater and topographic divides between the ravine and plateau areas.

Scaled root mean squared (SRMS) error is often used as a guide to assess overall match between measured and modelled values. Steady state and transient SRMS values are 3.6% and 3.9% respectively. Whilst there is no universal value that can be used to determine a good match, these values would typically be accepted as indicating a good match between modelled and measured values. This measure indicates performance of the model on a regional scale, as it is intended to be used.

The absolute residual mean indicates that, on average, modelled values are 21.09 m (steady state) and 23.78 m (transient) from measured values. When scaled by the range of observed values these errors are only 2.3% and 2.6% respectively but, when looking at absolute modelled head at an individual location, these differences may be considered significant.

The model is designed to predict regional-scale hydraulic head and water balance impacts, which are calculated as differences between a simulation of the project and a "null scenario" (without the project). By calculating a difference, duplicated biases or variations between modelled and actual hydraulic head or groundwater flow cancel each other out either partially or completely. In this way predictions of drawdown between a project scenario and a null scenario generally contain less uncertainty than predictions of absolute hydraulic head values.

Table 3.1 Overall calibration statistics

Statistic	Steady state	Transient
Number of observations	106	25,766
Residual mean	-5.79 m	-9.20 m
Absolute residual mean	21.09 m	23.78 m
RMS error	33.29 m	36.19 m
Scaled absolute residual mean	2.3%	2.6%
Scaled RMS	3.6%	3.9%

To quantify the goodness of fit between modelled and measured hydraulic head values on a more local scale, Table 3.2 presents steady state SRMS error calculated a) only for observations in a given hydrostratigraphic unit; and b) only for observations in a hydrostratigraphic unit or those with which it is in direct contact. Four units have no SRMS value reported for observations in that unit because, either there are no observations in that unit, or there is only one observation (in which case it cannot be normalised). Whilst these statistics have limited value where there are very few measurements, it is clear that the model provides a very good statistical match (SRMS of 1.47%) to near surface measurements located in model layer 1. These are generally drive point piezometers installed near rivers, creeks or bog/fen features which are important when considering potential impacts of the project.

Scatter plots of modelled and measured hydraulic head, coloured by hydrostratigraphic unit, are presented in Figure 3.13 (steady state) and Figure 3.14 (transient). The two figures are very similar due to the minor contribution of seasonality to hydraulic head values when compared with the impact of topography. The data align generally with a 1 to 1 line, both in slope and distribution, indicating no overall bias.

Figure 3.15 presents the distribution of residuals spatially, coloured and sized to indicate the direction and magnitude of differences between measured and modelled hydraulic head. All values are plotted regardless of the elevation/depth of the monitoring location. Positive and negative differences are distributed across the domain, although clustered around the project alignment. In some areas larger positive residuals are located adjacent larger negative residuals. In part this may be due to the highly heterogeneous nature of the fractured rock environment, but it may also indicate the limited accuracy of the measured hydraulic head data to date from several of the VWPs. In such a case the measured values do not represent the hydraulic head in the aquifer but, rather, a localised pressure around the grouted sensor in the hole.

Table 3.2 Steady state SRMS error by hydrostratigraphic unit

Hydrostratigraphic unit	Abbreviation	Number of measurements	SRMS: hydrostratigraphic unit only	SRMS: hydrostratigraphic unit plus neighbouring units
Weathered/alluvium/Tertiary basalt	WEATH/TBAS	17	1.47%	*
Kellys Plain Volcanics	KPV	1	-	15.42%
Tantangara Formation	TTF	12	17.59%	2.33%
Temperance Formation	TPF	3	13.69%	10.18%
Boggy Plains Suite	BPS	3	428.76%	18.29%
Gooandra Volcanics	GOV	28	7.20%	2.15%
Gooandra Volcanics Fractured zone	GOVF	3	10.44%	7.04%
Shaw Hill Gabbro	SHG	0	-	1.09%
Ravine Beds East	RBE	16	25.51%	7.39%
Byron Range Group	BRG	0	-	3.72%
Boraig Group	BOR	11	18.71%	3.66%
Ravine Beds West	RBW	12	8.07%	3.72%
Basement	BAS	0	-	2.68%

Note: - Unable to calculate due to lack of observations, or only one observation, in the hydrostratigraphic unit.
* Not calculated as weathered/alluvium unit spans entire model and contacts most other hydrostratigraphic units. Hence, the SRMS error for this is essentially the overall SRMS.

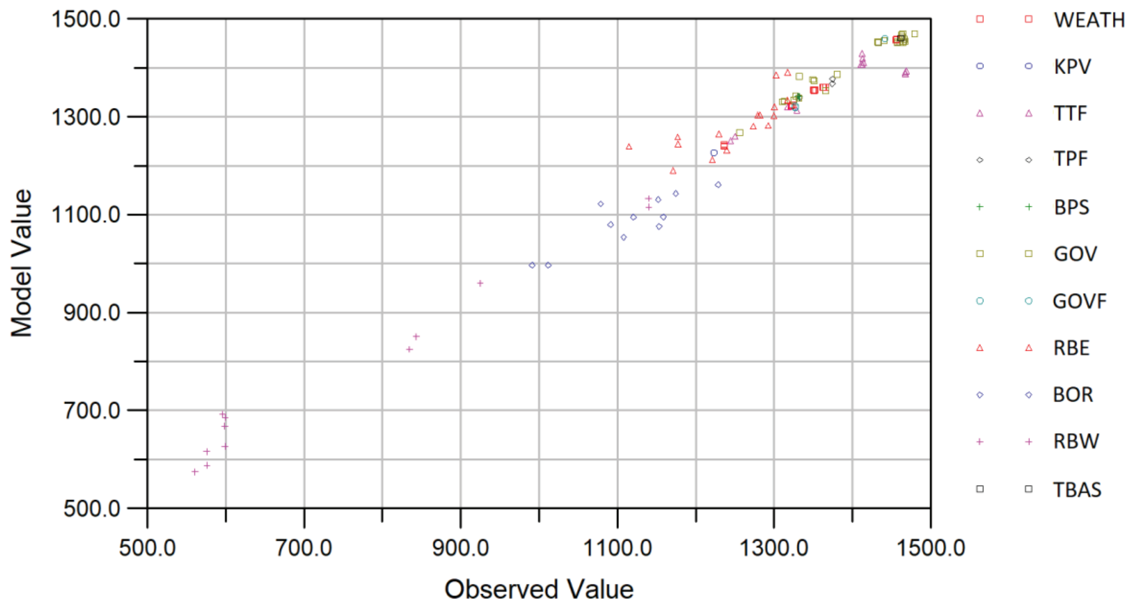


Figure 3.13 Scatter plot of steady state modelled vs measured hydraulic head

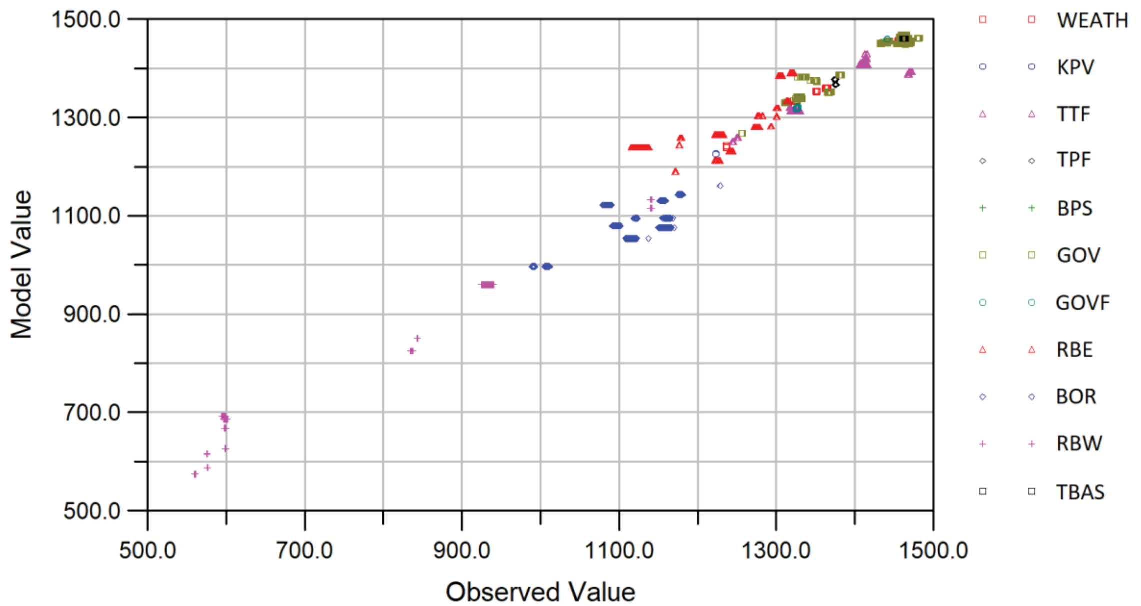
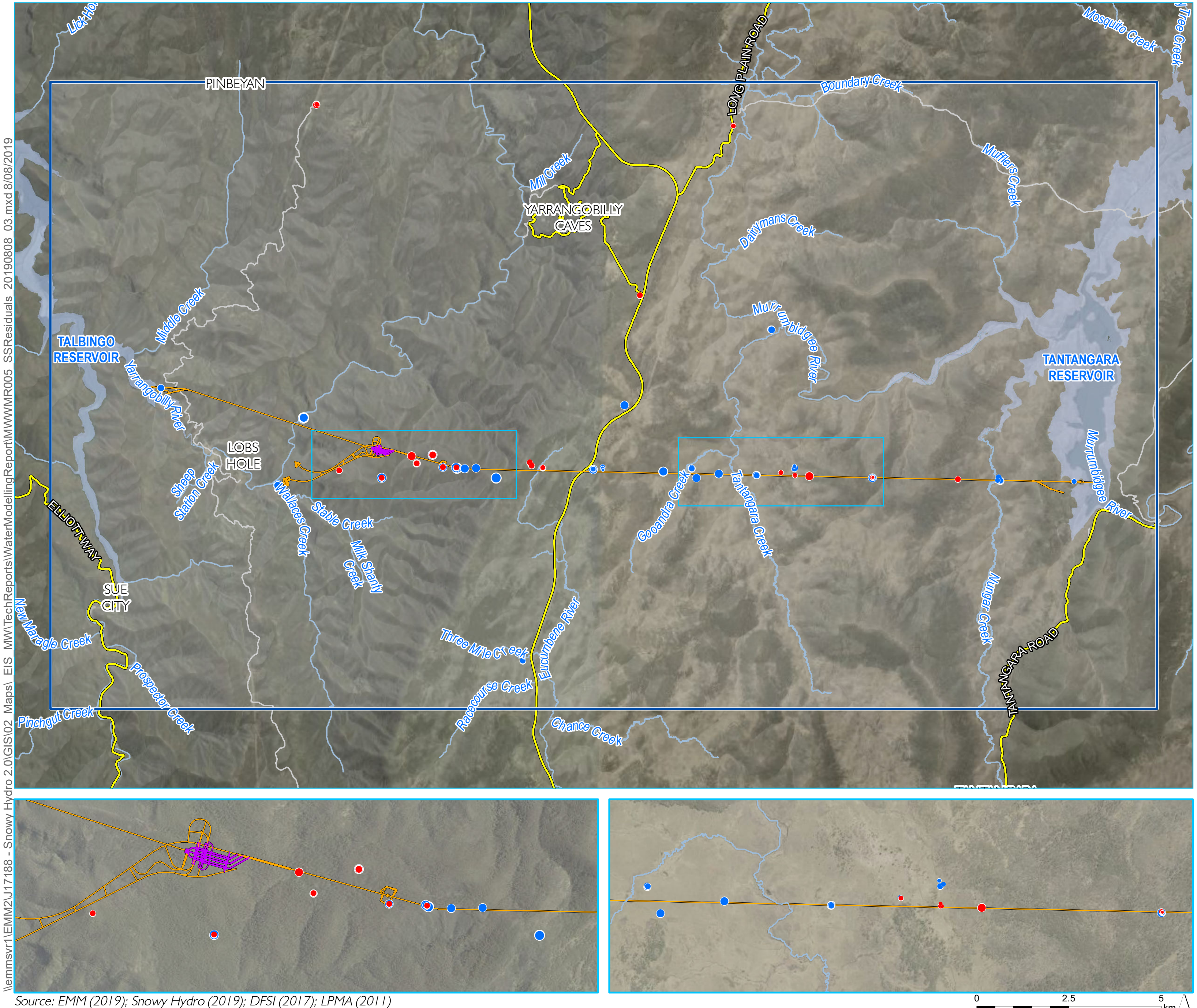


Figure 3.14 Scatter plot of transient modelled vs measured hydraulic head



KEY

Residual value (m)

- 5
- 10

Steady state hydraulic head residuals

- Negative residual value
- Positive residual value
- Model domain

Snowy 2.0 operational elements

- Tunnels, portals, intakes, shafts
- Power station

Existing environment

- Main road
- Local road
- Perennial watercourse
- Scheme storage

Steady state hydraulic head residuals (measured – modelled)

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

Model performance at nested sites in different hydrostratigraphic units across the project alignment are displayed in Figure 3.16 and Figure 3.17 over the transient history matching period for selected monitoring sites.

Measured data at site BH5110 display a downward vertical gradient, indicating potential groundwater recharge at this site. Whilst the modle does not replicate the absolute values at each of the three sensors, it does replicate the magnitude and direction of the observations.

Similarly, site BH5114, in the Ravine Beds east is a recharge site. Modelled hydraulic heads are closer to the absolute values at this site and replicate the magnitude and direction of the vertical gradient.

At site BH4101, located in the Gooandra Volcanics, measured hydraulic head data indicate a potential recharge site but with a much lower hydraulic gradient. Hydraulic testing data from the Gooandra Volcanics unit indicate it has a much higher vertical hydraulic conductivity than most of the other hydrostratigraphic units. This leads to lower vertical gradients when the same recharge is received. Although the modelled absolute hydraulic heads at this site are around 20 to 30 metres from the measured values, the direction and comparitively low magnitude of the vertical gradient are matched.

At site BH2101, located in the Tantangara Formation, the two sensors display an upward vertical gradient. This indicates potential groundwater discharge towards ground surface. The site is located approximately 100 m east of Nungar Creek, which is conceptualised as a gaining creek. The model replicates both the upward gradient and baseflow to Nungar Creek.

The following three sites (Figure 3.17), located at Gooandra Hill, Nungar Creek and Tantangara Creek are located in or near surface water features or bogs/fens. All three sites display modelled and measured hydraulic head values very close to and slightly above ground surface, consistent with these being groundwater discharge sites.

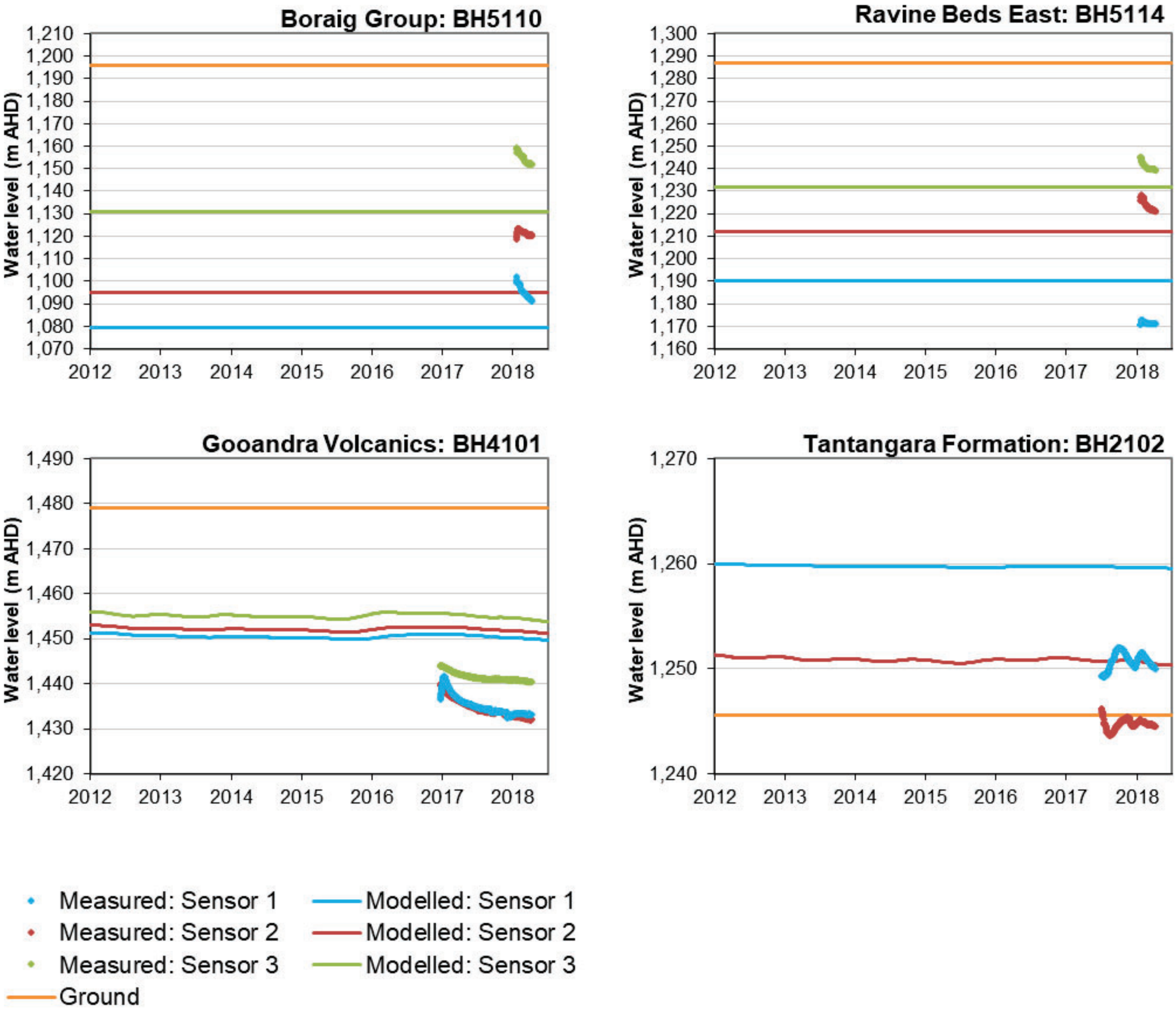


Figure 3.16 Selected measured and modelled groundwater hydrographs

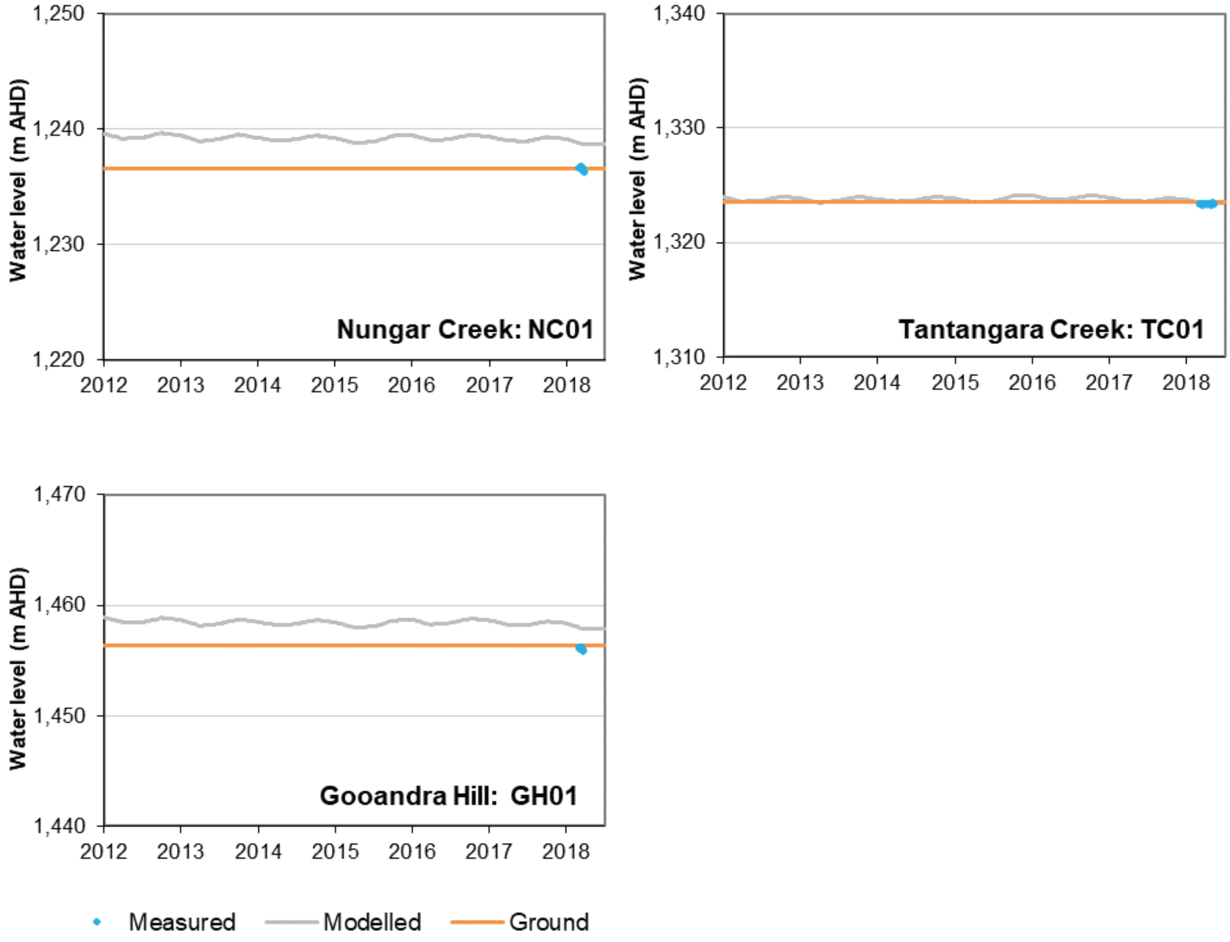


Figure 3.17 Selected measured and modelled groundwater hydrographs for weathered / alluvial material

River boundary condition reaches and topographic catchment were used to aggregated modelled baseflow to seven key surface water features using flow to the modelled feature itself and flow to its tributaries:

- Middle Creek;
- Yarrangobilly River upstream of the gauge (not including Wallaces Creek and Stable Creek);
- Wallaces Creek;
- Stable Creek;
- Eucumbene River;
- Murrumbidgee River upstream of the gauge (not including Tantangara Creek and Gooandra Creek);
- Tantangara Creek;
- Gooandra Creek; and
- Nungar Creek.

Figure 3.18 and Figure 3.19 present baseflow hydrographs from the surface water model and the groundwater model using quarterly averages. Yarrangobilly River, Murrumbidgee River and Eucumbene River each have catchments than extend beyond the model domain boundaries. Results presented include data only for the portion of these rivers within the groundwater model domain.

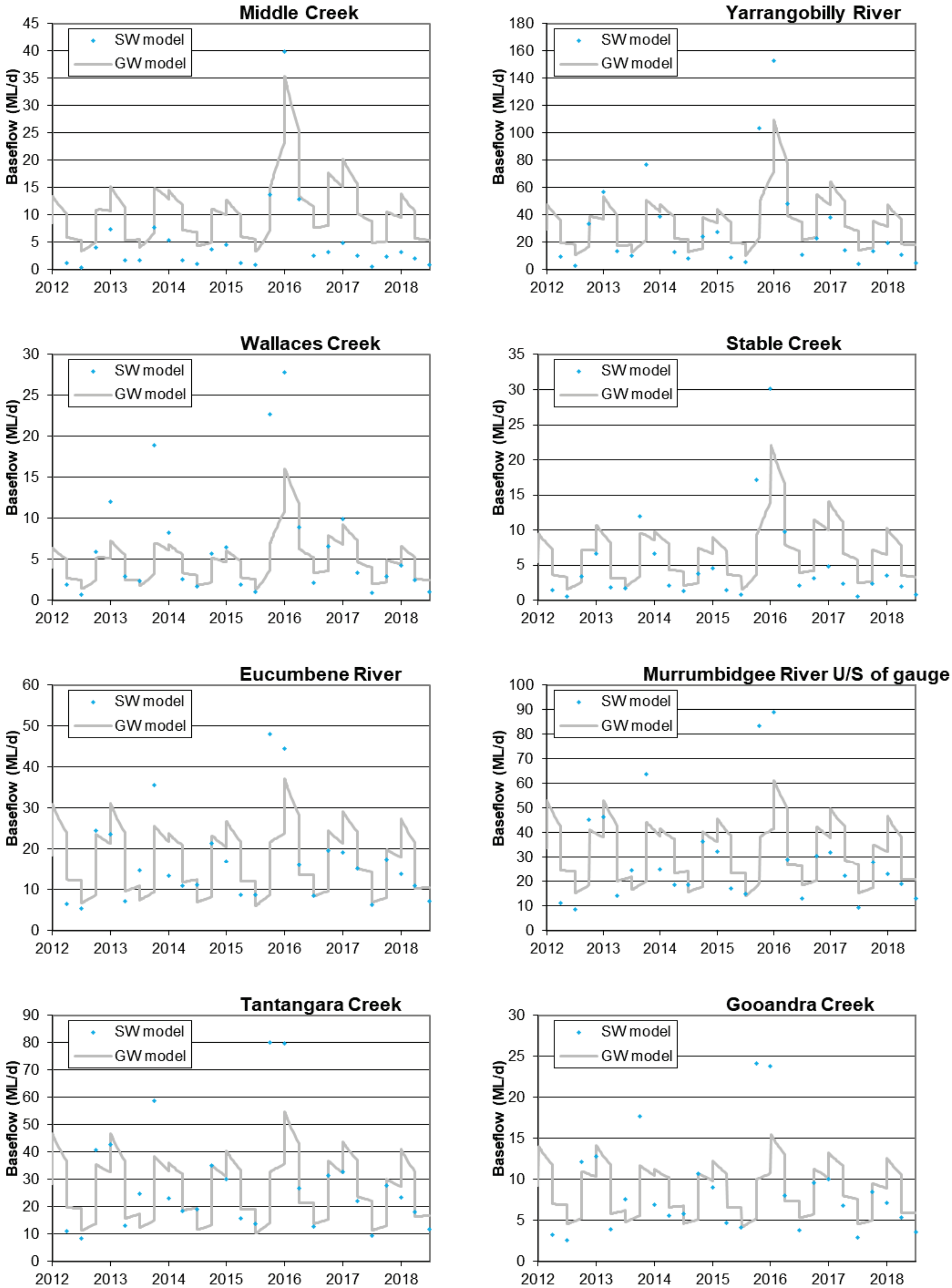


Figure 3.18 Comparison of groundwater and surface water modelled baseflow

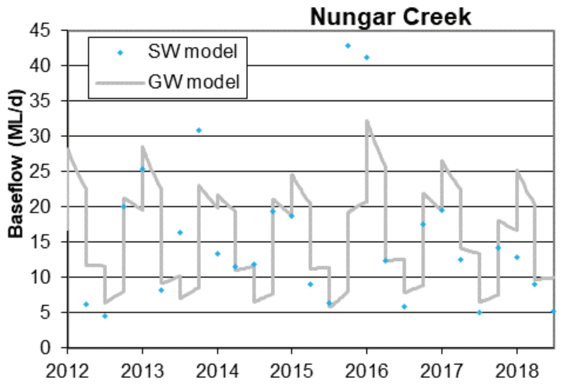


Figure 3.19 Comparison of groundwater and surface water modelled baseflow (Cont.)

3.3.5 Calibrated aquifer properties

Calibrated base case aquifer properties, along with results of field constant rate, constant head, slug, drill stem and packer tests are tabulated in Table 3.3. Adopted base case hydraulic conductivity values are within the anticipated ranges and consistent with the conceptual model.

The uppermost model layer, representing weathered material, alluvium and Tertiary basalt, is simulated as a highly permeable layer with relatively high storage. Specific yield of 10% was adopted. This value was also assigned as specific storage because this layer is effectively unconfined.

The majority of deeper hydrostratigraphic units have adopted hydraulic conductivity values in the order of 10^{-4} m/d. The exceptions are the Gooandra Volcanics, along with the Shaw Hill Gabbro and Gooandra Volcanics fractured zone that both occur within the extent of the Gooandra Volcanics, and the Kellys Plain Volcanics. Hydraulic conductivity values adopted for these units are approximately two orders of magnitude higher than for the rest of the deeper hydrostratigraphic units. These elevated hydraulic conductivity values are consistent with constant rate pumping tests conducted at PB04 and TMB03C in the Gooandra Volcanics and PB01 in the Kellys Plains Volcanics that indicated significant connection between production bores at tunnel invert levels and shallow monitoring bores.

Because the history matching period contains only climatic stresses that do not desaturate the deeper hydrostratigraphic units, the specific yield value of these units could not be calibrated and an indicative hard rock value of 1% was adopted. Specific storage of 5×10^{-6} 1/m was adopted for all deep units except for the granite/basement intrusions where a lower value of 1×10^{-6} 1/m was adopted. These are within the maximum range of plausible specific storage value recently identified by Rau et al (2018) as 2.3×10^{-7} 1/m to 1.3×10^{-5} 1/m.

The geology in the project area was observed to have a north-south strike, with dip angles of nearly 90° observed in the field near the Snowy Highway. This rotation of foliation planes could indicate that the north-south and vertical directions may have higher hydraulic conductivity than the east-west direction. Insufficient data was obtained during pumping tests to test this theory, and so isotropic assumptions were applied to most geological units in the model. If the east-west direction has a lower hydraulic conductivity than modelled, tunnel impacts would propagate ahead of the excavation at a slower rate than modelled.

Table 3.3 Calibrated and measured aquifer properties

		Calibrated property				Test type	Constant Rate and Constant Head test[1]			Slug test[2]	Drill Stem test[3]	Packer test[4]
Unit		Kh (m/d)	Kv (m/d)	Sy (-)	Ss (1/m)	Test site	Kh (m/d)	Kv (m/d)	Ss (1/m)	K (m/d)	K (m/d) (bore average)	K (m/d) (bore average)
Weathered/ Alluvium	WEATH	0.5	0.5	0.1	0.1 (unconfined)	GH01				1.2		
						GH02				0.41		
						GH03				0.63		
						TC01				0.013		
						TC02				0.015		
						TC03				0.035		
						BH01				0.13		
						BH03				0.10		
Tertiary Basalt	TBAS	0.5	0.5	0.1	0.1 (unconfined)	MB01B				11		
Ravine Beds West	RBW	0.001	0.0001	0.01	5×10^{-6}	PB05: BH7106	0.00033		2.6×10^{-7}			
						TMB05A				0.13		
						TMB05B				<0.0060		
						TMB01A				3.27		
						TMB01B				<0.00034		
						BH5107					0.00041	
Byron Range Group	BRG	0.0005	0.0001	0.01	5×10^{-6}							
Boraig Group	BOR	0.0005	0.0001	0.01	5×10^{-6}	BH5110					0.00004	
						BH5113C					0.00029	
						BH5105C					0.00002	
Ravine Beds East	RBE	0.0003	0.0003	0.01	5×10^{-6}	PB09: MB12B	0.0007		6.3×10^{-7}			
						PB09: MB12A	< detection	< detection				
						BH5111					0.00044	
						BH5114					0.031	
						BH5115					0.00027	

Table 3.3 Calibrated and measured aquifer properties

		Calibrated property				Test type	Constant Rate and Constant Head test[1]			Slug test[2]	Drill Stem test[3]	Packer test[4]
Unit		**Kh (m/d)**	**Kv (m/d)**	**Sy (-)**	**Ss (1/m)**	**Test site**	**Kh (m/d)**	**Kv (m/d)**	**Ss (1/m)**	**K (m/d)**	**K (m/d) (bore average)**	**K (m/d) (bore average)**
Gooandra Volcanics	GOV	0.005	0.005	0.01	5×10^{-6}	PB04: SMB04	0.032		7.8×10^{-6}			
						PB04: SMB05	0.013	0.017	1.1×10^{-5}			
						TMB03C: TBM03A	0.014		1.0×10^{-7}			
						TMB03C: TMB03B	0.00078	0.17	1.0×10^{-8}			
						MB02				0.037		
						MB03				4.2		
						MB07A				55		
						MB07B				0.013		
						TMB02A				0.11		
						TMB02B				0.59		
						TMB04				0.36		
						BH4106					0.041	
						BH4105					0.00005	
Shaw Hill Gabbro	SHG	0.01	0.01	0.01	5×10^{-6}							
Gooandra Volcanics Fractured Zone	GOVF	0.01	0.01	0.01	5×10^{-6}	MB01C				42		
						MB04A				0.013		
						MB04B				0.017		
Temperance Formation	TPF	0.0001	0.0001	0.01	5×10^{-6}	PB10	8×10^{-6}		2.5×10^{-6}			
						MB13B				0.0027		
						BH3102						0.0029

Table 3.3 Calibrated and measured aquifer properties

		Calibrated property				Test type	Constant Rate and Constant Head test[1]			Slug test[2]	Drill Stem test[3]	Packer test[4]
Unit		Kh (m/d)	Kv (m/d)	Sy (-)	Ss (1/m)	Test site	Kh (m/d)	Kv (m/d)	Ss (1/m)	K (m/d)	K (m/d) (bore average)	K (m/d) (bore average)
Boggy Plains Suite	BPS	0.0001	0.0001	0.01	5×10^{-6}	PB03	8.8×10^{-8}					
						BH3110				0.020		
						BH3110						0.0012
						BH3106						0.0028
Tantangara Formation	TTF	0.0001	0.0001	0.01	5×10^{-6}	PB06				0.0000041		
						MB08A				0.80		
						MB08B				0.00040		
						BH3111					0.0028	
						BH3113					0.0080	
						BH2102						0.011
						BH2103						0.0012
						BH3101						0.0002
						BH3104						0.0015
Granite/Basement	BAS	0.00001	0.00001	0.01	1×10^{-6}							
Kellys Plain Volcanics	KPV	0.01	0.01	0.01	5×10^{-6}	PB01:BH1115	0.0046		4×10^{-9}			
						PB01:BH1116	0.013	0.01	1.8×10^{-6}			
						BH2101						0.00074
						BH1115						0.26

Notes:
1. Constant head and constant rate pump tests were completed by EMM
2. Slug tests were completed by EMM
3. Drill stem tests were completed by GHD
4. Packer tests were completed by GHD and SMEC

3.3.6 Calibration sensitivity

Calibration sensitivity analysis was conducted by varying parameters from the adopted base case values and evaluating the impact of calibration performance. Calibration performance was evaluated using SRMS error on three scales: a) overall, b) locally (only within the unit itself) and c) regionally (within the unit and any it borders). The sensitivity of calibration performance, along with results of field testing and the conceptual model, were subsequently used to inform predictive uncertainty analysis.

Due to simulation run time constraints and the minor contributions of seasonal responses to calibration performance, compared to those of geographic location, calibration sensitivity analysis was conducted in steady state. This meant calibration performance would be insensitive to specific yield and specific storage and, hence, these were not explored.

Horizontal and vertical hydraulic conductivity values for each of the modelled hydrostratigraphic units were varied between two orders of magnitude lower and two orders of magnitude higher than the adopted base case values. Horizontal and vertical conductivities were varied together, maintaining the ratio of horizontal to vertical hydraulic conductivity. Additionally, river bed conductance was varied between two orders of magnitude lower and two orders of magnitude higher than the adopted base case values. River bed conductance was varied model-wide by the given values, not on an individual reach basis. Local and regional SRMS errors could not be defined as rivers are all modelled in model layer 1 and, hence, only overall SRMS was analysed for river bed conductance. However, total river inflow and total river outflow was analysed to identify their sensitivity.

SRMS error sensitivities presented in Figure 3.20 to Figure 3.22 indicate that the adopted base case hydraulic conductivity values generally minimise the differences between measured and modelled hydraulic head values. Several hydrostratigraphic units, including the Byron Range Group, Shaw Hill Gabbro, Gooandra Volcanics fractured zone, Basement and Kellys Plain Volcanics, display little sensitivity to the range of input values tested. This is a result of the combination of the size of the units, the number of hydraulic head observations in and near the units and their proximity to boundary conditions. For example, there are no monitoring locations in the Byron Range Group, Shaw Hill Gabbro or Basement. There is only one monitoring location in the Kellys Plain Volcanics. This unit has the added constraint of being adjacent to Tantangara Reservoir, which holds hydraulic head in the region relatively constant.

SRMS error and modelled river leakage displayed low sensitivity to modelled river bed conductance (Figure 3.23). Direct baseflow discharge to creeks decreased significantly with decreasing river bed conductance, with that water instead discharging as distributed baseflow (via the EVT package) nearby.

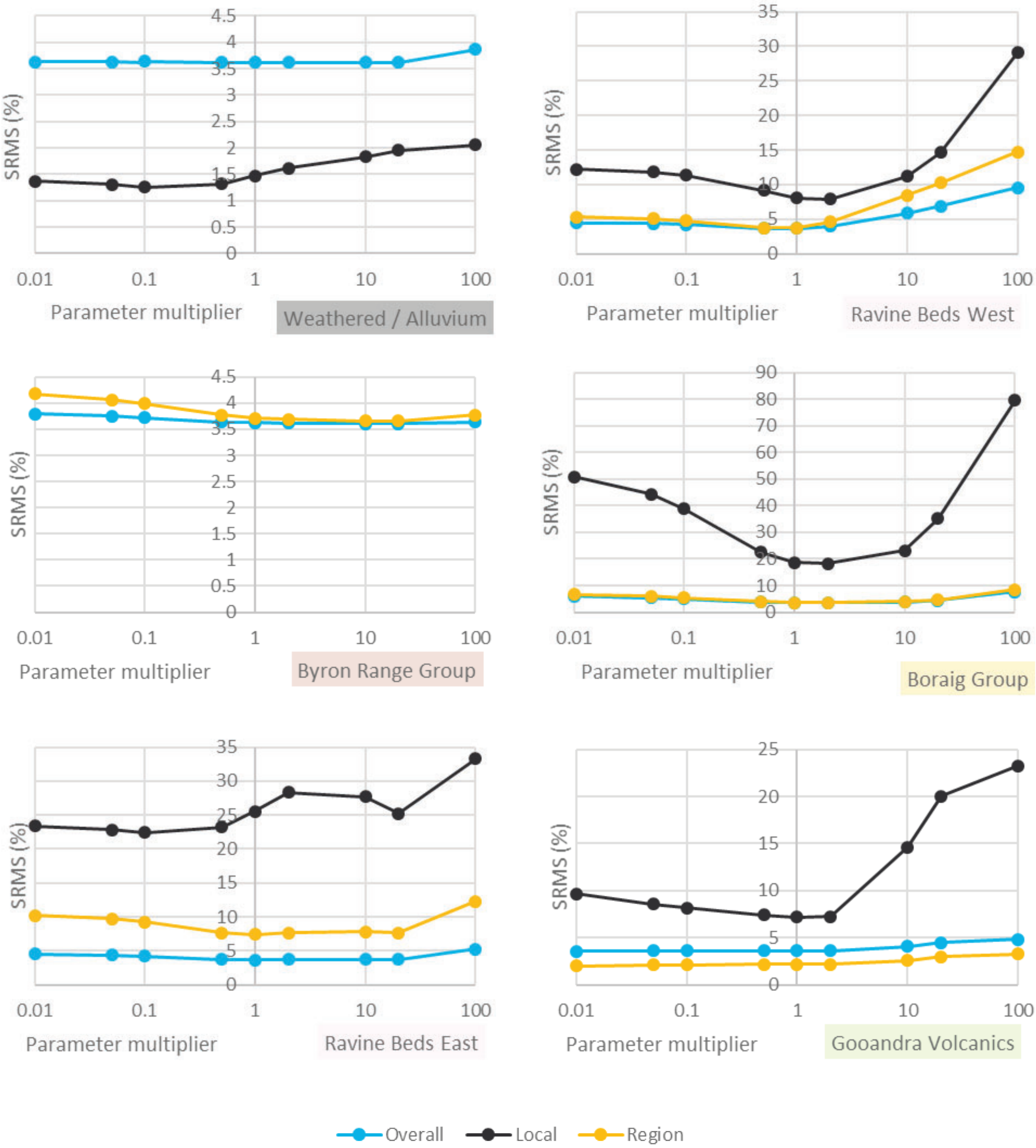


Figure 3.20 Calibration sensitivity to hydraulic conductivity (K_h and K_v)

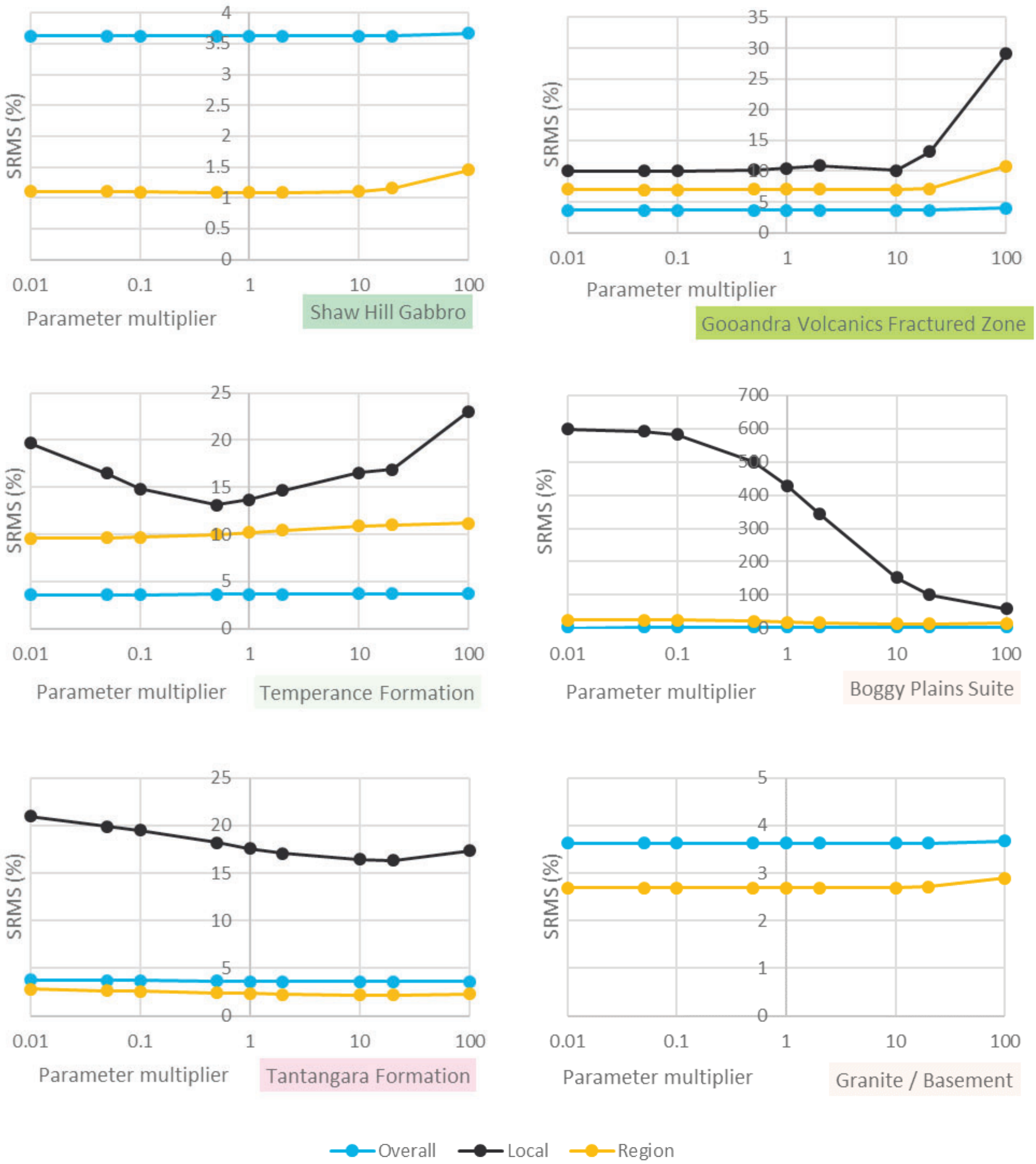


Figure 3.21 Calibration sensitivity to hydraulic conductivity (K_h and K_v) (Cont.)

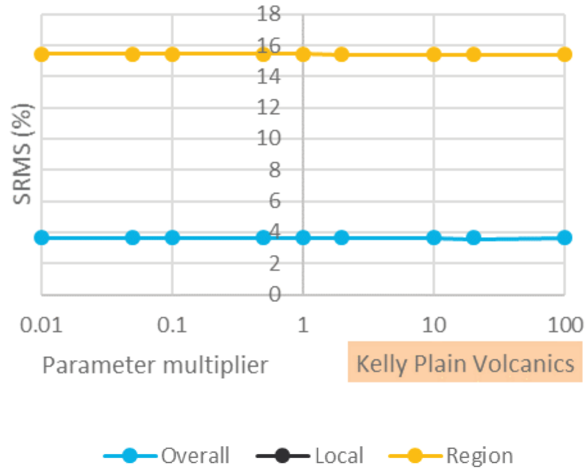


Figure 3.22 Calibration sensitivity to hydraulic conductivity (K_h and K_v) (Cont.)

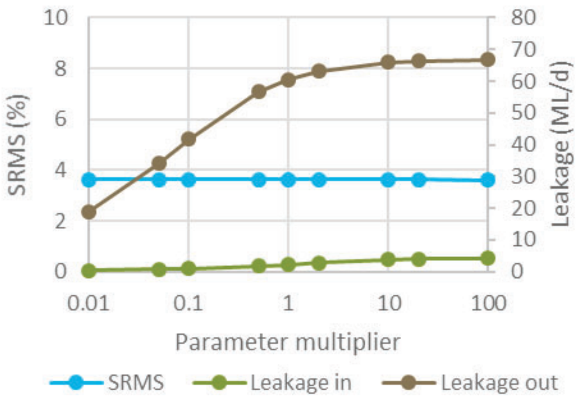


Figure 3.23 Calibration sensitivity to river bed conductance

3.4 Predictive scenario modelling

3.4.1 Construction and operation scenario description

i Scenario overview

A predictive scenario was developed to simulate construction and operation of Snowy 2.0. As was done for the history matching period, quarterly seasonally-aligned stress periods were employed to simulate:

- Climate-driven seasonality; and
- Progressive construction of the project.

A steady state initial stress period was employed to generate stable, internally-consistent initial heads. As for the history matching period, average climate inputs from the period December 2007–December 2012 were adopted. Transient stress periods then repeatedly recycle the first five years (December 2012–December 2017) of climate inputs from the history match period until the end of the simulation.

In line with the timing of the history matching model, transient predictions were designed to commence on 1 December. However, because construction is scheduled to commence in September 2019, the first three transient stress periods were assigned only climate stresses. This enabled the model to simulate seasons in line with the proposed timing of each construction component. The construction period was followed by 20 years of transient simulation, producing a total of 106 stress periods spanning the period 1 December 2018–1 March 2045. As for the transient history matching (calibration) period, stress periods were each divided into 20 time steps using a multiplier of 1.2. This resulted in the first time step of each stress period being on the order of 0.5 days long and the last, and longest, time step in each stress period on the order of 15 days long (with variability depending on the number of days, 90, 91 or 92, in a given season).

A table summarising transient climate inputs and the schedule of modelled construction and operational boundary conditions, on a stress period by stress period basis, is presented in Attachment H.

ii Excavation sequencing

Excavation Sequencing is the process of managing the order that the excavation occurs to ensure critical sections remain open for the least amount of time possible.

Early identification of critical sections of highly permeable or vertically connected formations was undertaken through the drilling and pumping test program (Annexure A of the water assessment Attachment D). This process identified that the Gooandra Volcanics had a higher hydraulic conductivity than other geological units in the project area. Understanding the critical nature of this location, the construction program was planned such that the Gooandra Volcanics region was excavated late in the construction program so that the excavation would remain open for the shortest period of time.

The progression of drain and general head boundary conditions assigned within the model is presented for key times in Figure 3.24 to Figure 3.29. A series of figures presenting the full time series of excavation boundary conditions is presented in Attachment G.

The excavation sequence in the model includes both Exploratory Works and Main Works excavations. Exploratory Works excavations occur within approximately the first 6 months of the overall construction period modelled, with Main Works excavations occurring during the remainder of the modelled construction period.

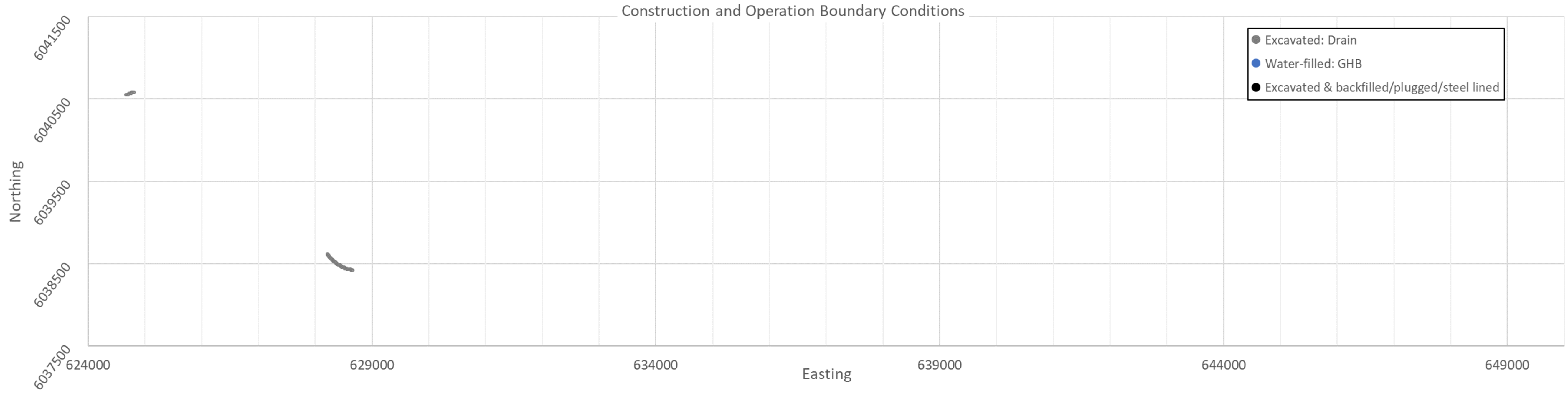
The commissioning phase of the project was not modelled explicitly. In the model, following completion of the construction phase the power waterway is filled with water and the model transitions to modelling operations.

Excavations were simulated using the MODFLOW drain (DRN) package. In any stress period, all underground excavations in progress were assigned as drain boundary conditions. Tunnel components were assigned stage equal to the tunnel invert level (see Figure 3.2) in the centre of the model cell. The Machine Hall, Transformer Hall, Ventilation Shaft, Headrace Surge Shaft and Tailrace Surge Shaft all span multiple model layers. Drain boundary conditions were assigned to all model cells intercepted by the excavations on a transient basis such that progressive excavation upward or downward was represented layer by layer. For these “stacked” drain boundary conditions drain stages were set 0.5 m above the cell bottoms to enable the boundary conditions to remain active.

Some excavations will be temporary and will be backfilled or plugged when no longer needed. Other components will be steel lined. Drain boundary conditions representing these features were deactivated at the stress period in the model corresponding with the time in the project schedule when feature will no longer be actively drained and/or hydraulically connected to the groundwater system.

Snowy 2.0 is scheduled to first commence filling of the power waterway with water in March 2025, corresponding with model stress period 27. From this time onward the drain boundary conditions representing components of the power waterway that are not steel lined were replaced by MODFLOW general head boundary (GHB) conditions.

When Snowy 2.0 is generating power, water will move from Tantangara Reservoir to Talbingo Reservoir. Due to head losses in the power water way due to friction, the head immediately east of the power station will be a little lower than the head at the Tantangara Reservoir. When Snowy 2.0 is replenishing Tantangara Reservoir, the head gradient will be reversed and the head immediately east of the power station will be slightly higher than Tantangara Reservoir. These fluctuations could not be modelled with the quarterly stress period adopted in the groundwater model, and so constant values were assigned to the general head boundary conditions during the operation period. For the tailrace tunnel (west of the power station), the average Talbingo Reservoir hydraulic head of 541 m AHD was assigned. For the headrace tunnel (east of the power station), the average Tantangara Reservoir hydraulic head of 1,215 m AHD was assigned.



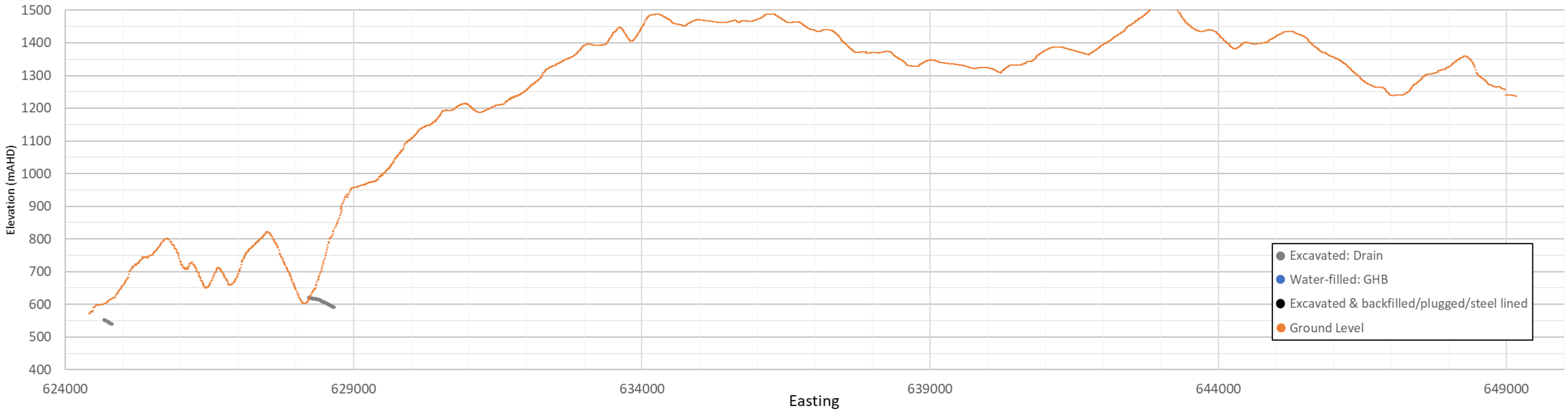


Figure 3.24 Boundary conditions for excavations, stress period 8, ending September 2020, after 1 year of construction, plan (top) and elevation (bottom)

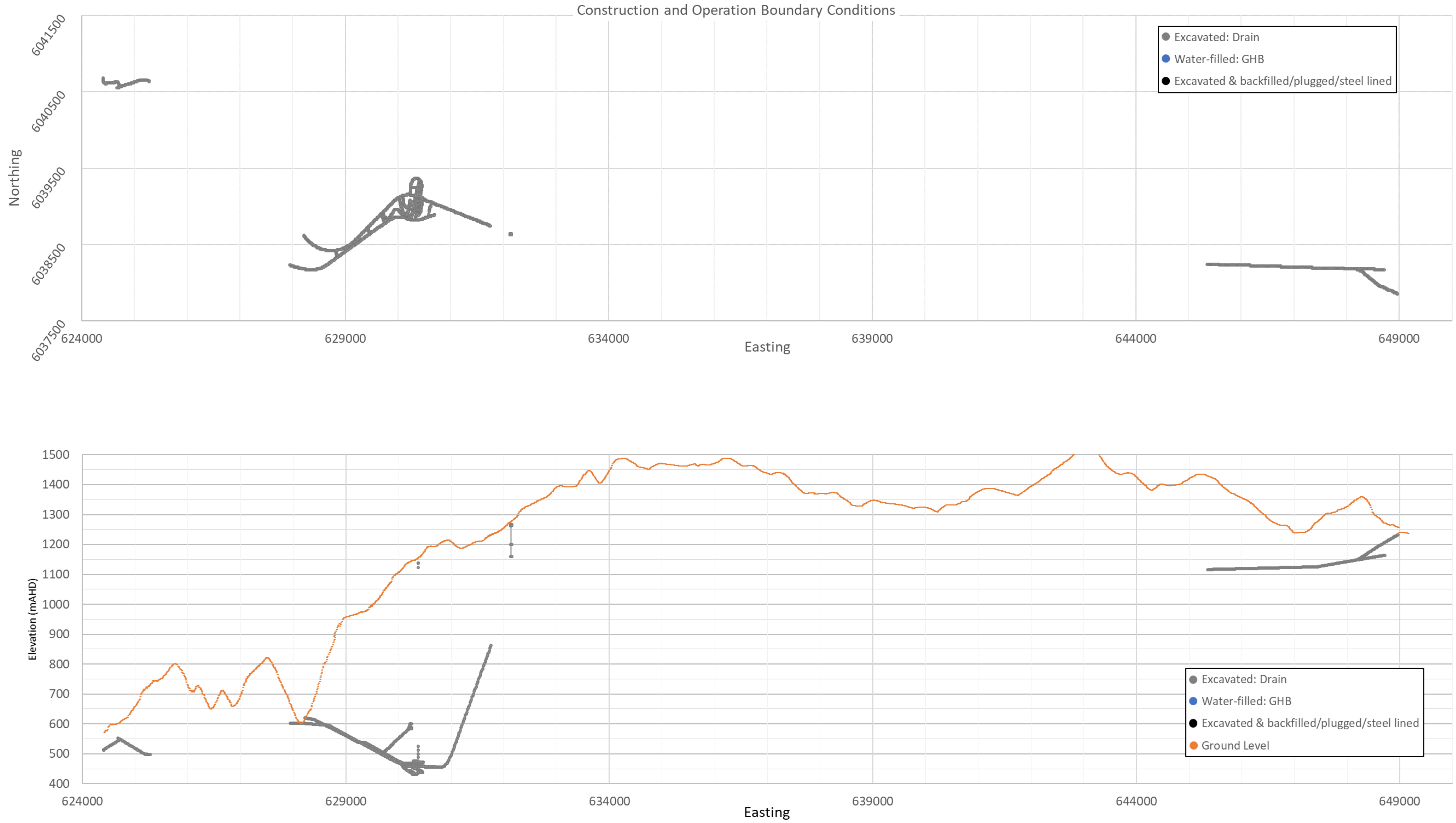
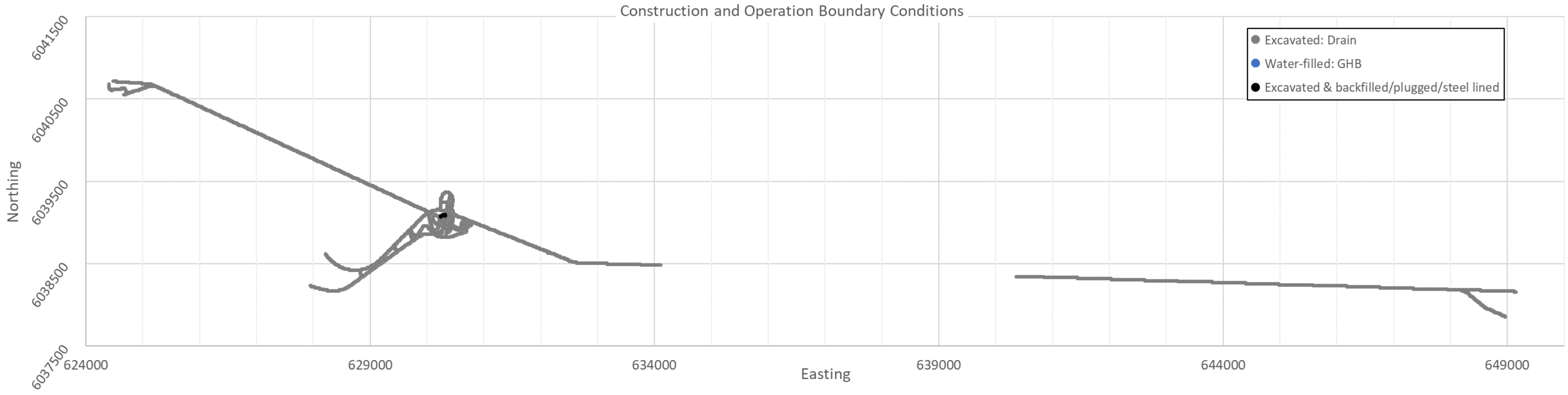


Figure 3.25 Boundary conditions for excavations, stress period 12, ending September 2021, after 2 years of construction, plan (top) and elevation (bottom)



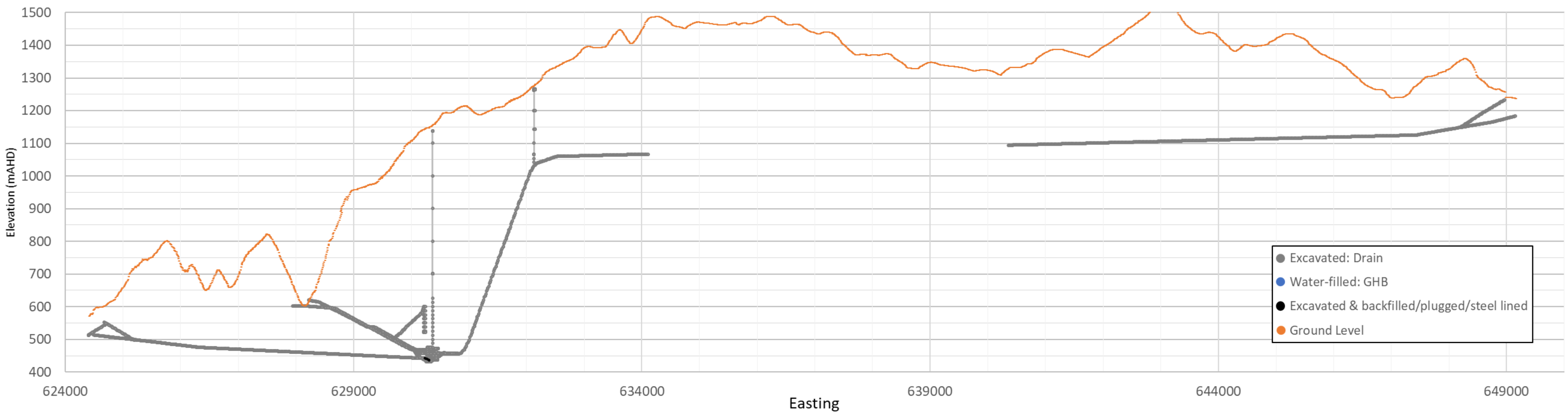


Figure 3.26 **Boundary conditions for excavations, stress period 16, ending September 2022, after 3 years of construction, plan (top) and elevation (bottom)**

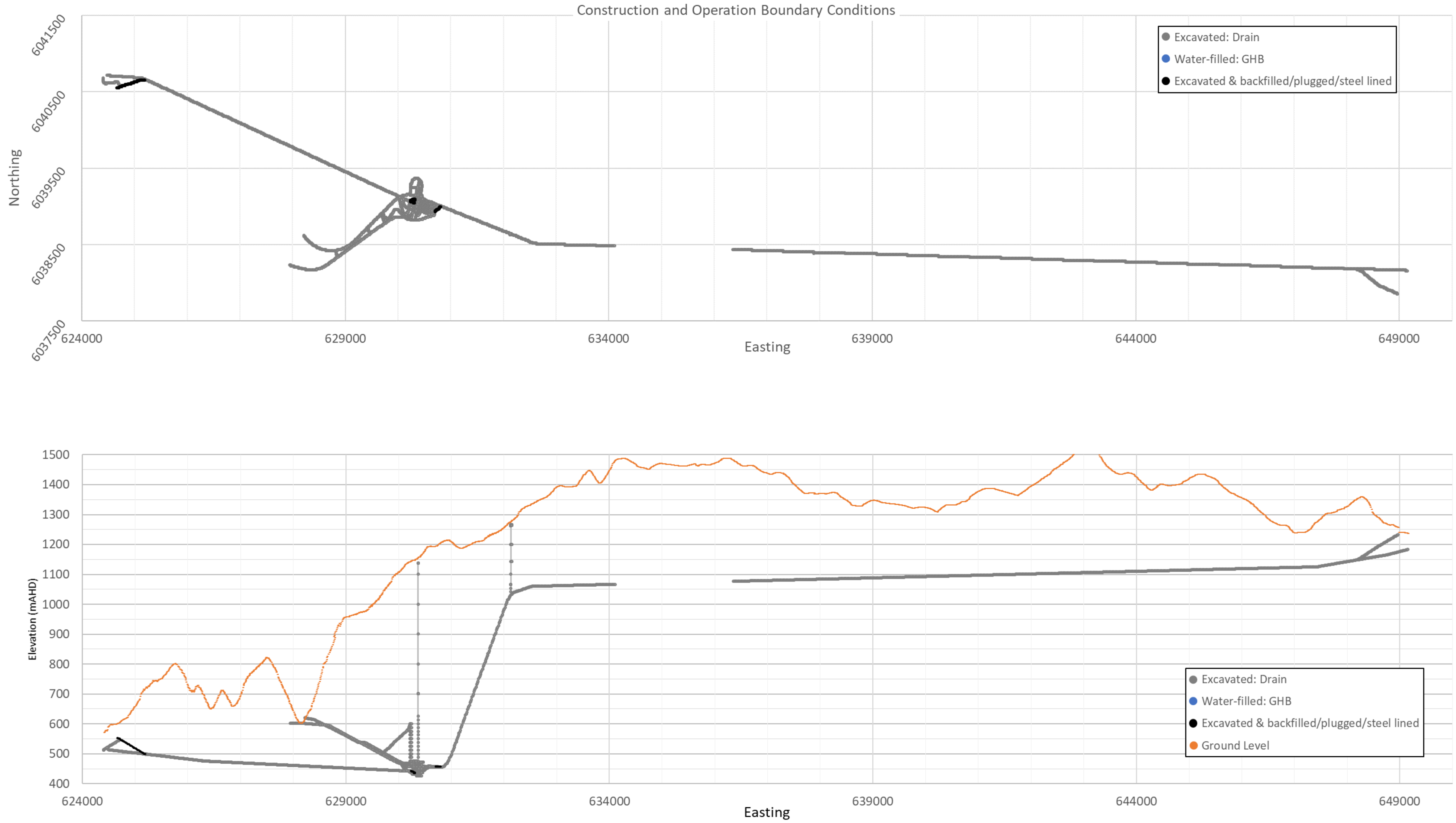


Figure 3.27 Boundary conditions for excavations, stress period 20, ending September 2023, after 4 years of construction, plan (top) and elevation (bottom)

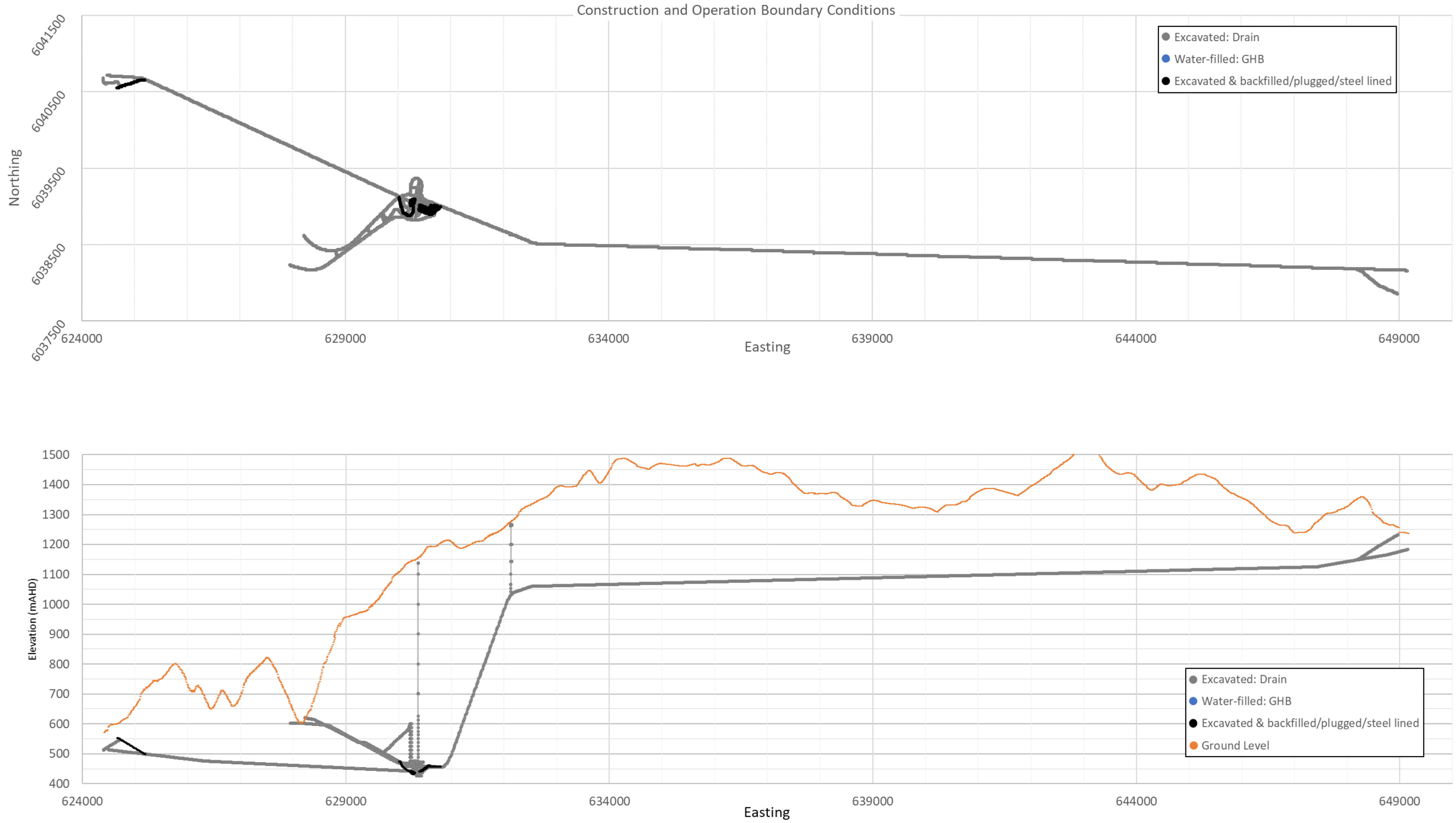


Figure 3.28 Boundary conditions for excavations, stress period 24, ending September 2024, plan (top) and elevation (bottom)

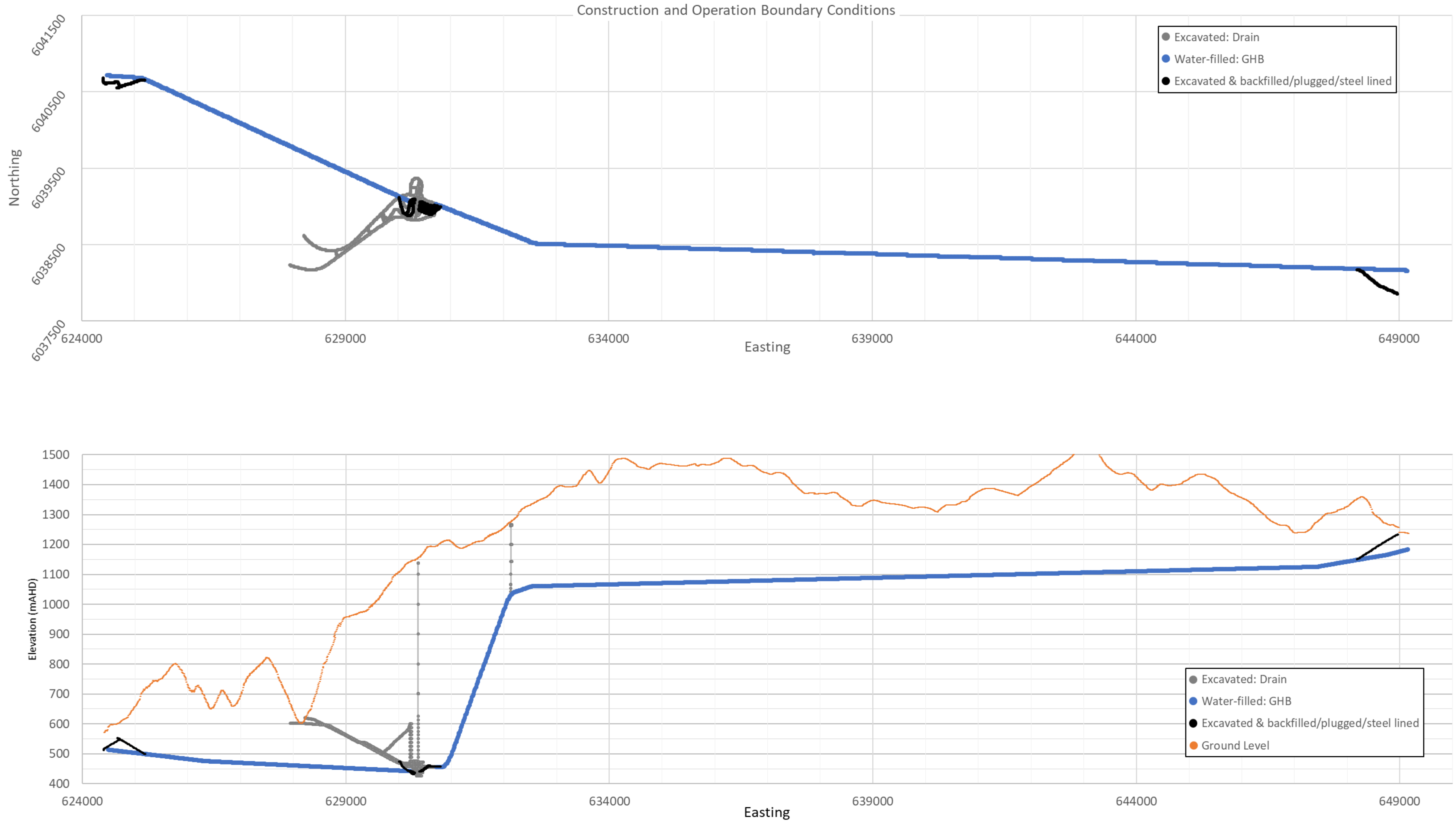


Figure 3.29 Boundary conditions for excavations, stress period 27, beginning March 2025, operation, plan (top) and elevation (bottom)

iii Grouting and lining

Pre-grouting may be conducted ahead of the tunnel boring machines to reduce the hydraulic conductivity of the rock mass of the excavation face when high inflows are expected, for example due to the traversal of a region of fractured rock. Post-grouting may be conducted to reduce the hydraulic conductivity of the rock mass after tunnel construction if leakage rates into the tunnel are higher than desired (Wannenmacher & Wenner, 2009). Pressure relief holes within the segmental lining will mean that the lining has minimal impact on reducing flow into the tunnel where pre- or post-grouting is not undertaken.

The exact locations and extent of inflow mitigation strategies are not yet known as they will align to local fractures and higher inflow areas as encountered during tunnelling. Hence, the groundwater modelling adopted a conservative approach of simulating all excavations as non-mitigated/controlled and grouting and lining will reduce the tunnel inflow and therefore also reduce project impact.

Although not presented as part of this study, a number of excavation grouting options were simulated to investigate benefits that may be had with regard to tunnel inflows and environmental impacts. Grouting was simulated in these unreported scenarios by varying the tunnel general head boundary condition conductance parameter. Therefore, it was important to have base case (no grouting) conductance values set at the value such that reductions in conductance would result in reductions in tunnel inflow. For the calibrated K (rock mass hydraulic conductivity) values presented in section 3.3.5, this tipping point occurs at a tunnel lining conductance of around 1 m^2/day. By adopting a conductance value of 1 m^2/day for drains and general head boundary conditions, underground excavations were effectively modelled as “free-draining”, with no mitigation or control of inflows, and grouting scenarios could be modelled by reducing the conductance value below 1 m^2/day.

iv Climate

As described in section 2.7.5i, three climate sequences were used to assess the impacts of the project during the construction phase.

‘Average’ rainfall conditions were simulated using climate data from December 2012–December 2017. Through this period the average Murrumbidgee River flow was 127 GL/year, close to the post 1997 average of 131 ML/year.

‘Wet’ rainfall conditions were simulated using climate data from December 1988 to December 1993. Through this period the average Murrumbidgee River flow was 188 GL/year, and each year experienced above average flow. This climate sequence includes 1990, during which year extensive flooding occurred in NSW.

‘Dry’ climate conditions were simulated using climate data from December 2001 to December 2006. Through this period the average Murrumbidgee River flow was 96 GL/year. Four of these years experienced lower than average streamflow, and one year experienced above average streamflow. This climate sequence includes the driest years of the Millennium Drought.

The ‘average’ climate sequence was cycled when modelling the operation phase of the project.

Climate change influences on recharge were not included in the model.

3.4.2 Predicted hydraulic head

Base case predicted drawdown of the regional watertable after 1, 2, 3, 4 and 5 years of construction is presented in Figure 3.30 to Figure 3.34. Drawdown is calculated as the difference between a “null scenario” that simulates only transient climate stresses and a model run simulating construction and operation of Snowy 2.0.

After one year of construction almost no drawdown is predicted.

After two years of construction a drawdown footprint is predicted near the western edge of Tantangara Reservoir and associated with excavation of the headrace tunnel. In the area immediately adjacent the reservoir the tunnel will be constructed in the Kellys Plain Volcanics. The base case model simulates this unit with horizontal and vertical hydraulic conductivity of 0.01 m/d, around two orders of magnitude higher than most of the model domain.

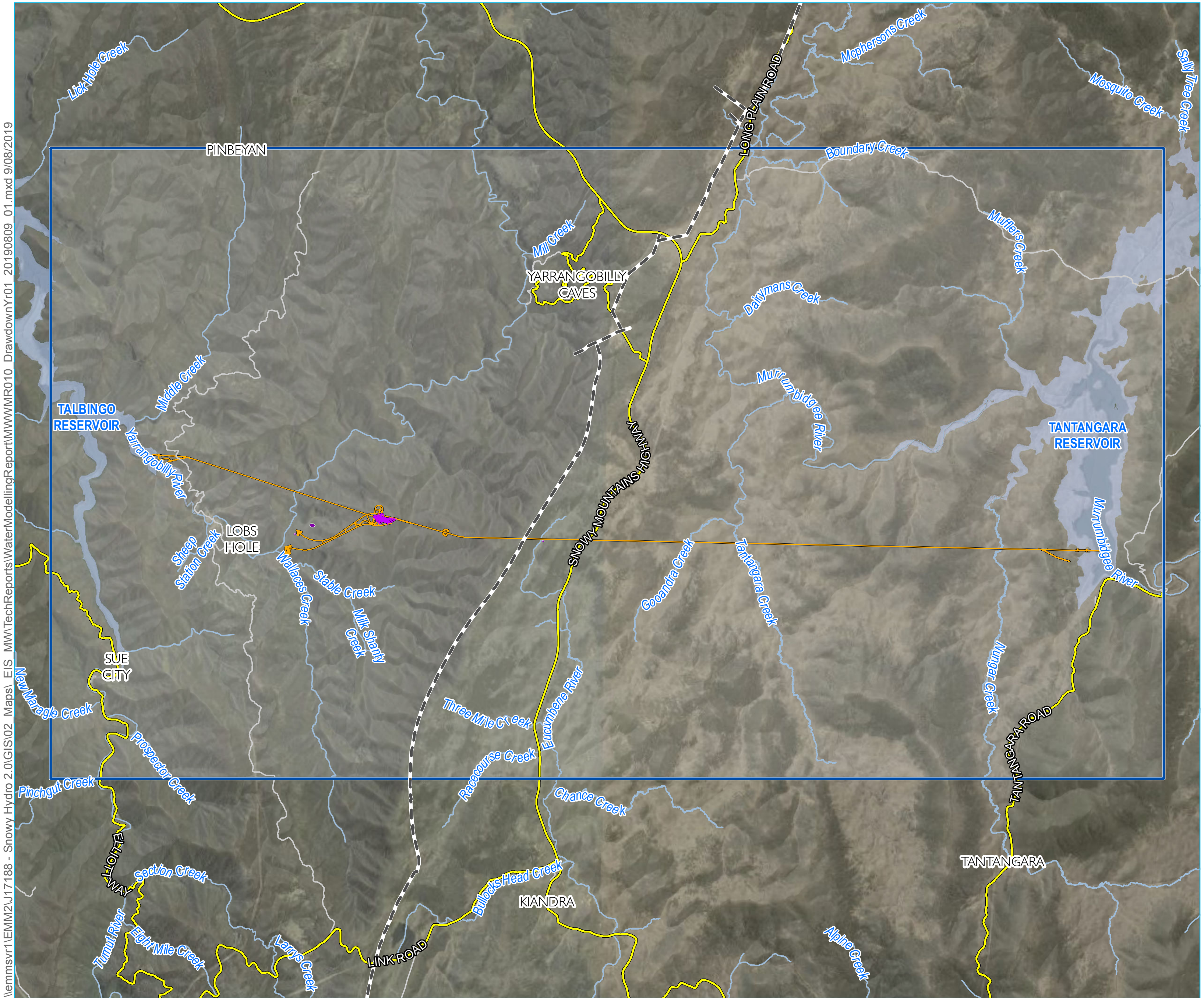
After three and four years of construction the drawdown footprint associated with the Kellys Plain Volcanics expands and increases in magnitude immediately above the headrace tunnel to over 50 m. Small pockets of minor drawdown are predicted above other parts of the project and a region of drawdown is predicted to be growing above the headrace tunnel in the Gooandra Volcanics region.

After five years of construction the Kellys Plain Volcanics drawdown is predicted to further expand and the drawdown in the Gooandra Volcanics is predicted to reach magnitudes of greater than 20 m. Groundwater levels at the Yarrangobilly Caves are not predicted to be impacted during construction.

Figure 3.35 and Figure 3.36 present predicted base case drawdown after one year and 20 years of operation. In the Kellys Plain Volcanics area most of the watertable drawdown occurs during construction and reduces from year 1 to year 20 of operations. However, the drawdown in the Gooandra Volcanics area continues to expand outward and increase in magnitude to over 50 m by the end of 20 years of operation. Patchy, localised, drawdown above the Ravine Beds is also predicted to increase.

Figure 3.37 presents predicted steady state operational drawdown. Drawdown in the Kellys Plains Volcanics and the Gooandra Volcanics is reduced compared to after 20 years of operation. Likewise, the localised drawdown patches in the ravine area are reduced. This indicates a long-term (decades) period required for filling of the power waterway with water to result in re-equilibration of the groundwater system.

To quantify potential drawdown impacts associated with a long delay in the power waterway being commissioned from an excavated tunnel to an operating scheme, a steady state simulation of a fully drained scheme was run (see Figure 3.38). Whilst this is a scenario that would not eventuate, as it represents pumping out of all inflows to excavations for infinite time, it provides a very conservative indication of drawdown potential associated with the project. Whilst drawdown of the watertable is predicted to exceed 50 m in a 1 km section in the Kellys Plain Volcanics and for a large section around 5 km long in the Gooandra Volcanics, the predicted 0.5 m drawdown contour remains several kilometres distant from the Yarrangobilly Caves.



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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KEY

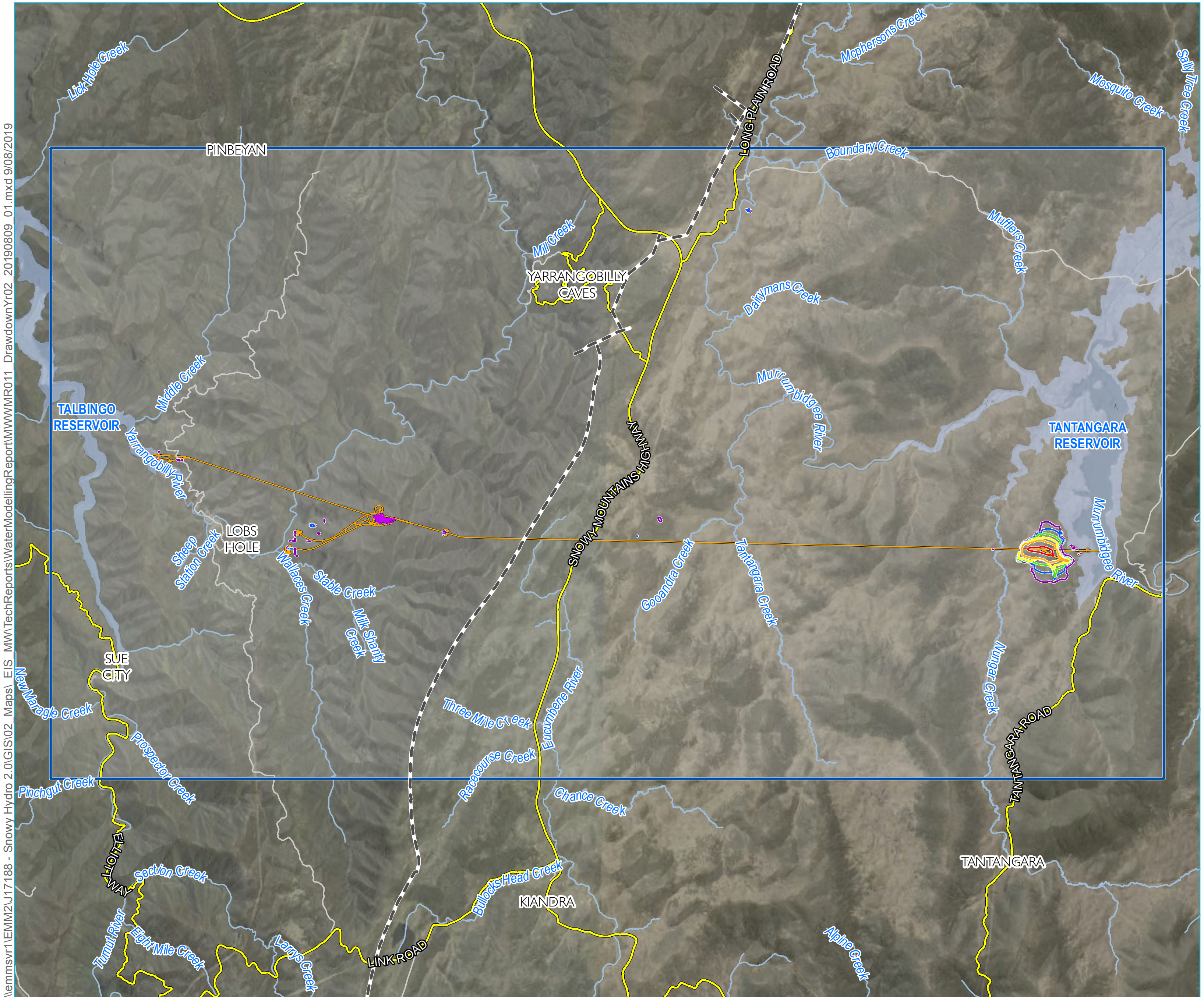
Modelled drawdown (m)
- 0.5
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

Predicted base case drawdown after 1 year of construction, September 2020

Snowy 2.0
Modelling Report
Main Works
Figure 3.30



KEY

Modelled drawdown (m)
- 0.5
- 2
- 5
- 10
- 20
- 50
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

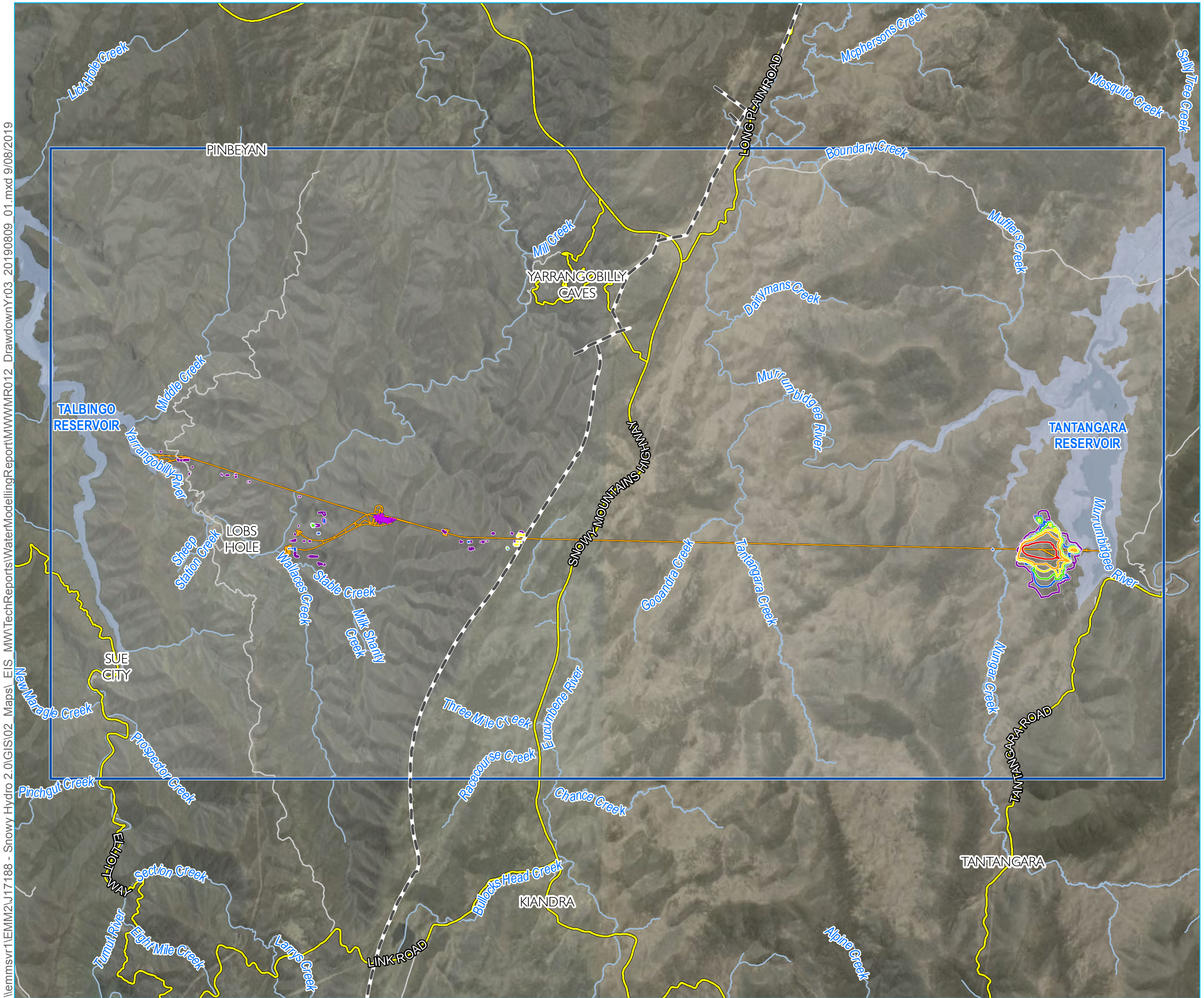
0 2.5 5 km
GDA 1994 MGA Zone 55
N

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

\\emmsvr1\EMM2\J17188 - Snowy Hydro 2.0\GIS\02_Maps_EIS_MW\TechReports\WaterModellingReport\MWWMR011_DrawdownYr02_20190809_01.mxd 9/08/2019

Predicted base case drawdown after 2 years of construction, September 2021

Snowy 2.0
Modelling Report
Main Works
Figure 3.31



KEY

Modelled drawdown (m)
- 0.5
- 2
- 5
- 10
- 20
- 50

- Long Plain Fault
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

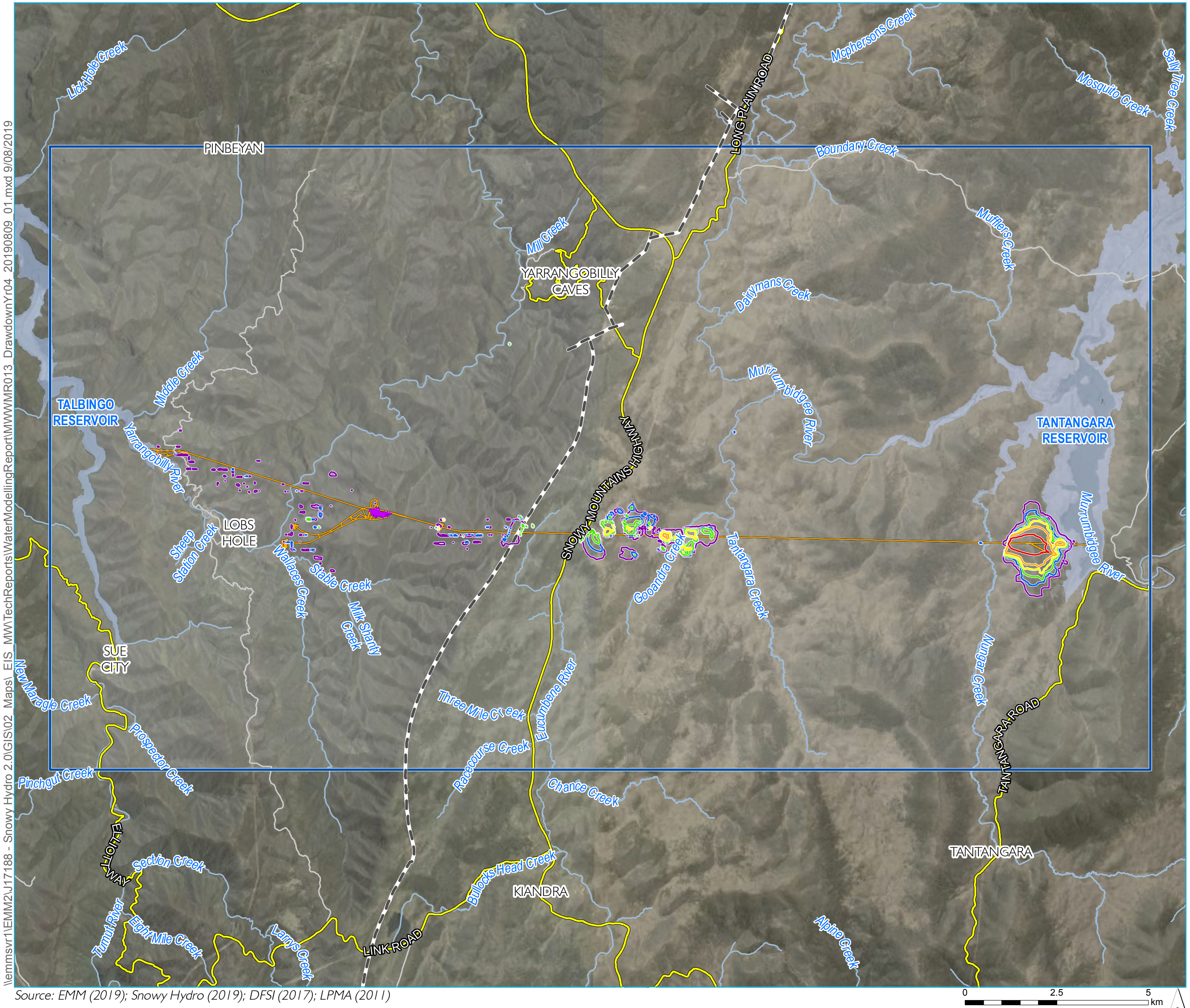
Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

Predicted base case drawdown after 3 years of construction, September 2022

Snowy 2.0
Modelling Report
Main Works
Figure 3.32

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

\emmsvr1\EMM2\J17188 - Snowy Hydro 2.0\GIS\02_Maps_EIS_MW\TechReports\WaterModellingReport\MWWMR012_DrawdownYr03_20190809_01.mxd 9/08/2019



KEY

Modelled drawdown (m)

- 0.5
- 2
- 5
- 10
- 20
- 50
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements

- Tunnels, portals, intakes, shafts
- Power station

Existing environment

- Main road
- Local road
- Perennial watercourse
- Scheme storage

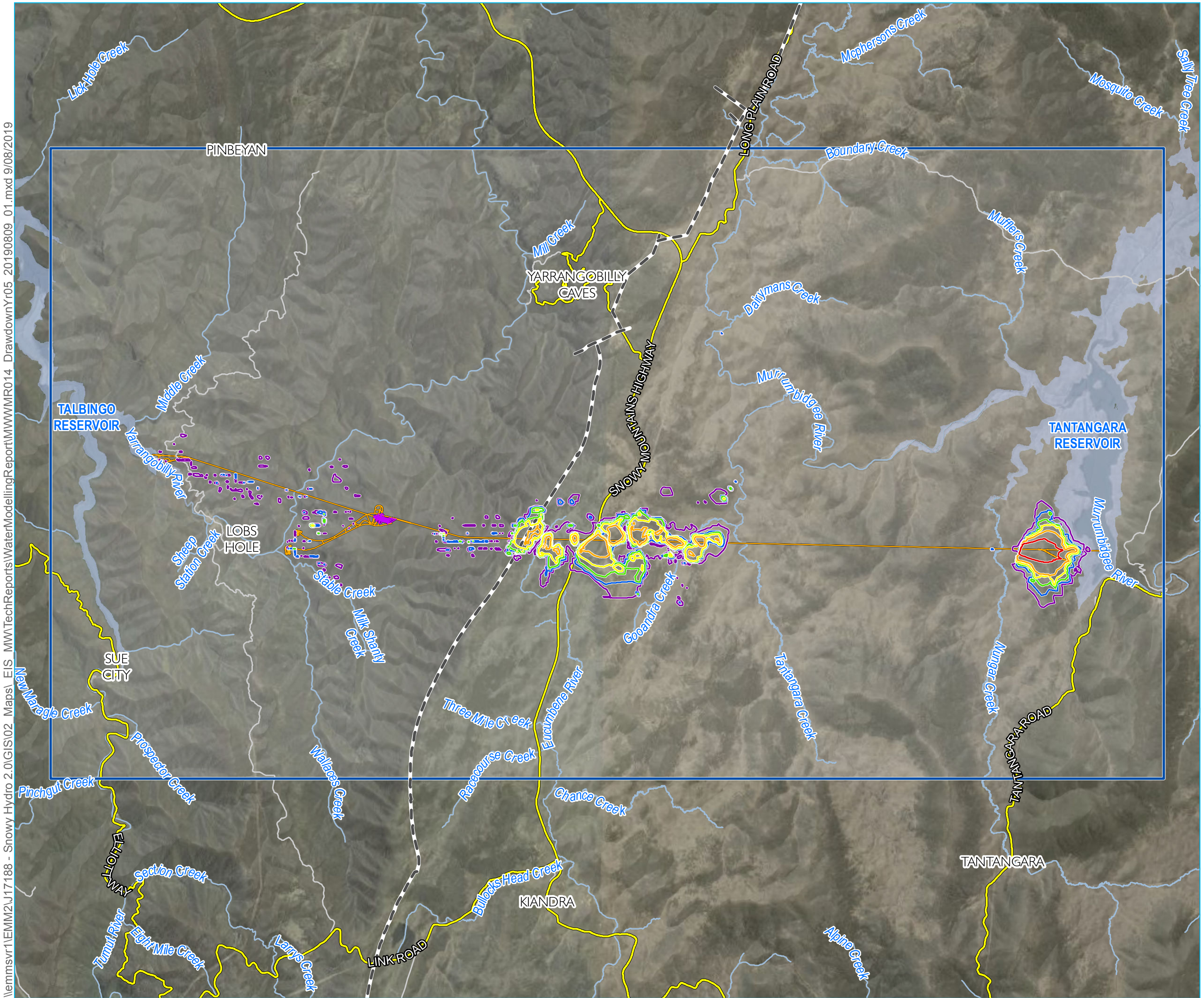
Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

Predicted base case drawdown after 4 years of construction, September 2023

Snowy 2.0
Modelling Report
Main Works
Figure 3.33

snowy 2.0

EMM creating opportunities



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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

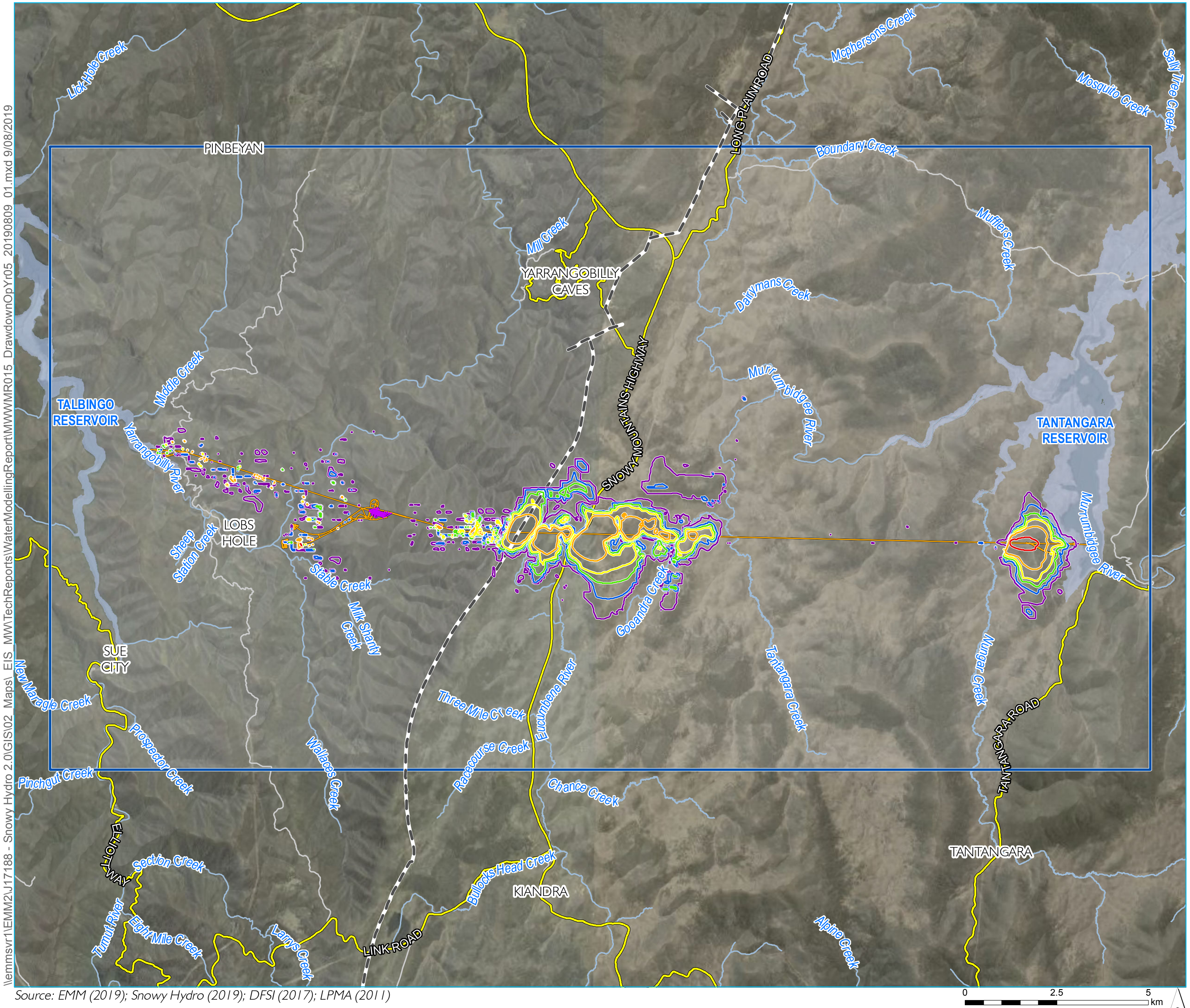
Modelled drawdown (m)
- 0.5
- 2
- 5
- 10
- 20
- 50
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

Predicted base case drawdown after 5 years of construction, September 2024

Snowy 2.0
Modelling Report
Main Works
Figure 3.34



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

Modelled drawdown (m)
- 0.5
- 2
- 5
- 10
- 20
- 50
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

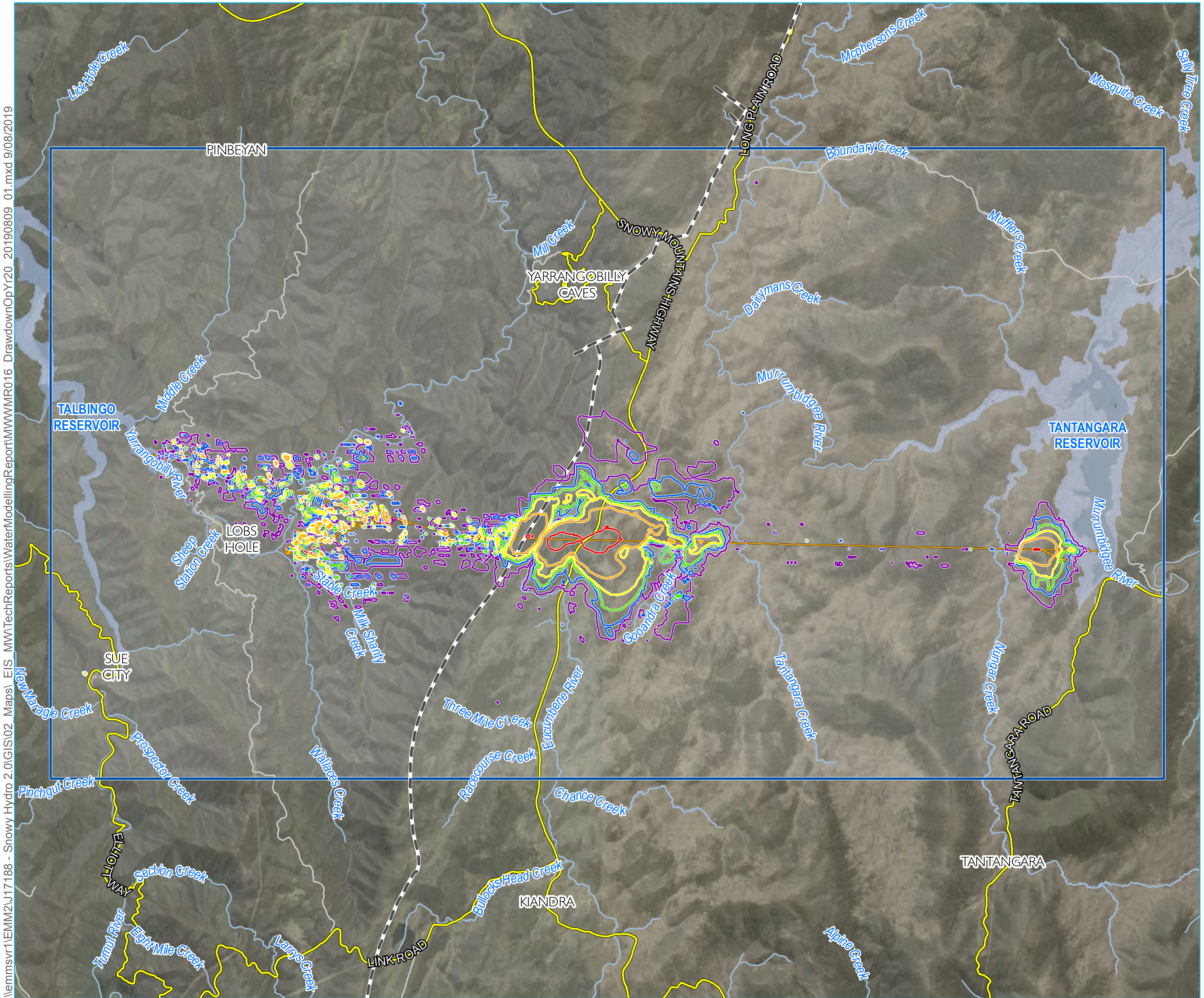
Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

Predicted base case drawdown after 1 year of operation, March 2026

Snowy 2.0
Modelling Report
Main Works
Figure 3.35

snowy 2.0

EMM creating opportunities



KEY

Modelled drawdown (m)
- 0.5
- 2
- 5
- 10
- 20
- 50
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

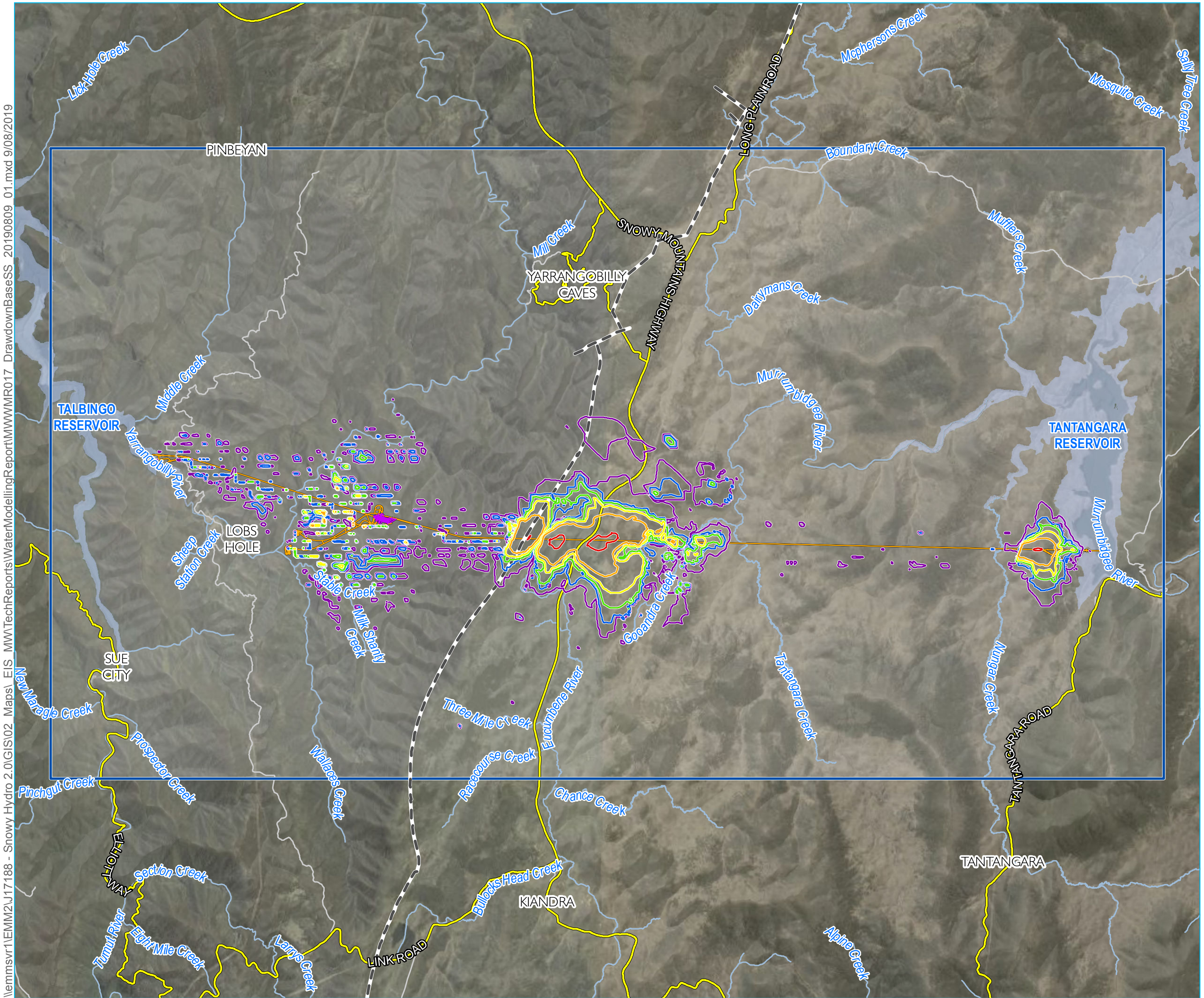
Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

Predicted base case drawdown after 20 years of operation, March 2045

Snowy 2.0
Modelling Report
Main Works
Figure 3.36

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

\\emmsvr1\EMM2\J17188 - Snowy Hydro 2.0\GIS\02_Maps_EIS_MW\TechReports\WaterModellingReport\MWWMR016_DrawdownOpYr20_20190809_01.mxd 9/08/2019



\\emmsvr1\EMM2\J17188 - Snowy Hydro 2.0\GIS\02_Maps_EIS_MW\TechReports\WaterModellingReport\MWWMR017_DrawdownBaseSS_20190809_01.mxd 9/08/2019

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

Modelled drawdown (m)
- 0.5
- 2
- 5
- 10
- 20
- 50
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements
- Tunnels, portals, intakes, shafts
- Power station

Existing environment
- Main road
- Local road
- Perennial watercourse
- Scheme storage

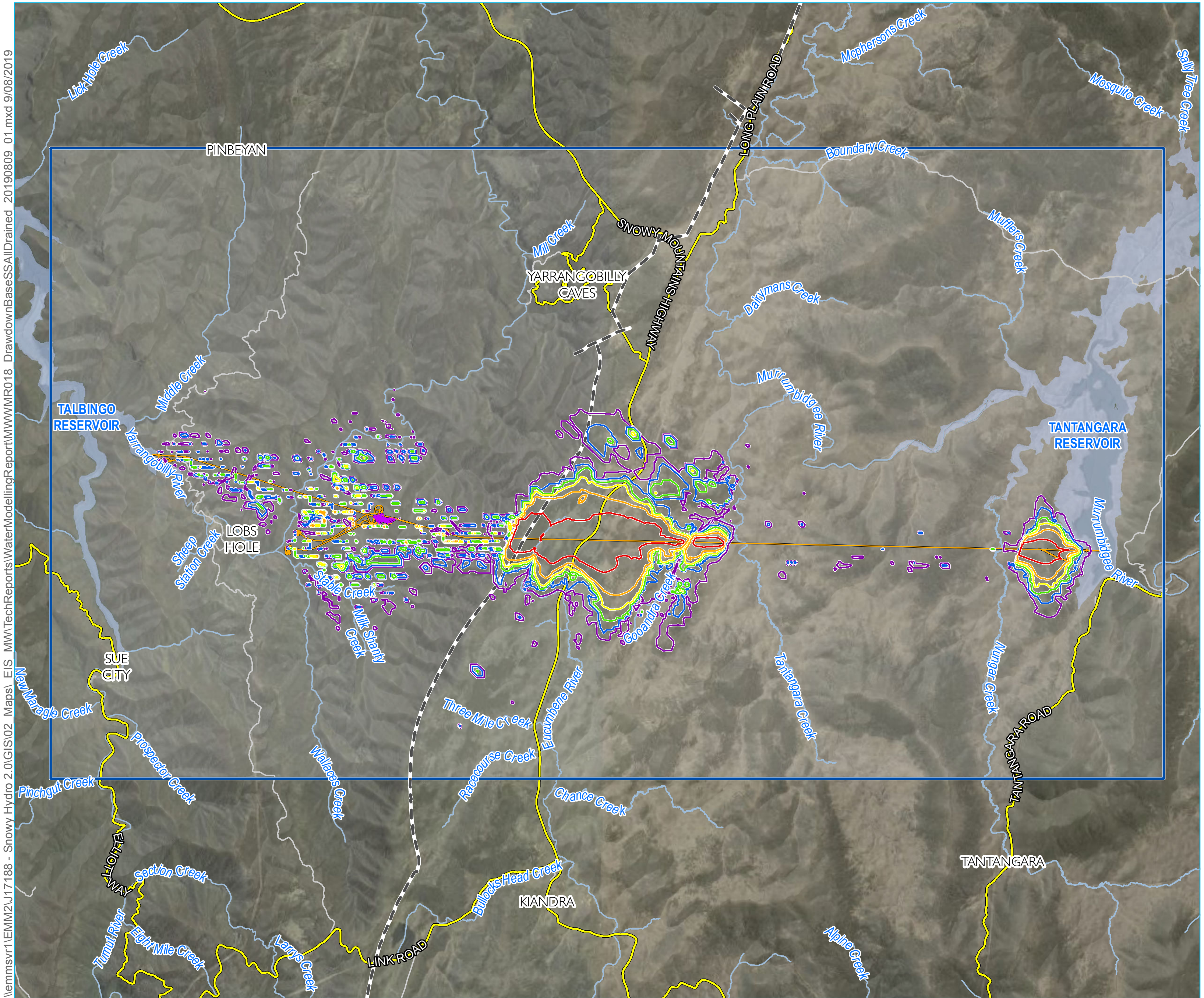
Predicted base case drawdown in steady state, operational

Snowy 2.0
Modelling Report
Main Works

Figure 3.37

snowy 2.0

EMM creating opportunities



\\emmsvr1\EMM2\J17188 - Snowy Hydro 2.0\GIS\02_Maps_EIS_MW\TechReports\WaterModellingReport\MWWMR018_DrawdownBaseSSAllDrained_20190809_01.mxd 9/08/2019

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

KEY

Modelled drawdown (m)

- 0.5
- 2
- 5
- 10
- 20
- 50
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements

- Tunnels, portals, intakes, shafts
- Power station

Existing environment

- Main road
- Local road
- Perennial watercourse
- Scheme storage

Predicted base case drawdown in steady state, all excavations drained

Snowy 2.0
Modelling Report
Main Works
Figure 3.38

snowy 2.0

EMM creating opportunities

3.4.3 Predictive uncertainty analysis

Predictive uncertainty associated with aquifer hydraulic properties was addressed using information from the calibration performance sensitivity analysis, results of field testing and the conceptual model. Information from these sources was used to define minimum and maximum plausible aquifer property values and river bed conductance, presented in Table 3.4 as multipliers applied to base case values. For each parameter, and river bed conductance, a steady state simulation of operational components was run, producing a total of 29 uncertainty analysis runs including the base case.

The uncertainty of predicted drawdown, associated with adopted aquifer and river properties, is presented in Figure 3.39 (0.5 m), Figure 3.40 (2 m) and Figure 3.41 (5 m).

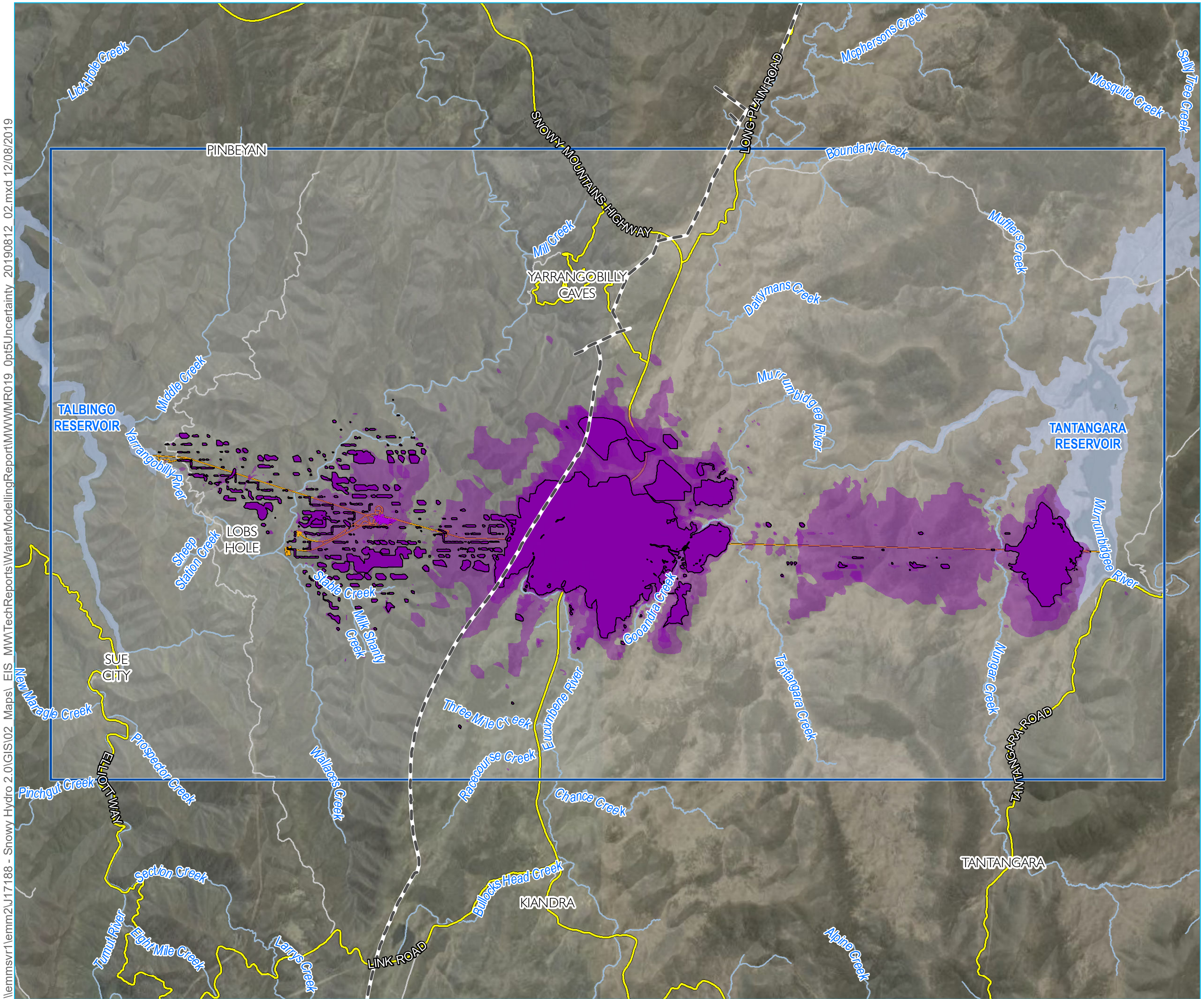
Even for the most conservative parameter values a drawdown magnitude of 0.5 m does not reach the Yarrangobilly Caves.

Whilst the range of drawdown footprints extend beyond that of the base case simulation, they do not extend much further from the project alignment than the furthest extent predicted by the base case and most of the additional drawdown is along the alignment itself.

Water balance data were not extracted for each of these runs and so the surface water model was not used to assess the possible change in streamflow due to each of these 29 runs, and the range in tunnel inflow rates has not been presented.

Table 3.4 Aquifer property uncertainty bounds

		Calibrated property				
Unit		**Kh (m/d)**	**Kv (m/d)**	**C (m^2/d)**	**Min multiplier**	**Max multiplier**
Weathered/Alluvium	WEATH	0.5	0.5	-	0.1	2
Tertiary Basalt	TBAS	0.5	0.5	-	0.1	2
Ravine Beds West	RBW	0.001	0.0001	-	0.5	2
Byron Range Group	BRG	0.0005	0.0001	-	0.5	100
Boraig Group	BOR	0.0005	0.0001	-	0.5	10
Ravine Beds East	RBE	0.0003	0.0003	-	0.5	10
Gooandra Volcanics	GOV	0.005	0.005	-	0.1	2
Shaw Hill Gabbro	SHG	0.01	0.01	-	0.01	2
Gooandra Volcanics Fractured Zone	GOVF	0.01	0.01	-	0.01	10
Temperance Formation	TPF	0.0001	0.0001	-	0.1	10
Boggy Plains Suite	BPS	0.0001	0.0001	-	0.01	20
Tantangara Formation	TTF	0.0001	0.0001	-	0.1	100
Granite/Basement	BAS	0.00001	0.00001	-	0.01	20
Kellys Plain Volcanics	KPV	0.01	0.01	-	0.05	20
Rivers		-	-	12.5-20,000	0.1	100



Predicted operational 0.5 m drawdown in steady state, uncertainty due to aquifer

Snowy 2.0
Modelling Report
Main Works
Figure 3.39

Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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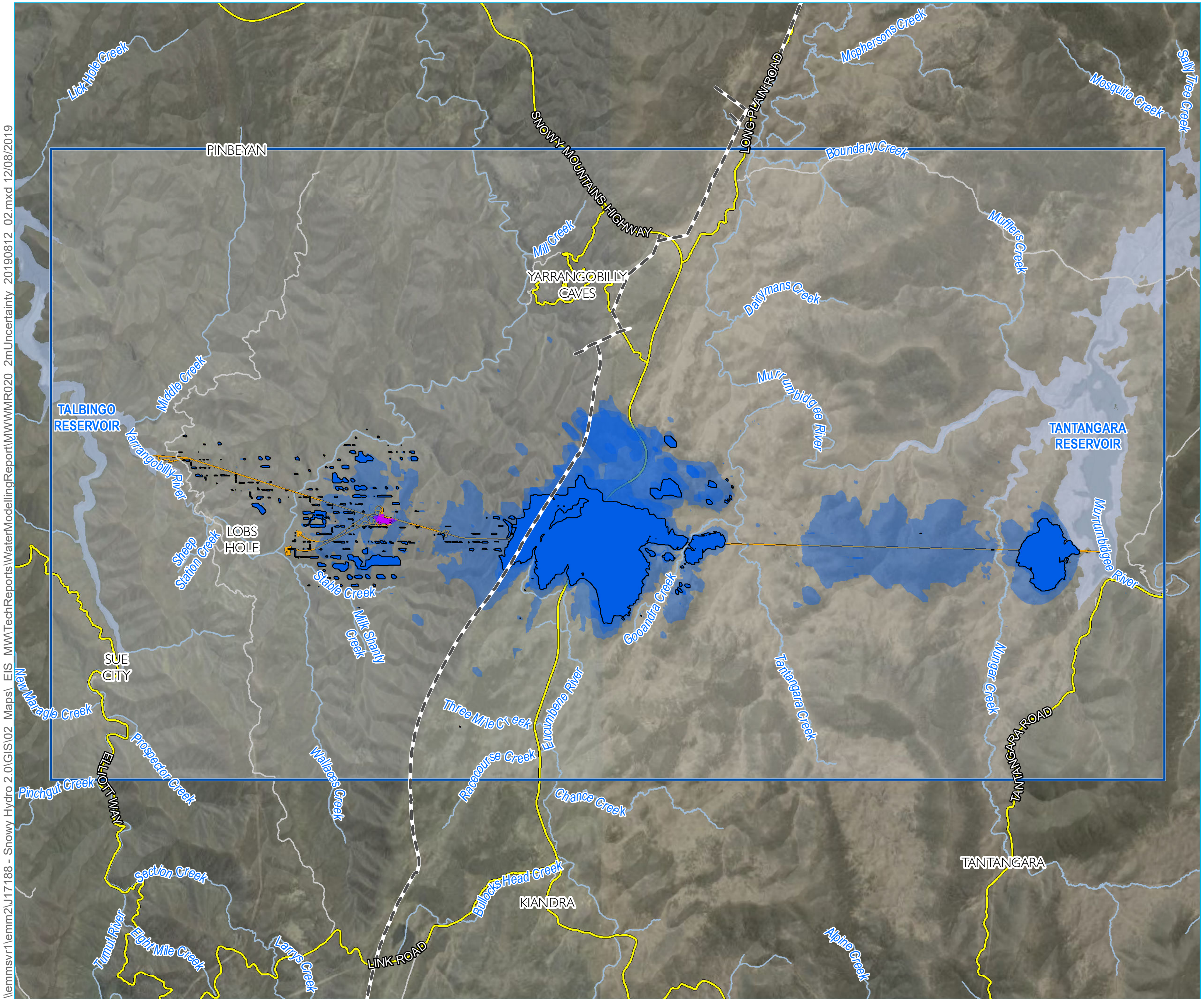
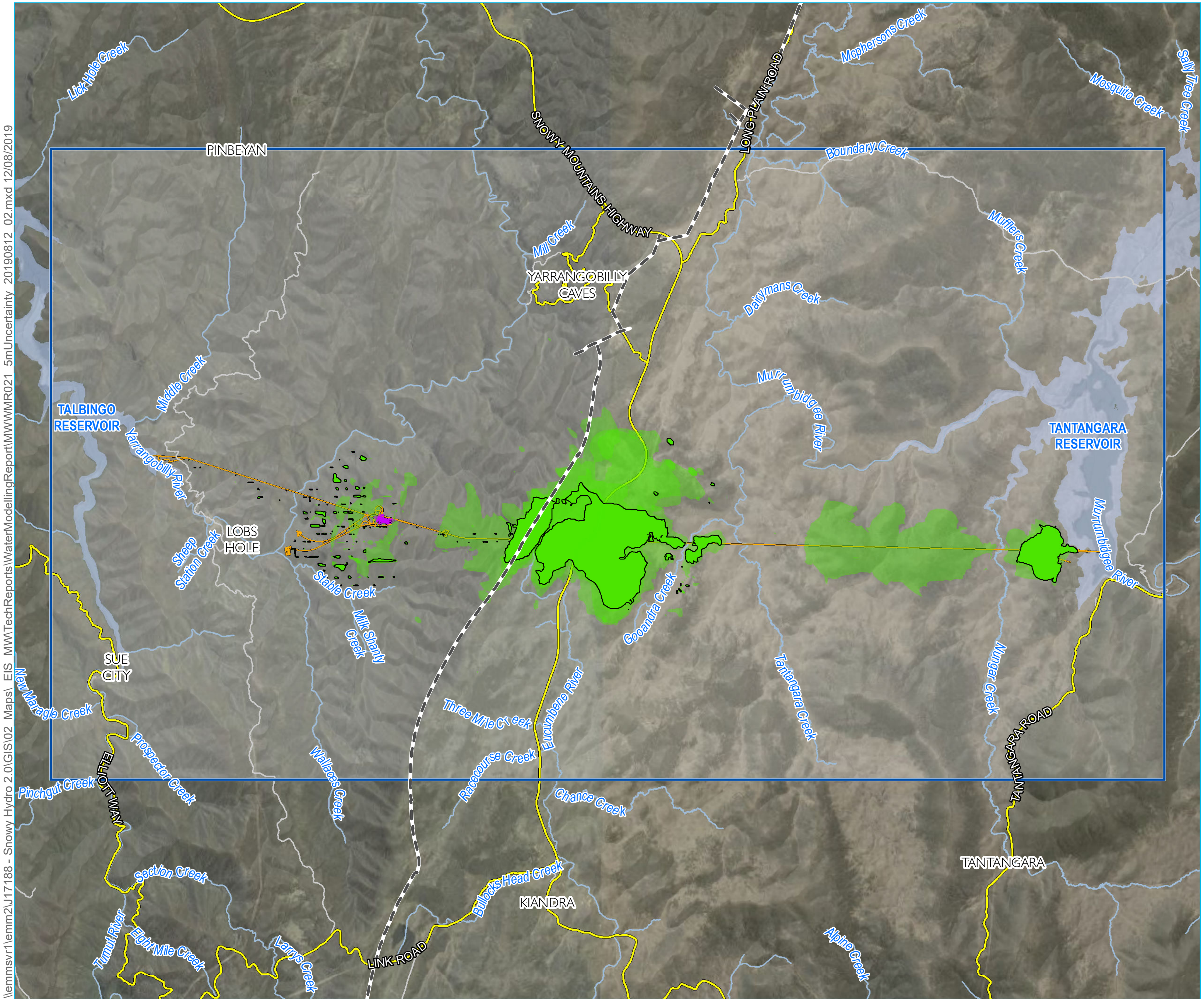


Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

\\emmsvr1\emm2\J17188 - Snowy Hydro 2.0\GIS\02_Maps_EIS_MW\TechReports\WaterModellingReport\MWWMR020_2mUncertainty_20190812_02.mxd 12/08/2019

Predicted operational 2 m drawdown in steady state, uncertainty due to aquifer

Snowy 2.0
Modelling Report
Main Works
Figure 3.40



Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

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KEY

- Base case
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements

- Tunnels, portals, intakes, shafts
- Power station

Existing environment

- Main road
- Local road
- Perennial watercourse
- Scheme storage

Number of simulations

- 29
- 1

Predicted operational 5 m drawdown in steady state, uncertainty due to aquifer

Snowy 2.0
Modelling Report
Main Works
Figure 3.41

snowy 2.0

EMM creating opportunities

Predicted base case groundwater hydrographs for all monitoring locations used in calibration history matching are presented in Attachment I. Figure 3.42 and Figure 3.43 present predicted base case groundwater hydrographs for selected sites across the project alignment, the same sites as those presented for the history matching period in Figure 3.16.

At BH5110 in the Boraig Group hydraulic head is predicted to decline at all three monitoring depths during construction then recover to varying degrees once operational. The site retains a downward gradient, behaving as a recharge site, throughout the prediction. Recovery is predicted to be greatest at the shallow monitoring site, as it is furthest removed from the underlying excavation.

At BH5114 in the Ravine Beds east hydraulic head is predicted to decline and partially recover at all three monitoring locations. During construction he deepest monitoring location is predicted to experience the least drawdown and, temporarily, has the highest head in a reversal of vertical gradient. During operation heads restabilise to a recharge site with downward vertical gradient but at reduced absolute head values.

BH4101 in the Gooandra Volcanics displays a later drawdown than the previous two sites, because excavation of the underlying headrace tunnel does not occur until late in the construction schedule at this location. However, drawdown at all three monitoring depths is more rapid due to the comparatively high hydraulic conductivity of the Gooandra Volcanics. Whilst some recovery is predicted following filling of the headrace tunnel with water, it is to a lesser degree than the previous two sites.

At BH2102 in the Tantangara Formation construction and operation cause a reversal of the vertical gradient. What was an upward vertical gradient, supporting discharge to Nungar Creek approximately 100 m away laterally, becomes a downward gradient.

At GH01, located at Gooandra Hill above the highly permeable Gooandra Volcanics, the model predicts ongoing drawdown of around 60 m. This level of drawdown would mean the site would no longer be groundwater discharge area if reliant only on discharge from the regional watertable.

At NC01 and TC01, located near Nungar Creek and Tantangara Creek respectively, no drawdown is evident in model predictions.

Hypothetical monitoring points, spaced every 2 km along the project alignment (see Figure 3.44) and at various depths, were employed in the model to extract predicted hydraulic head profiles with depth. The resulting head profiles, at several times prior to construction, during construction and during operation, are presented in Figure 3.45 and Figure 3.46. Most sites experience little to no drawdown at the watertable but large drawdown at the tunnel depth during construction followed by some degree of recovery at depth when the tunnel is filled with water. The largest watertable drawdown is experienced at the site located at a chainage of 14,000m, just west of the Snowy Mountains Highway. This site is located in the Gooandra Volcanics where the elevated hydraulic conductivity causes propagation of greater drawdown from the tunnel invert elevation up to the watertable.

Of interest is the site located at a chainage of 18,000 m. Whilst nothing significant is evident at the watertable elevation, and excavation causes drawdown at the tunnel depth like at other sites, once the tunnel is filled with water, this site is predicted to re-equilibrate to higher head at depth than was originally present. This occurs because this site is located part way down the ridge into the Ravine area at an elevation of approximately 1,200 m AHD. Prior to construction the modelled head at the tunnel depth is 1,114 m AHD and there is a downward vertical gradient. When the tunnel is filled with water the head in the tunnel is controlled by the head in Tantangara Reservoir, set at an average level of 1,215 m AHD in the model. This is higher than the pre-construction head at the tunnel level and, hence, reverses the gradient between tunnel and surrounding aquifer such that the head race tunnel is losing water to the groundwater system at this location.

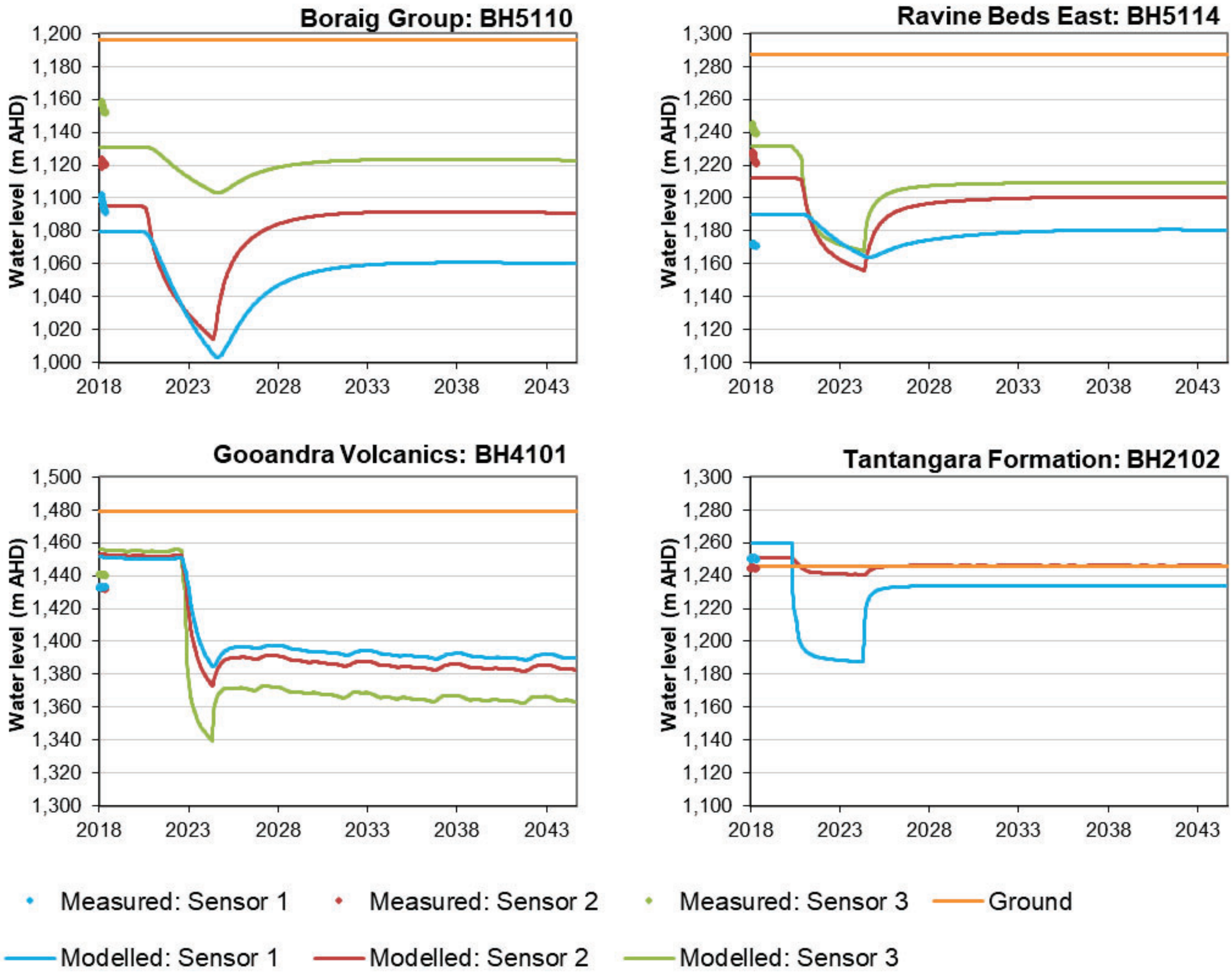


Figure 3.42 Selected predicted groundwater hydrographs

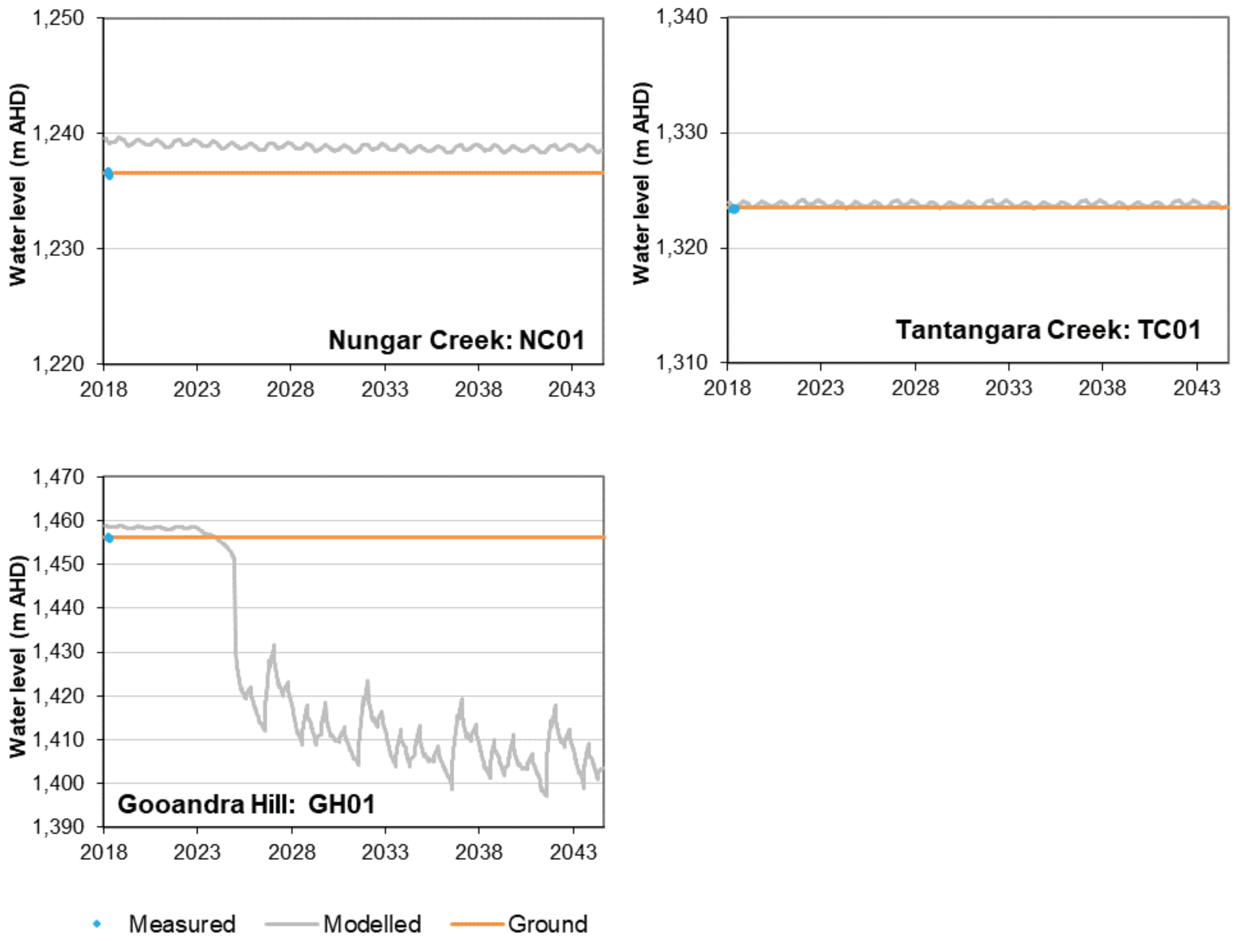
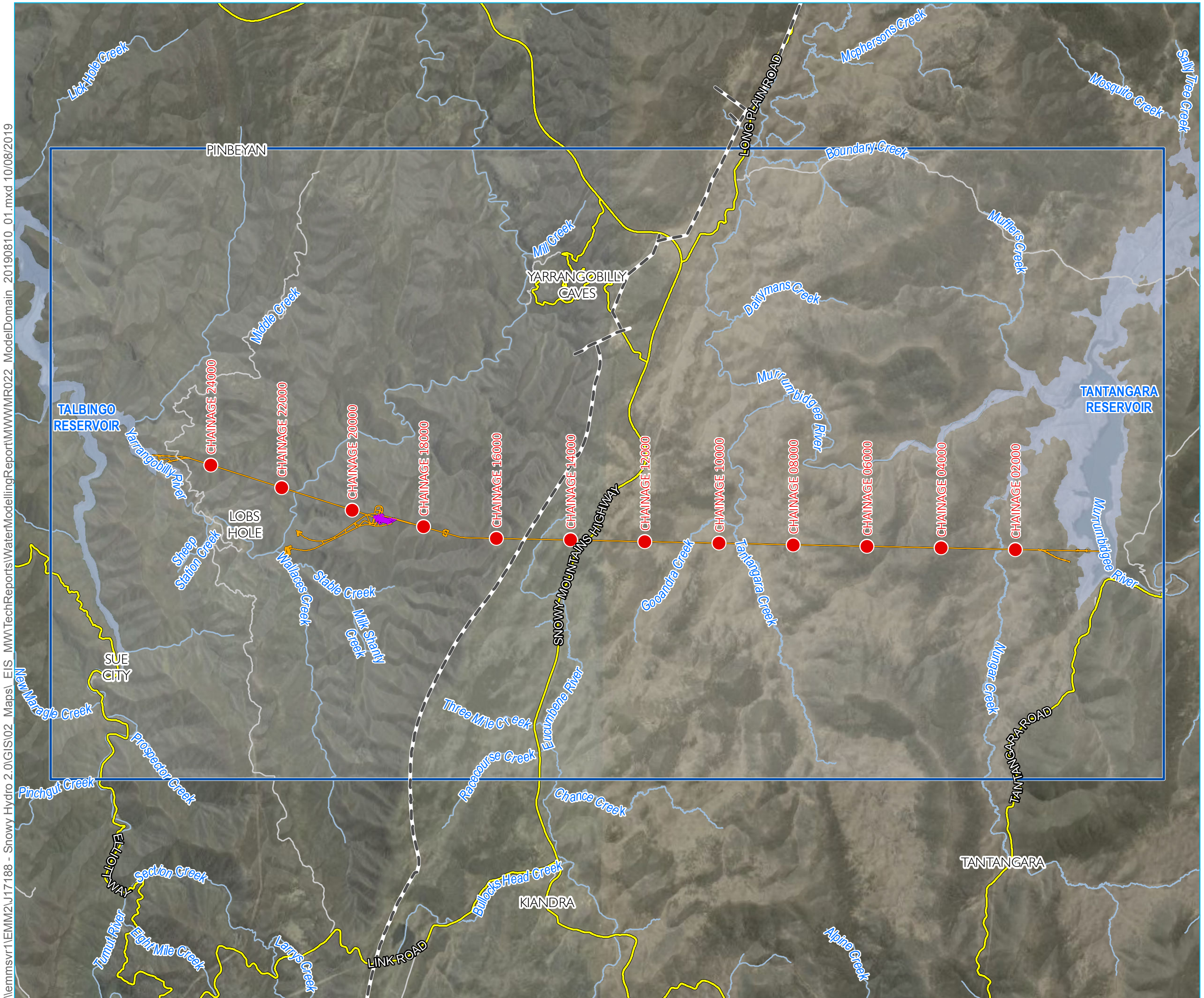


Figure 3.43 Selected predicted groundwater hydrographs for weathered / alluvial material



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Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

0 2.5 5 km

GDA 1994 MGA Zone 55

N

KEY

- Hydraulic head monitoring location
- Long Plain Fault
- Model domain

Snowy 2.0 operational elements

- Tunnels, portals, intakes, shafts
- Power station

Existing environment

- Main road
- Local road
- Perennial watercourse
- Scheme storage

Hydraulic head monitoring locations along project alignment

Snowy 2.0
Modelling Report
Main Works
Figure 3.44

snowy 2.0

EMM creating opportunities

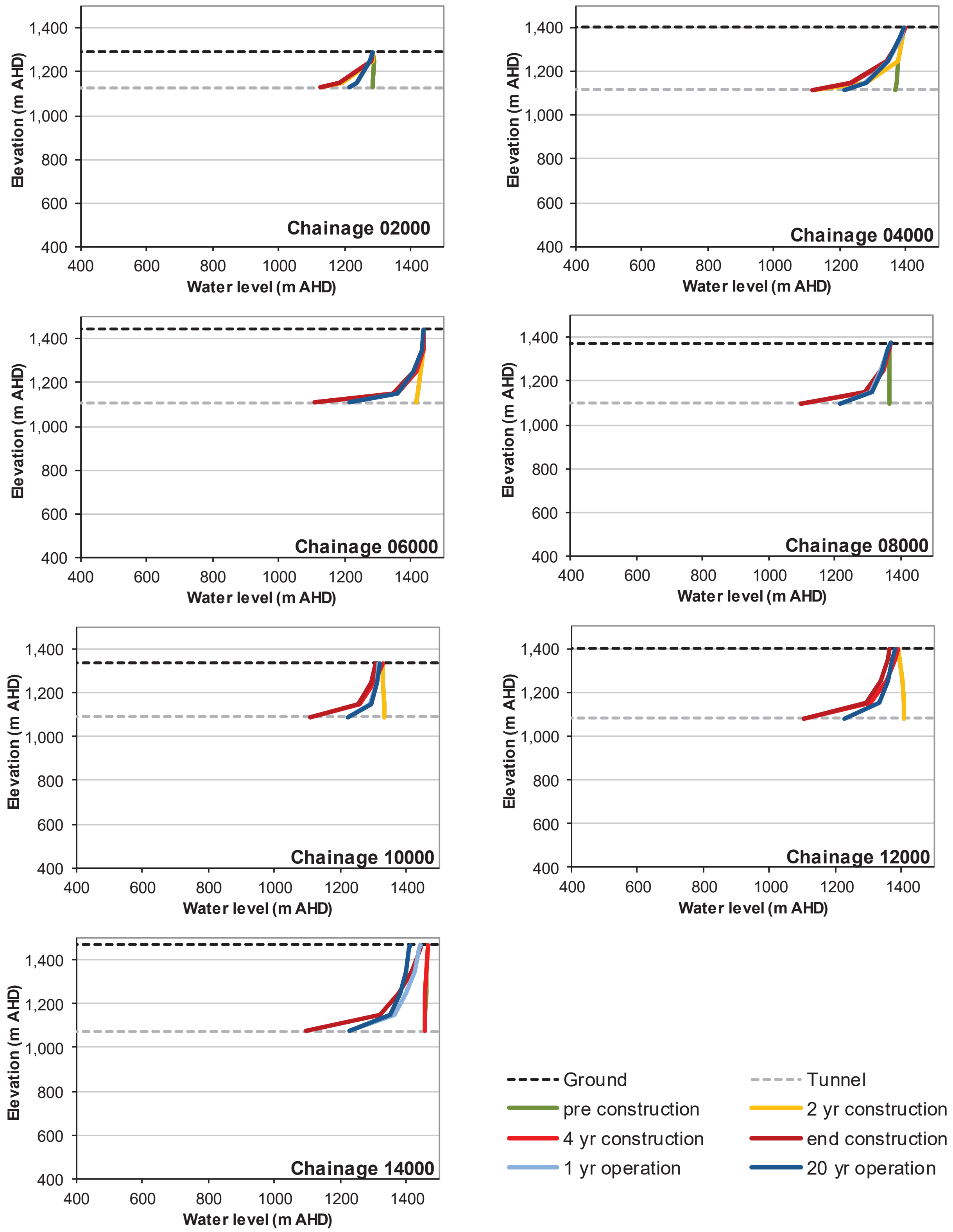

Figure 3.45 Predicted hydraulic head profiles along project chainage

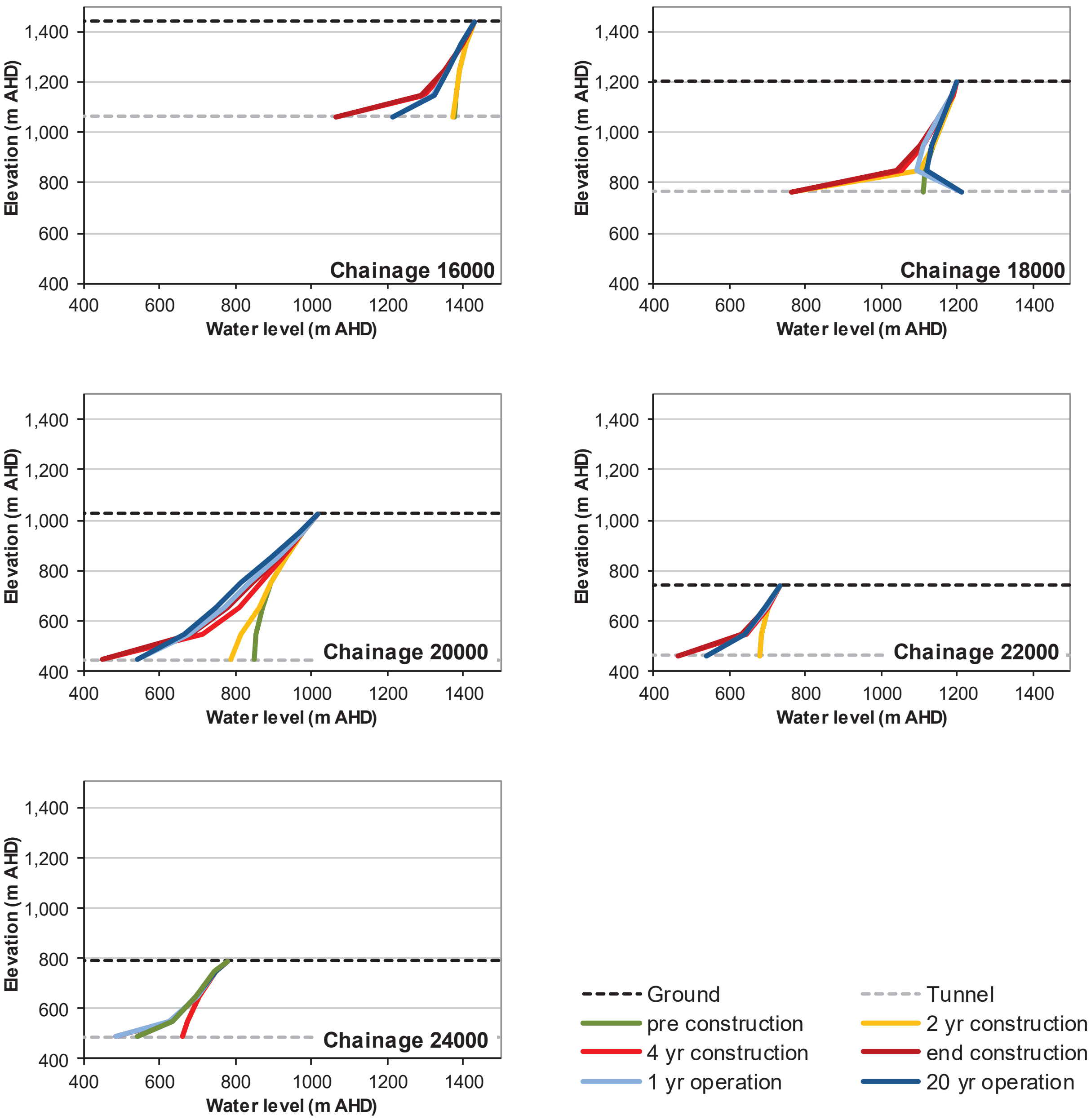

Figure 3.46 Predicted hydraulic head profiles along project chainage (cont.)

3.4.4 Predicted water balance

Figure 3.47 presents the modelled transient water balance, averaged over quarterly stress periods for the modelled construction and operation periods. The flow rates presented are for the entire 30 km by 17 km model domain. On this scale, as for the transient history matching period, the largest inflow component is recharge, which is balanced primarily by evapotranspiration and, to a lesser degree, discharge as baseflow. Movement of water into and out of storage buffers the seasonality of climate stresses. The water balance components associated with construction and operation of Snowy 2.0 are almost undetectable on this regional scale, despite the evident drawdown impacts predicted at construction depths and at the watertable.

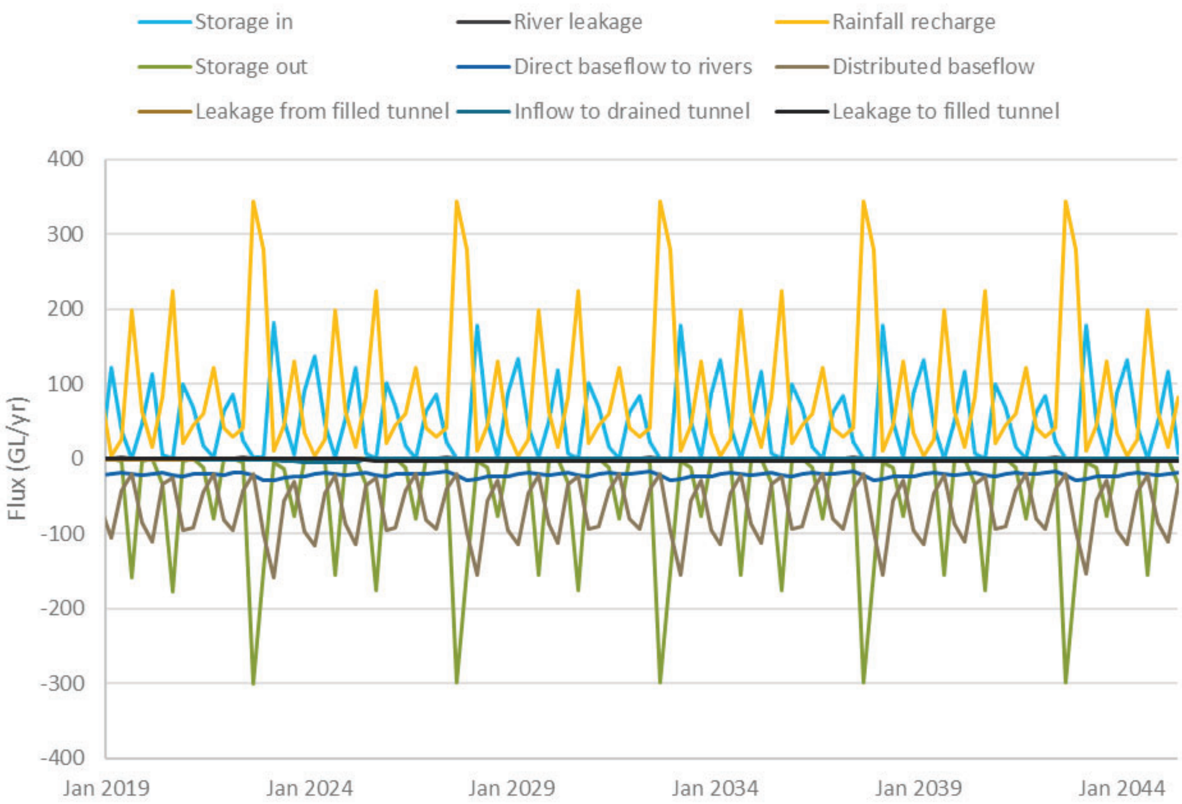

Figure 3.47 Modelled transient base case water balance

i Inflow to excavations

Predicted flows to excavation components over the construction and operation periods are presented in Figure 3.48. By far the greatest inflows, peaking at 142 L/s in the quarter ending 1 June 2024, occur in the head race tunnel. This is the longest project component and, also, is excavated through the two deep rock units with the highest modelled hydraulic conductivity; the Kellys Plain Volcanics and the Gooandra Volcanics (and associated Gooandra Volcanics fractured zone and Shaw Hill Gabbro).

The second largest inflows occur in the adit to the headrace tunnel (included with headrace tunnel data in in Figure 3.48), located in the relatively permeable Kellys Plains Volcanics. Inflow to this component peaks at 9.6 L/s in the quarter ending 1 December 2021.

The third largest inflows are the tail race tunnel, peaking at 7 L/s in the quarter ending 1 September 2022.

Total inflow to all excavated components peaks at 161 L/s in the quarter ending 1 June 2024.

When the power waterway is filled with water, from March 2025, inflows decrease rapidly and quickly reach a new dynamic equilibrium, with relatively minor variations controlled by seasonal climatic variability. During operation inflows average around 85 L/s. The headrace tunnel remains the largest receptor of groundwater inflow, at around 70 L/s, even when filled with water at Tantangara Reservoir driving head level.

The uncertainty in tunnel inflows associated with climate during the construction period was investigated using average (1 December 2012 to 1 December 2017), wet (1 December 1988 to 1 December 1993) and dry (1 December 2001 to 1 December 2006) climate sequences. The peak inflows varied from 160 L/s with the dry climate to 168 L/s with the wet climate sequence (Figure 3.49).

Table 3.5 presents annualised inflows to and from excavations. Annual volumes are reported for years ending 1 June, in line with the seasonal stress periods employed by the model. On an annual basis groundwater inflows to excavations peak at 4476 ML, 4606 ML and 4413 ML for the average, wet and dry climate scenarios.

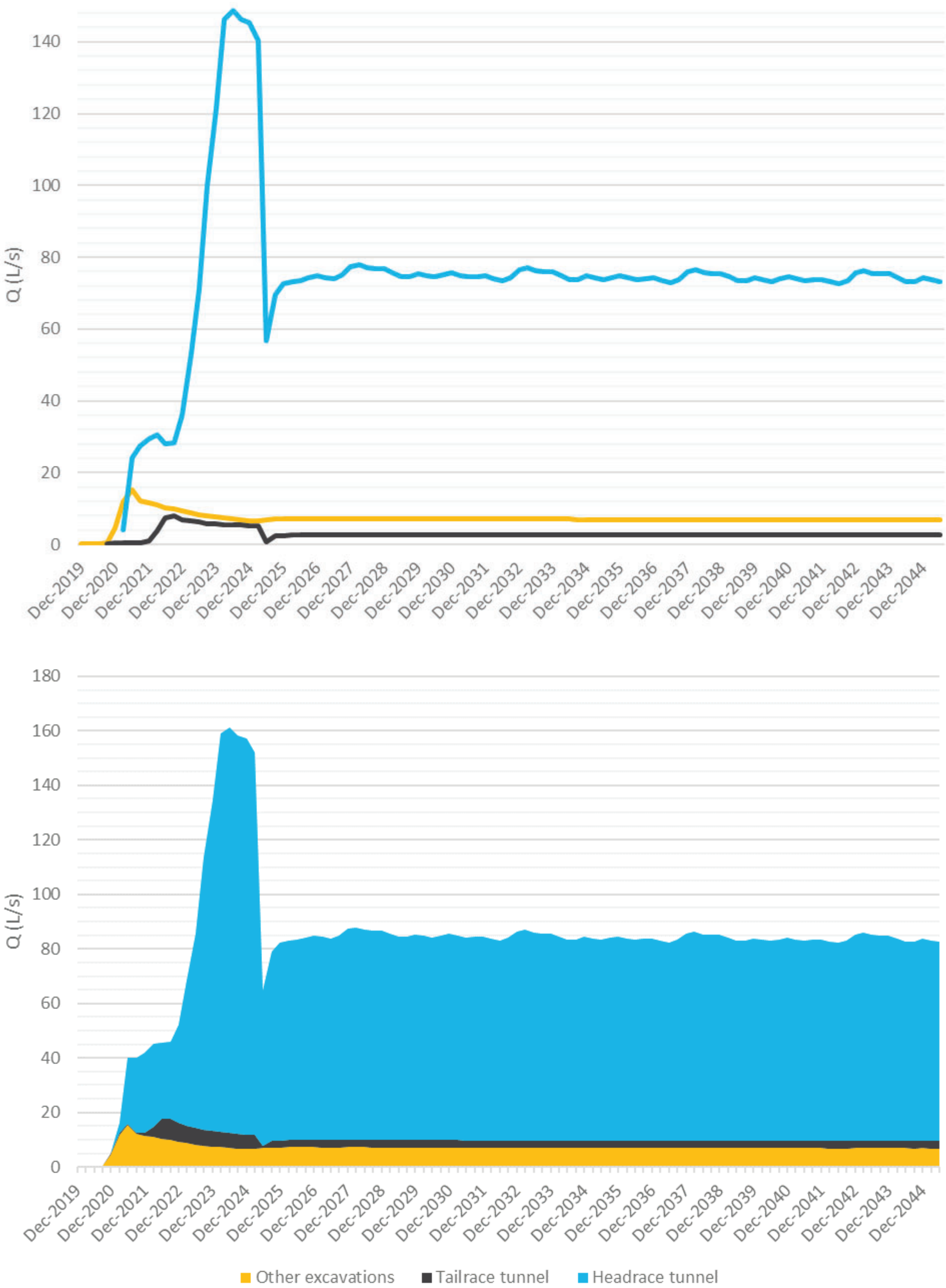

Figure 3.48 Predicted inflow to excavations during construction and operation

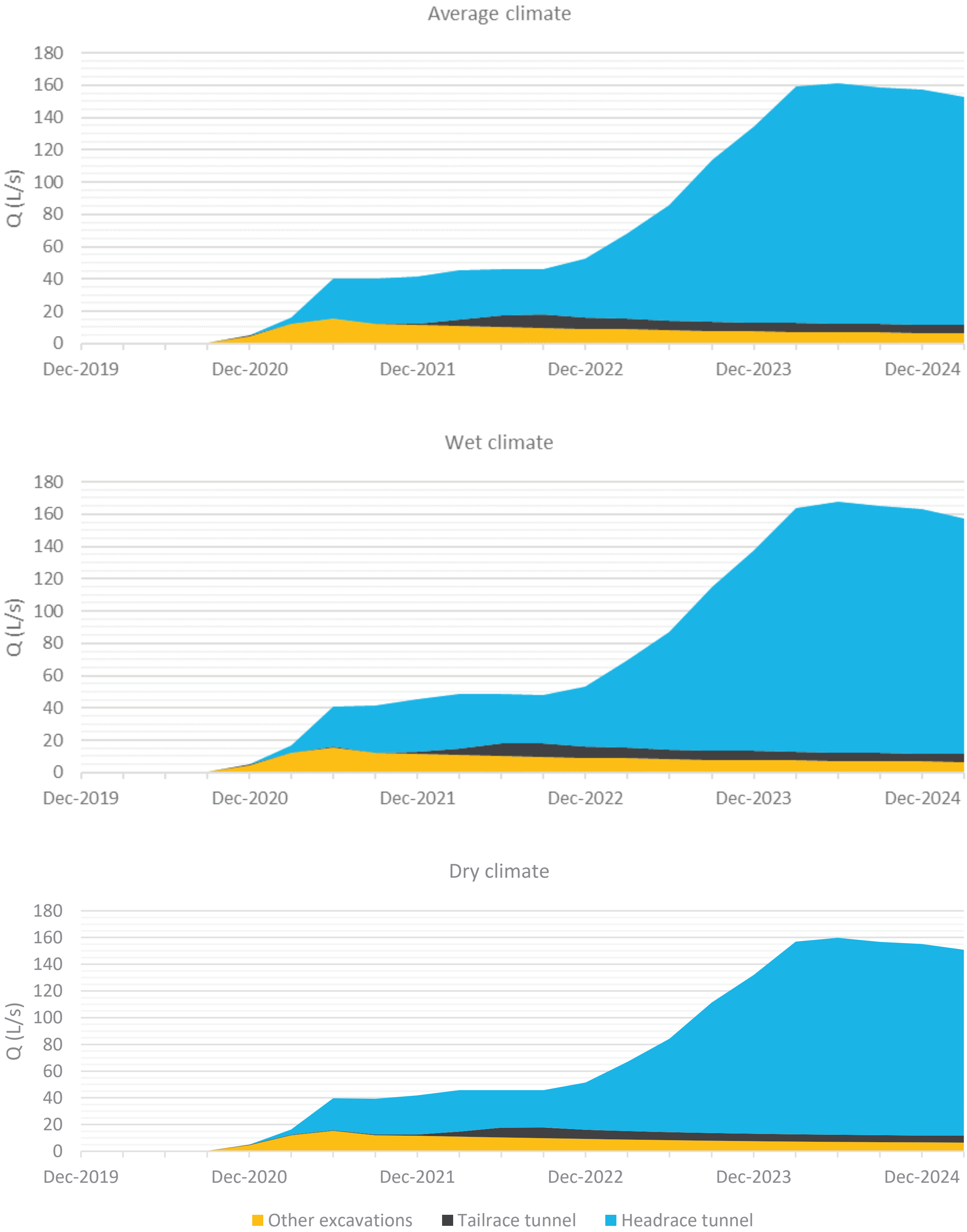

Figure 3.49 Predicted inflow to excavations during construction

Table 3.5 Predicted annual inflows to excavations for average, wet and dry climates

		Dry climate	Wet climate	Average climate		
Project phase	Year Ending	Flow to excavations (ML)	Flow to excavations (ML)	Flow to excavations (ML)	Flow to power waterway (ML)	Flow from power waterway (ML)
Construction	1-Jun-19	0	0	0		
	1-Jun-20	-3	-3	-3		
	1-Jun-21	-471	-481	-474		
	1-Jun-22	-1343	-1438	-1343		
	1-Jun-23	-1949	-2021	-1981		
	1-Jun-24	-4413	-4606	-4476		
	1-Jun-25	-3629	-3811	-3728		
Operation	1-Jun-26			-227	-2438	76
	1-Jun-27			-228	-2499	67
	1-Jun-28			-229	-2583	64
	1-Jun-29			-227	-2543	63
	1-Jun-30			-224	-2511	62
	1-Jun-31			-223	-2515	62
	1-Jun-32			-222	-2496	62
	1-Jun-33			-222	-2547	61
	1-Jun-34			-221	-2515	61
	1-Jun-35			-220	-2485	61
	1-Jun-36			-220	-2498	61
	1-Jun-37			-218	-2467	61
	1-Jun-38			-219	-2528	61
	1-Jun-39			-219	-2500	61
	1-Jun-40			-218	-2478	61
	1-Jun-41			-217	-2480	61
	1-Jun-42			-216	-2458	61
	1-Jun-43			-218	-2520	61
	1-Jun-44			-218	-2501	61
	1-Mar-45			-162	-1848	46
	Steady State			-213	-2532	62

ii Changes to baseflow

The groundwater model predicted that localised baseflow discharges to creeks and rivers would be seen in the catchments upstream of Tantangara Reservoir, Lake Eucumbene, and Talbingo Reservoir (Figure 3.50 and Table 3.6). While inflows to the excavations are predicted to peak in the final year of construction (Figure 3.48), impacts to baseflow are predicted to develop more slowly, with peak impacts occurring several decades after the completion of construction (Figure 3.50). The total steady state reduction in baseflow is approximately equivalent to the tunnel inflow volume, as expected based on the whole of catchment water balance (Figure 1.3); inflows to the tunnel are directly offset by reduction in baseflow, with a time lag as the impact propagates to the surface.

A detailed breakdown of predicted baseflow discharge rates is included in Attachment J.

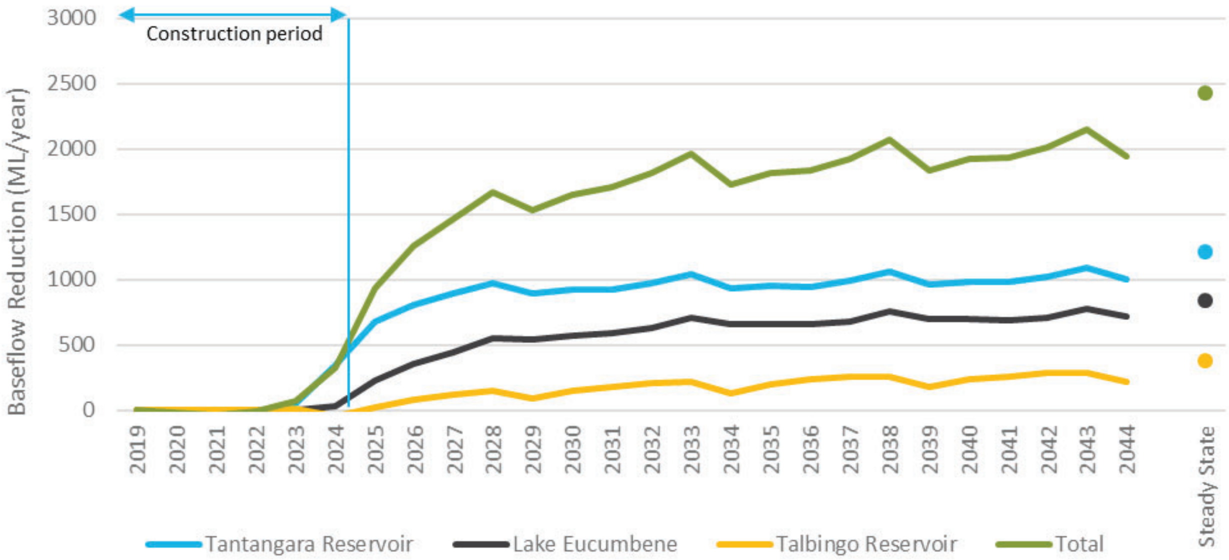

Figure 3.50 Baseflow reduction predicted by the groundwater model (average climate) within each reservoir catchment

Table 3.6 Long-term (steady state) streamflow impacts predicted by the groundwater model

Receiving Waterbody	Catchment	Baseflow Reduction (ML/yr)	Total (ML/yr)
Tantangara Reservoir	Murrumbidgee River (including Gooandra Creek and Tantangara Creek)	1,123	**1,179**
	Nungar Creek	56	
Lake Eucumbene	Eucumbene River	840	**840**
Talbingo Reservoir	Yarrangobilly River (including Wallaces Creek and Stable Creek)	373	**375**
	Middle Creek	2	
Total			**2,394**

3.5 Summary, model limitations and recommendations

The SH4.0 model has been constructed, calibrated and used to predict watertable drawdown, inflows to excavations and associated changes to components of the water balance, particularly baseflow to rivers and creeks.

The model was designed to provide regional-scale predictions of potential impacts associated with Snowy 2.0 subsurface excavations and operation in accordance with the NSW Aquifer Interference Policy (DPI Water 2012). The model is not intended to provide absolute predictions of heads or flows on localised scales or at local features.

The SH4.0 numerical groundwater flow model was not designed to explicitly simulate soil water, surface water or perched groundwater nor water quality/solute transport.

For the purposes of modelling groundwater, a conservative approach of simulating all excavations as fully drained (during construction) and unlined was adopted. The majority of the intercepted geological units have very low hydraulic conductivity values, and hence are predicted to contribute minimal relative inflow. However, the hydraulic properties for the Gooandra Volcanics and the Kellys Plain Volcanics are two orders of magnitude higher than adjacent geological units in the area.

The model predictions are considered conservative due to the design scenario assumptions (unlined and unmitigated) and the adoption of conservative hydraulic parameters (as per field measurements). Therefore, it is considered that the predicted inflow (and subsequent impacts) will be lower than predicted due to mitigation and management measures committed to during construction (ie pre-grouting and segmental lining).

Groundwater flow into the tunnel is expected to occur primarily as a function of secondary porosity (ie via fractures and along bedding planes). The groundwater model assumes significant connection between the tunnel and the watertable in the Gooandra Volcanics and the Kellys Plains Volcanics due to the hydraulic testing undertaken throughout the unit. It is possible that additional field testing may reveal that locations with vertical connection occur only in isolated locations.

The model cannot simulate individual fractures because the locations and conductivity of individual fractures will not be known until the tunnel intersects them. Because the exact locations and extent of inflow mitigation strategies are not yet known, the groundwater modelling adopted a conservative approach of simulating all excavations as non-mitigated/controlled. Attempts to simulate unknown geological occurrences or design elements are not in-line with the Australian Groundwater Modelling Guidelines (a core requirement of NSW Governments AIP for groundwater modelling) and have therefore not been undertaken. The modelling results are therefore conservative for two reasons:

- modelling does not consider mitigating activities;
  - conservative as during construction the discrete fractures that yield excess water will be grouted and will reduce the actual overall tunnel inflow volume;
- hydraulic parameters within the numerical model for the Gooandra Volcanics and the Kellys Plain Volcanics are assume significant connection to the water table based on limited pumping test data;
  - potentially conservative as the entirety of the Gooandra Volcanics and the Kellys Plain Volcanics may not behave like this, with some parts being less permeable or less connected.

Therefore, the model predictions of tunnel inflow, baseflow reduction and water table drawdown are likely to be over estimating project impacts. The results of this conservative model approach need to be considered within this overall context to accurately assess the project on its true merits for impacts to water resources.

Uncertainty analysis was conducted by adopting the maximum and minimum plausible parameter values for the modelled hydrostratigraphic units. It is very unlikely that the maximum bounds adopted for hydraulic conductivity apply on a regional scale. Therefore, the regional drawdown predictions are expected to be upper limits. Predictive uncertainty analysis for hydraulic properties of the groundwater system was conducted only in steady state due to the computation demands of the transient simulations. However, steady state predictions provide an appropriate assessment of long-term regional-scale impacts on the groundwater system.

Climate change has not been addressed in this study, although climate variability during construction was simulated. This indicated that short term variability in climate impacts primarily on near-surface components of the water balance and has only a minor impact (approximately 5%) on total groundwater inflows to underground excavations.

The SH4.0 model (and linked surface water model) should be kept as a live groundwater management tool. It should be validated and, if necessary, recalibrated to new groundwater monitoring data as the monitoring record increases. Of particular benefit will be measured groundwater responses to the commencement of excavations. Dewatering of excavations provides a much greater stress on the groundwater system, to which history matching can be conducted, than climate-driven stresses. It is recommended than assessment of the monitoring record and groundwater affecting activities, along with model updates, be undertaken at least annually as the Exploratory Works commence, through construction of Main Works and into operation until it is evident that the update frequency can be reduced.

4 References

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