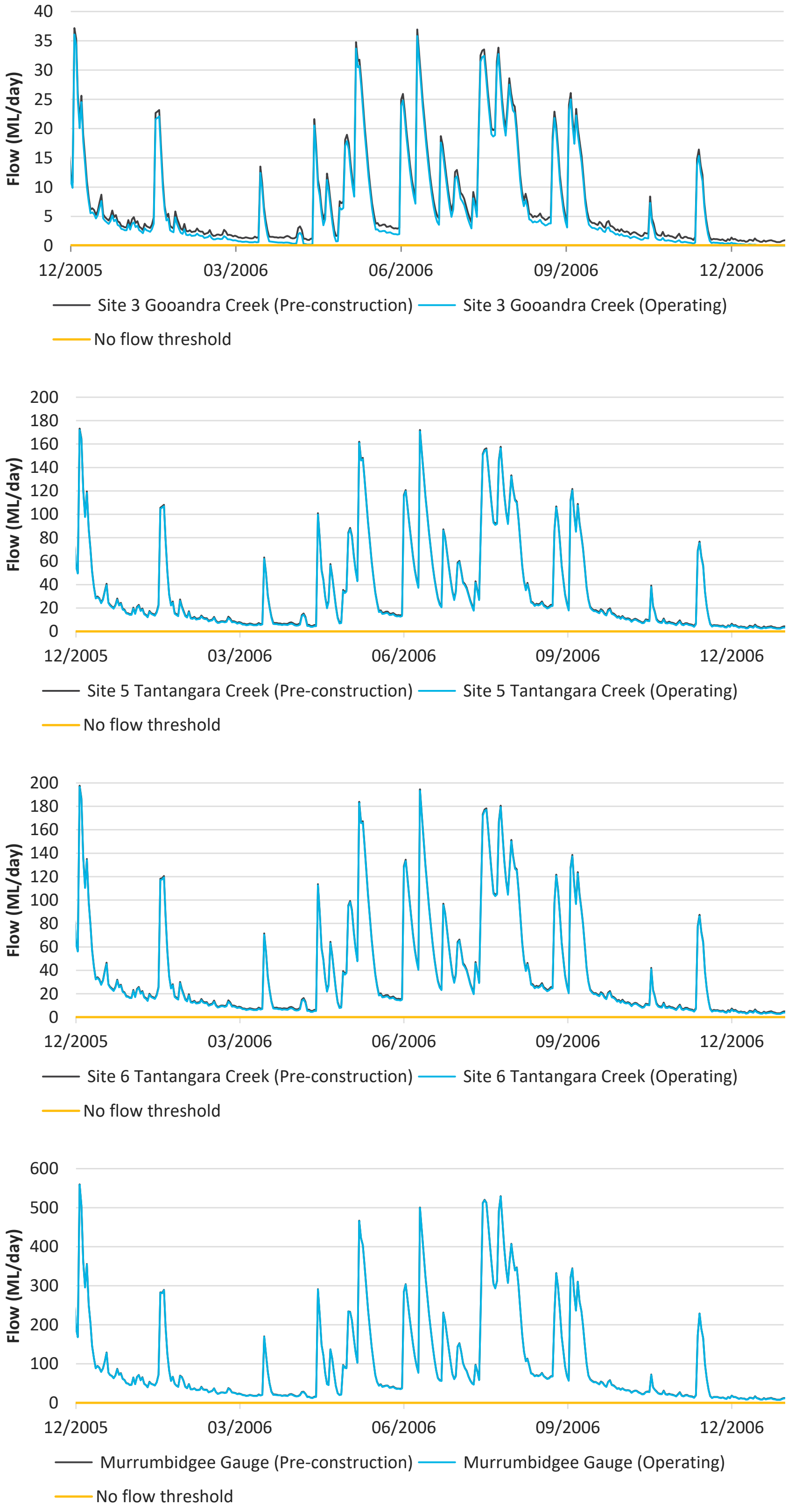


Figure 2.65 Operation phase: hydrographs for the Gooandra Creek reporting sites

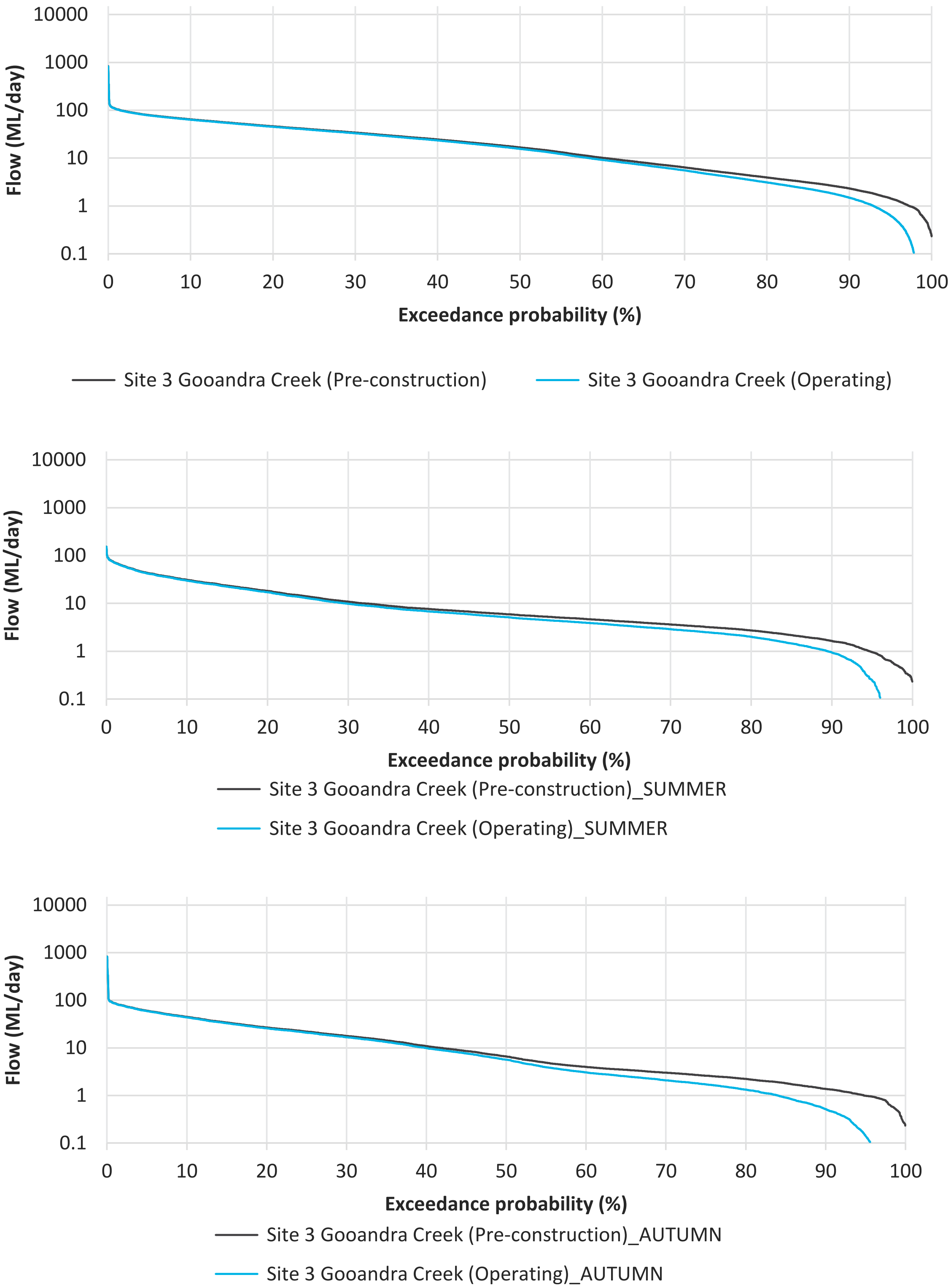
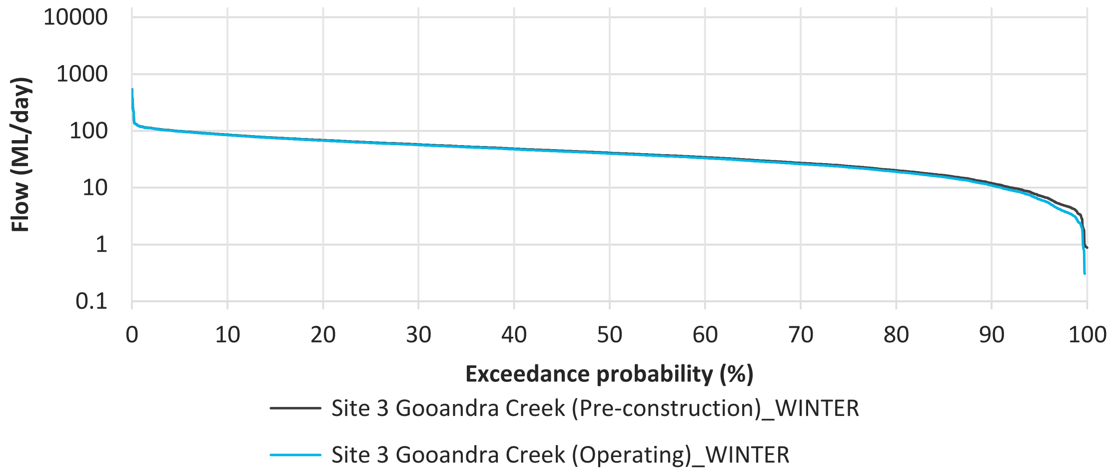


Figure 2.66 Operation phase: flow duration curves for Gooandra Creek reporting site, Site 3 (Total, Summer and Autumn)



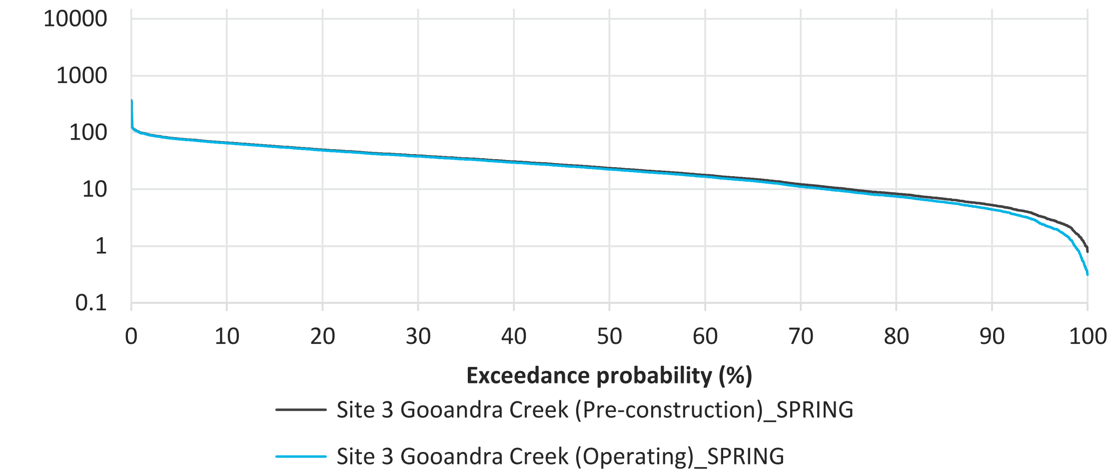


Figure 2.67 Operation phase: flow duration curves for Gooandra Creek reporting site, Site 3 (Winter and Spring)

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 of the project:

- Gooandra Creek will change from having a perennial streamflow regime to being ephemeral (days with 'no flow' increase from 0% to 2% 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)

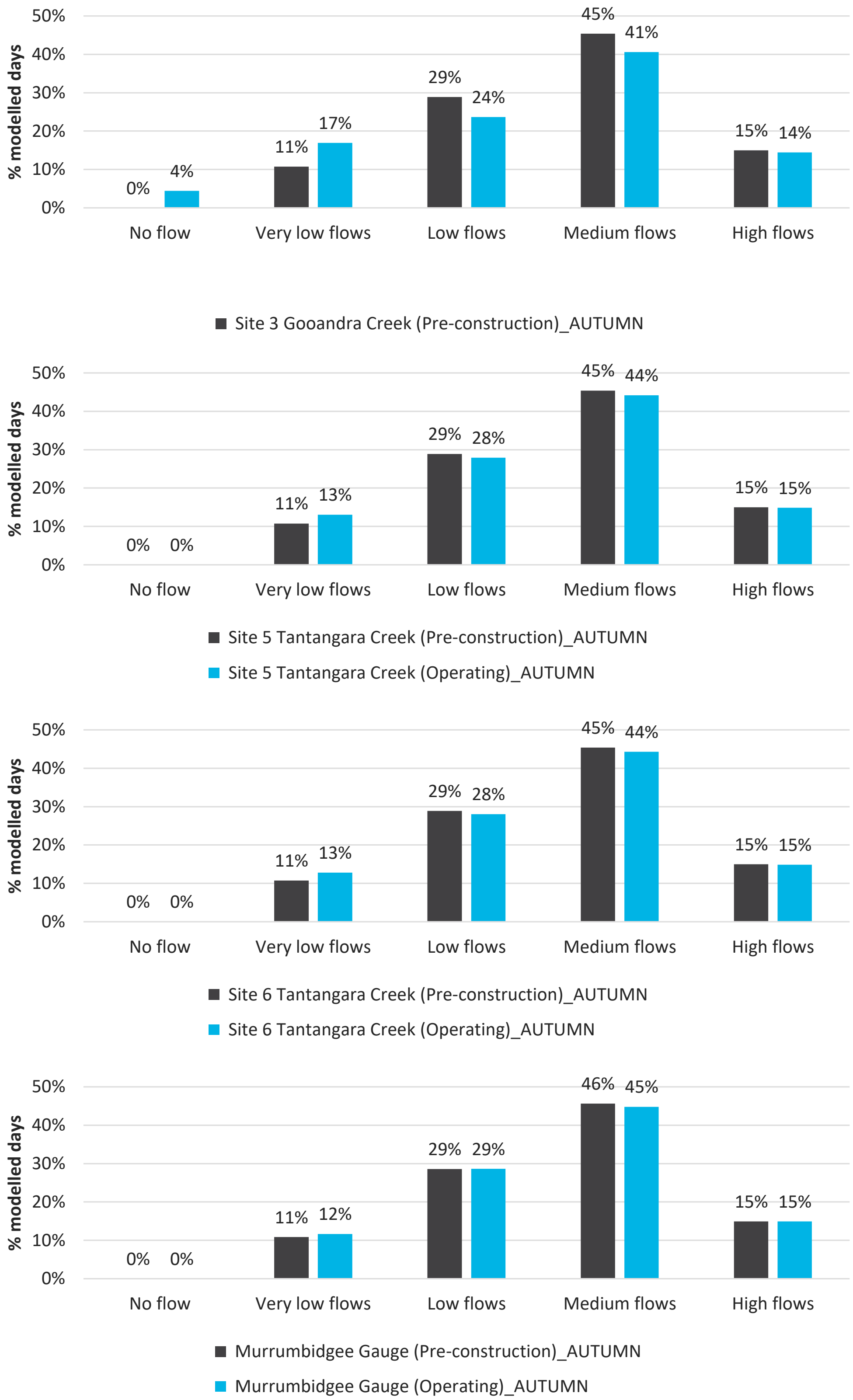


Figure 2.70 Percentage autumn days in each flow category (Gooandra Creek reporting sites)

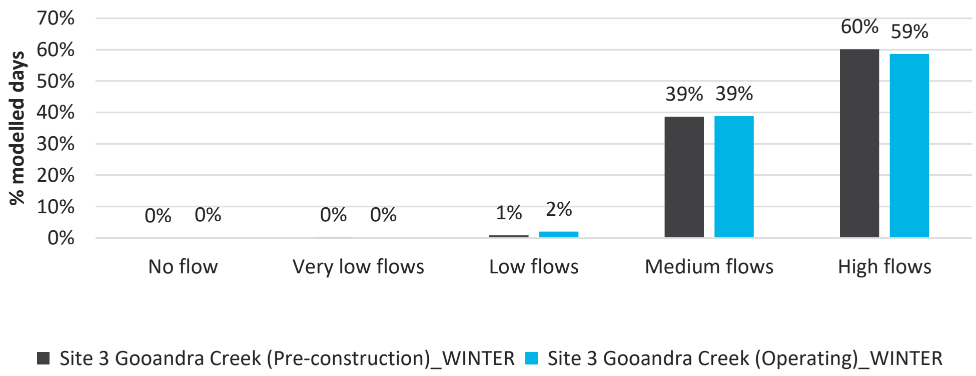


Figure 2.71 Percentage of winter days in each flow category (Site 3)

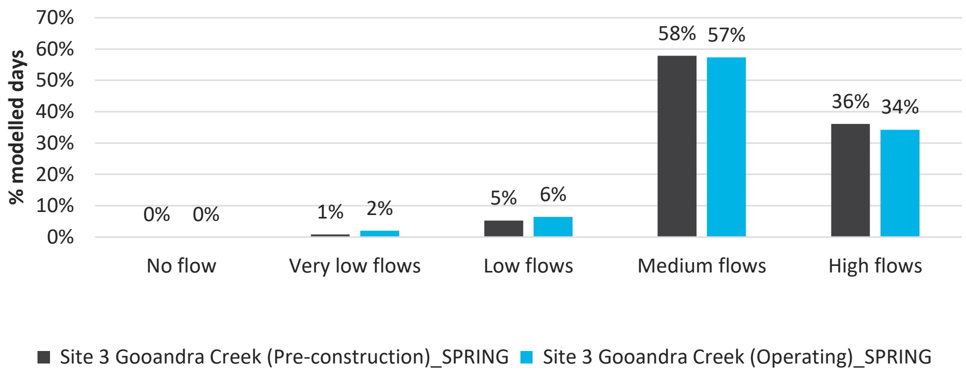


Figure 2.72 Percentage of spring days in each flow category (Site 3)

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.

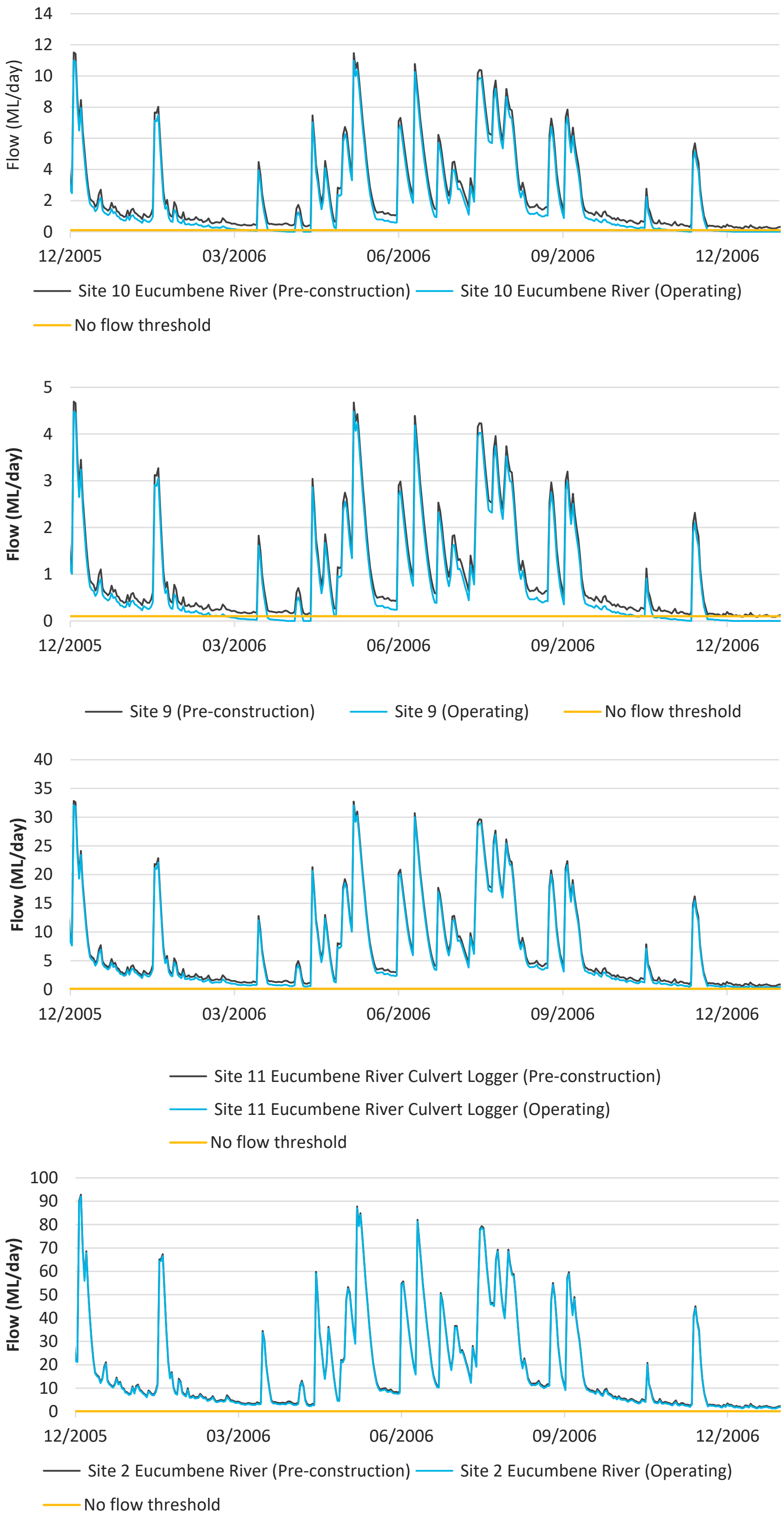


Figure 2.73 Operation phase: hydrographs for the Eucumbene River reporting sites

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

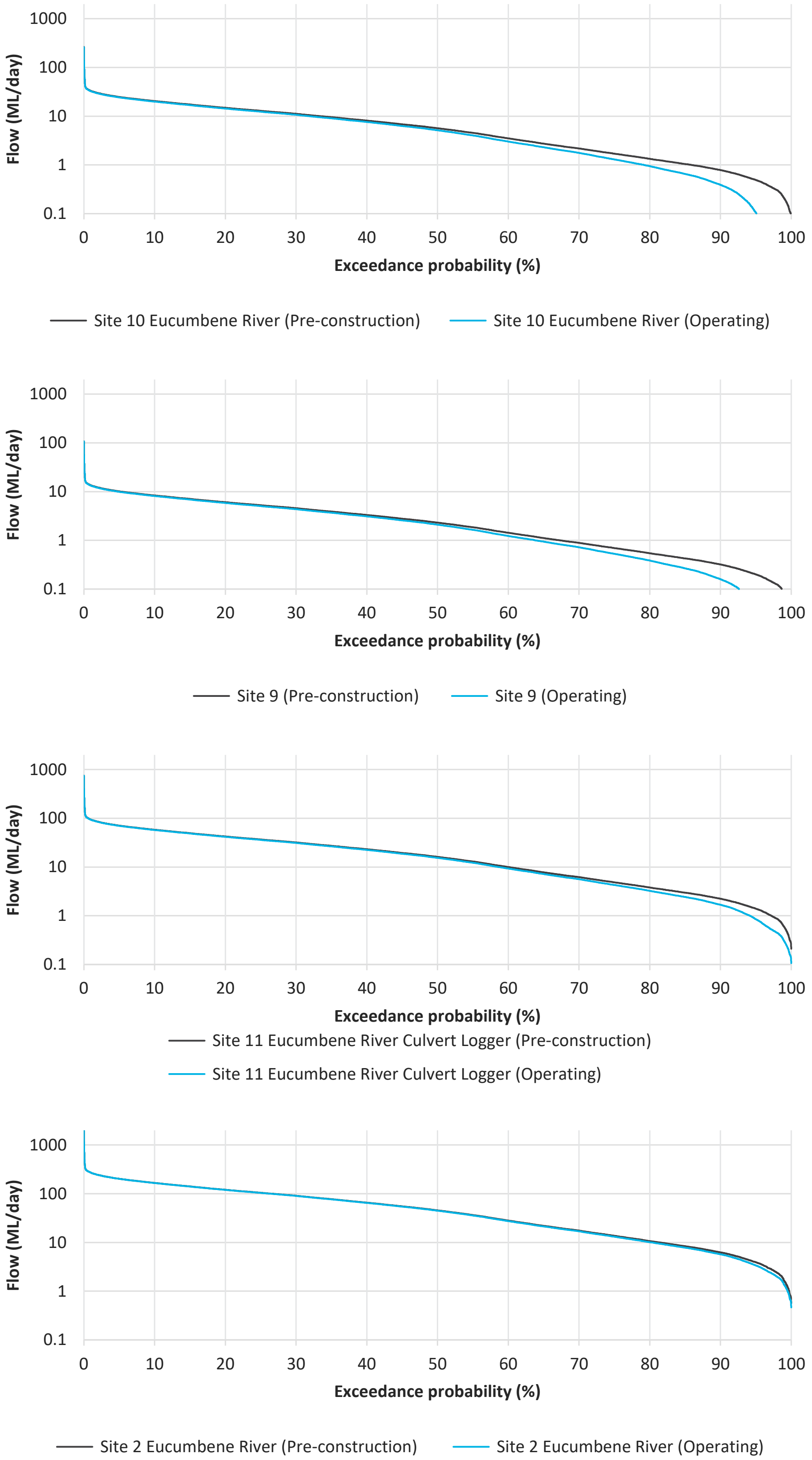


Figure 2.74 Operation phase: flow duration curves for Eucumbene River reporting sites (total)

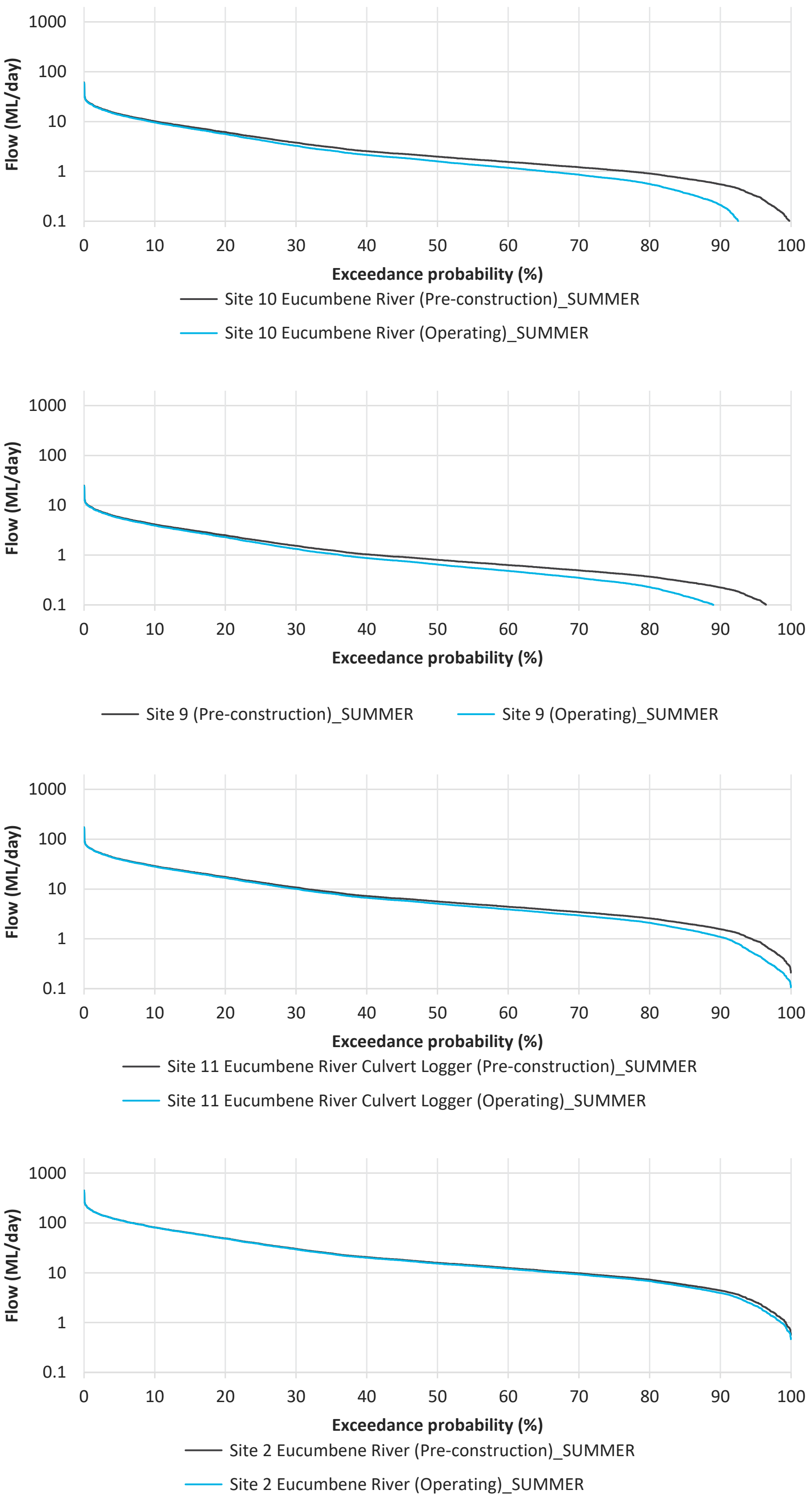


Figure 2.75 Operation phase: flow duration curves for Eucumbene River reporting sites (Summer)

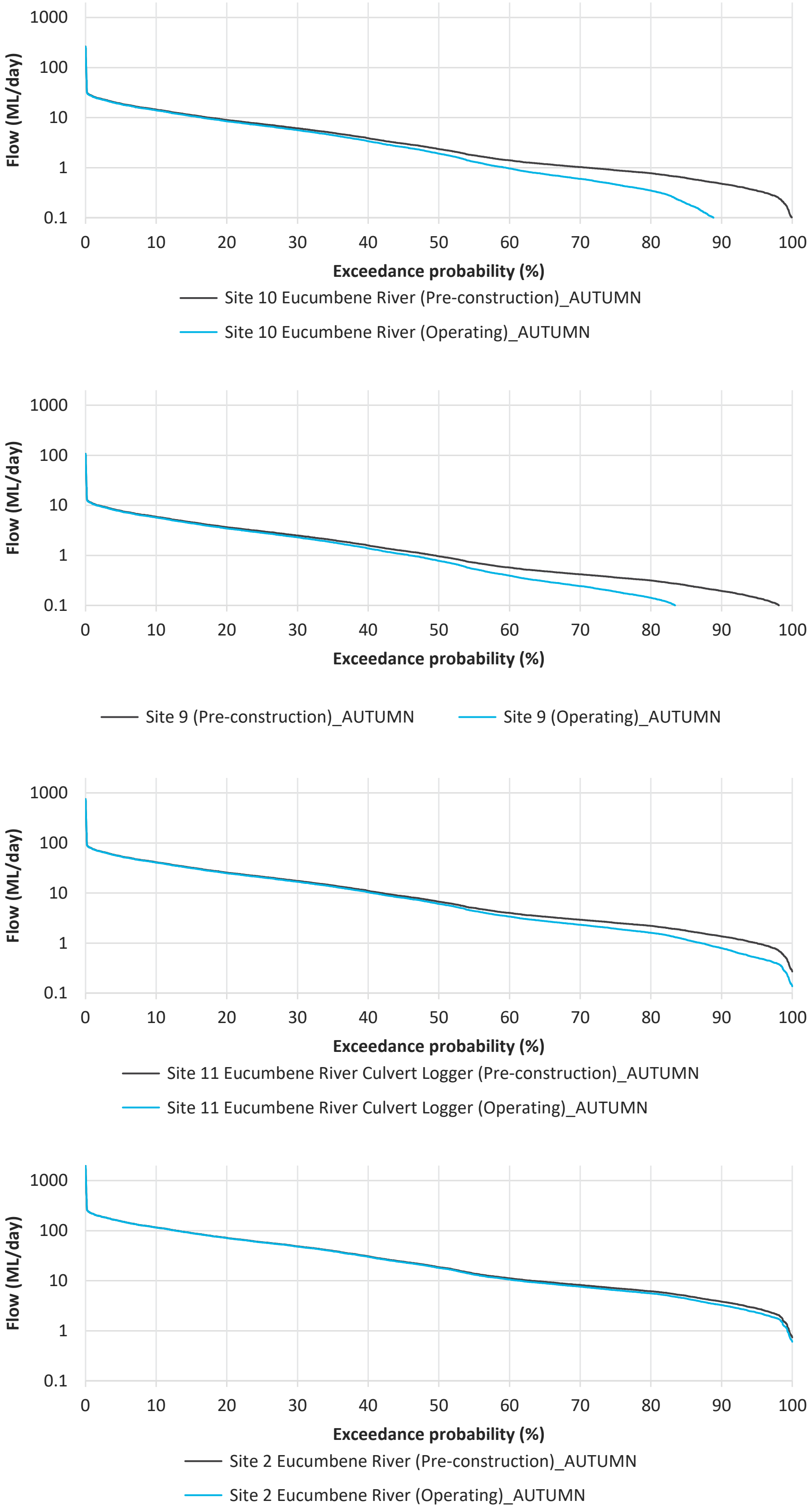


Figure 2.76 Operation phase: flow duration curves for Eucumbene River reporting sites (Autumn)

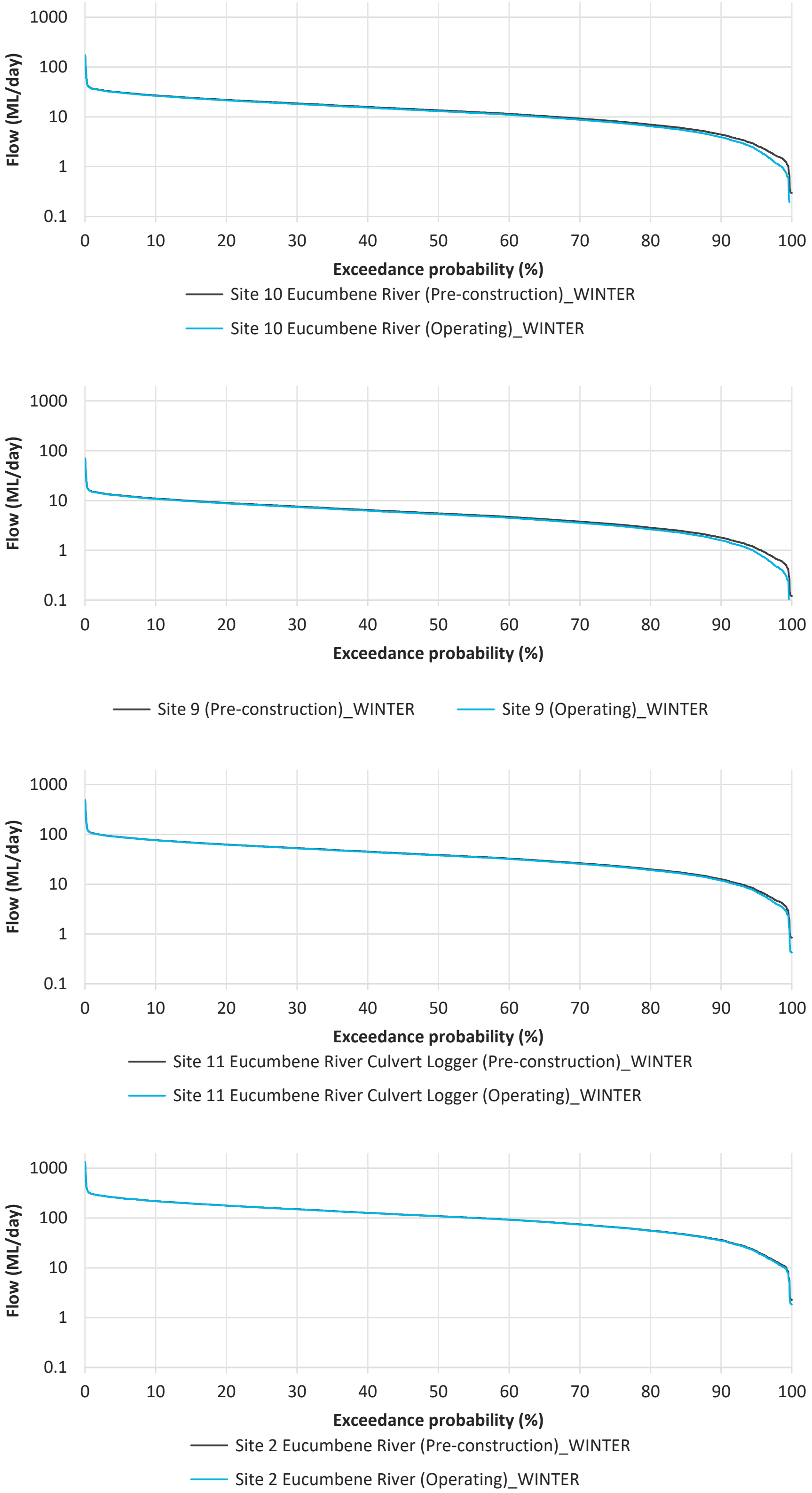
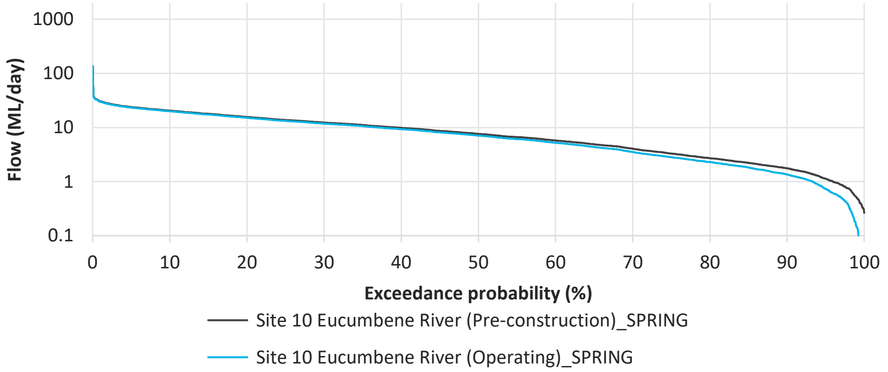
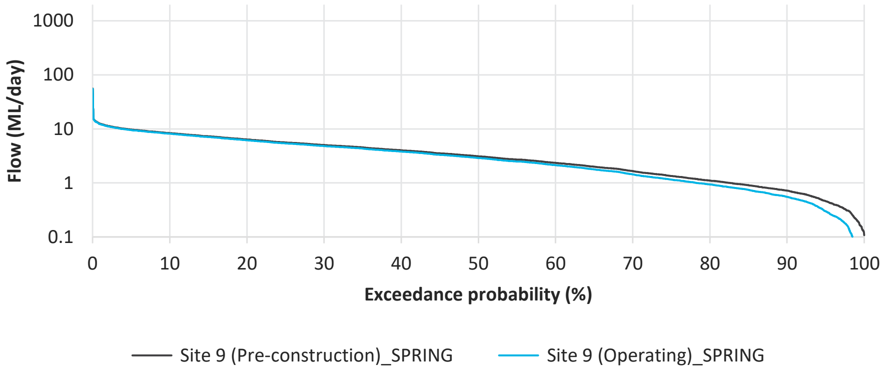
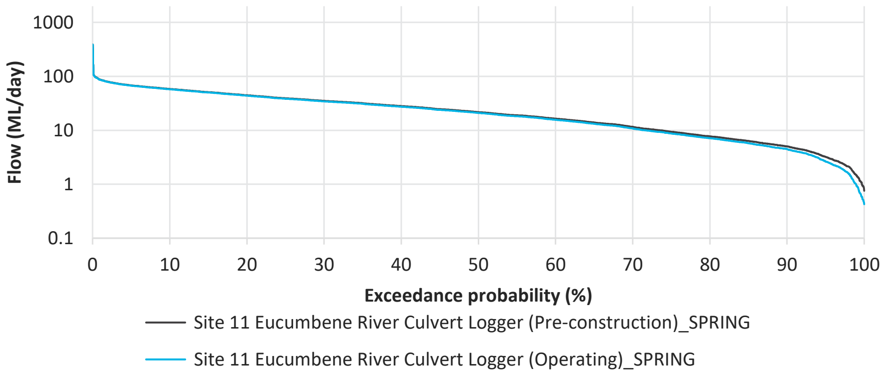


Figure 2.77 Operation phase: flow duration curves for Eucumbene River reporting sites (Winter)







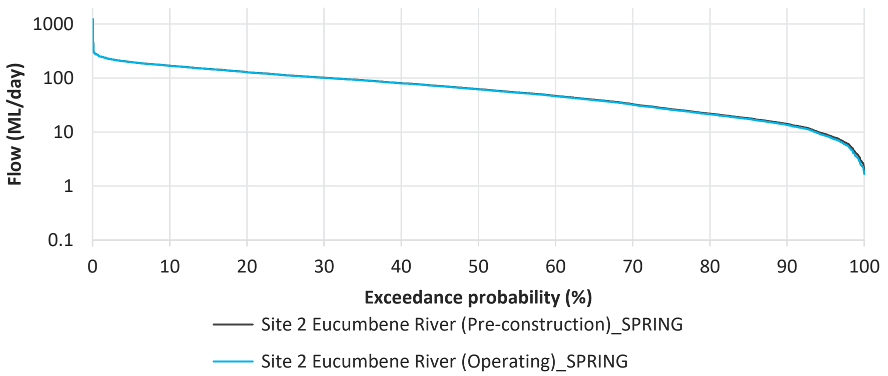


Figure 2.78 Operation phase: flow duration curves for Eucumbene River reporting sites (Spring)

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 5−7% 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)

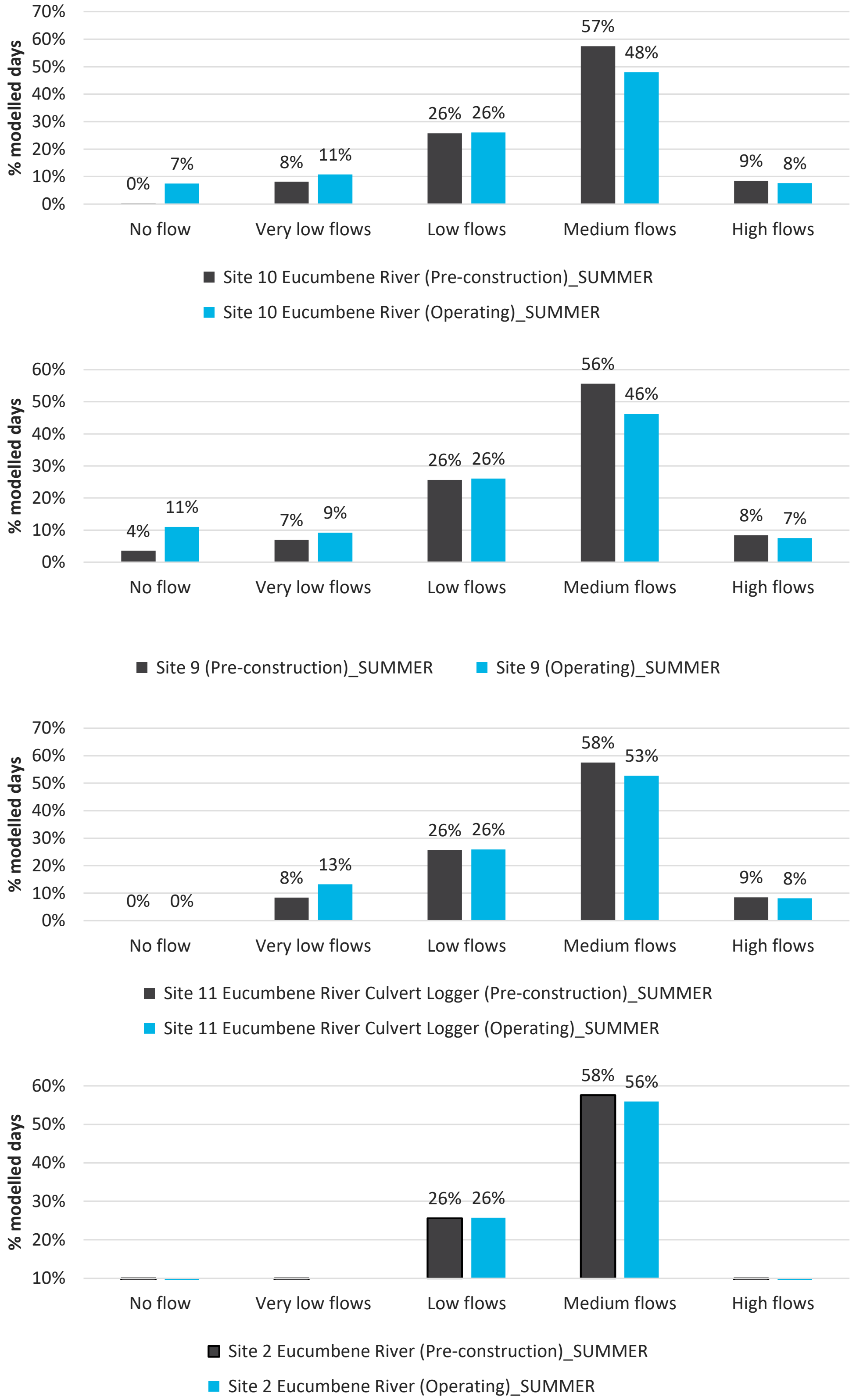


Figure 2.80 Percentage of summer days in each flow category (Eucumbene River reporting sites)

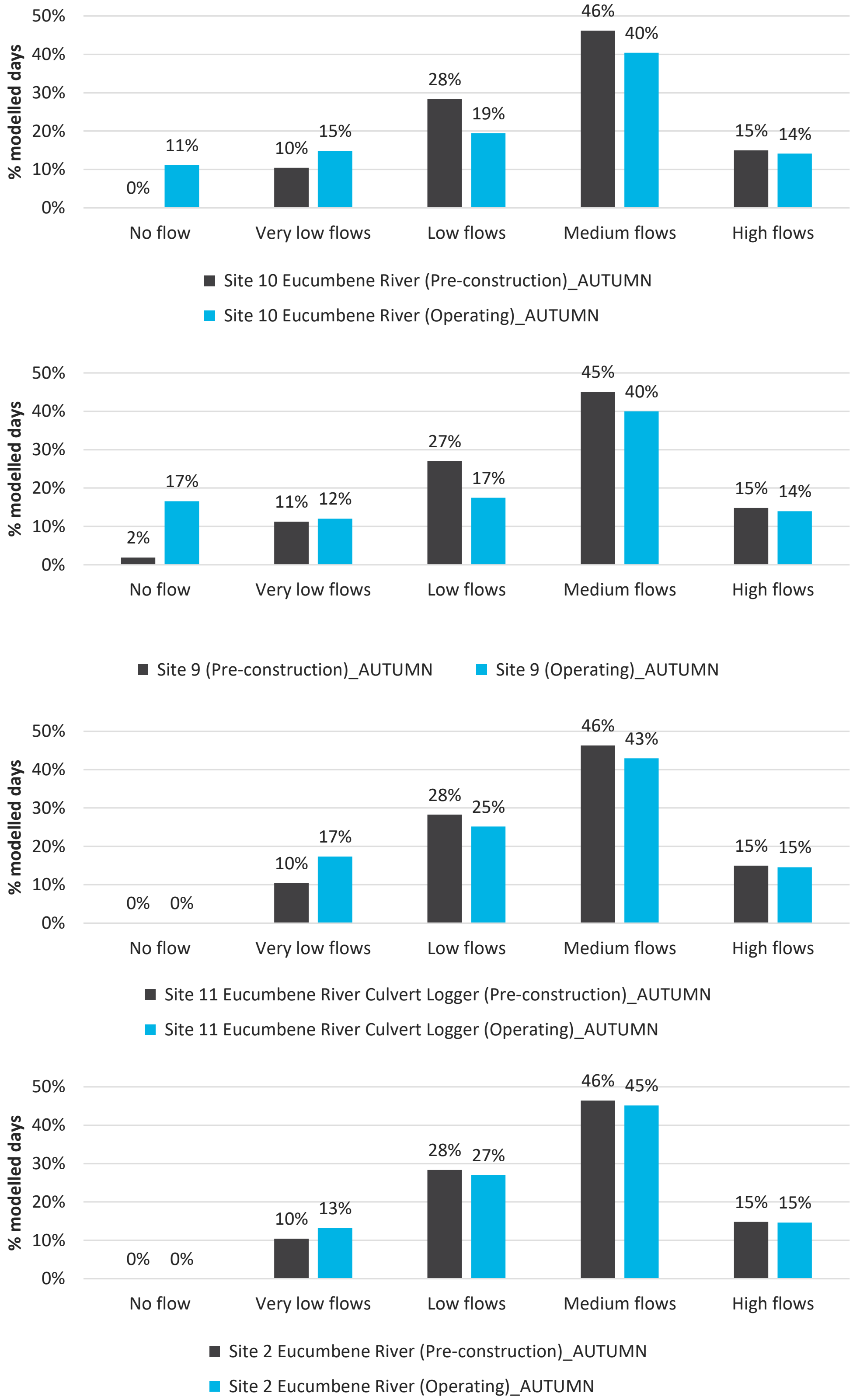


Figure 2.81 Percentage of autumn days in each flow category (Eucumbene River reporting sites)

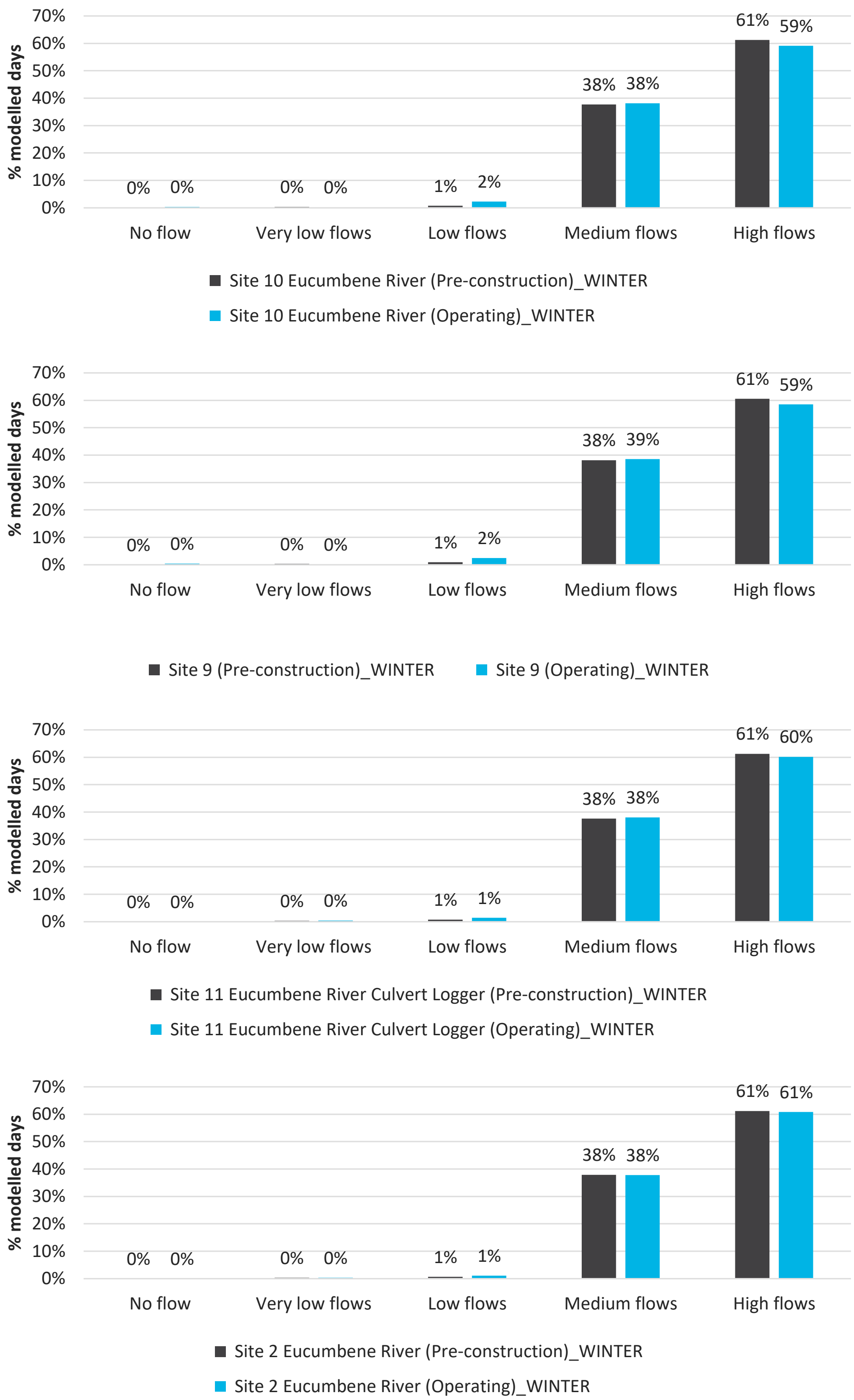


Figure 2.82 Percentage of winter days in each flow category (Eucumbene River reporting sites)

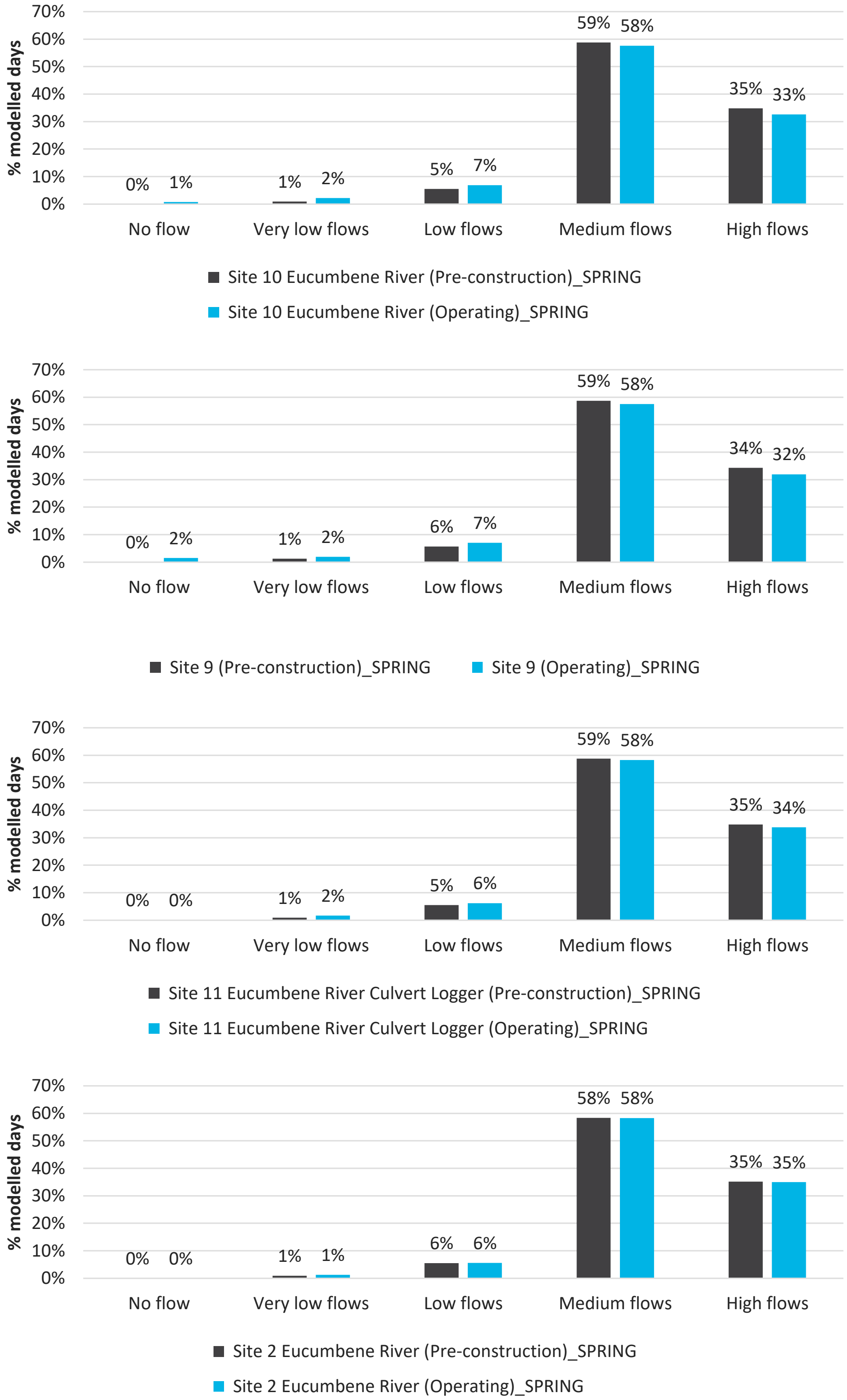


Figure 2.83 Percentage of spring days in each flow category (Eucumbene River reporting sites)

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 approximately +2% to +10%, and at Site 10 (Eucumbene River - upstream of Snowy Mountains Highway), where the increase in no and very low flow days ranged from approximately +4% to +13%; and
- at the Murrumbidgee Gauge downstream, the increase in no and very low flow days was a much smaller spread of +0.2% to +0.5%.

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.

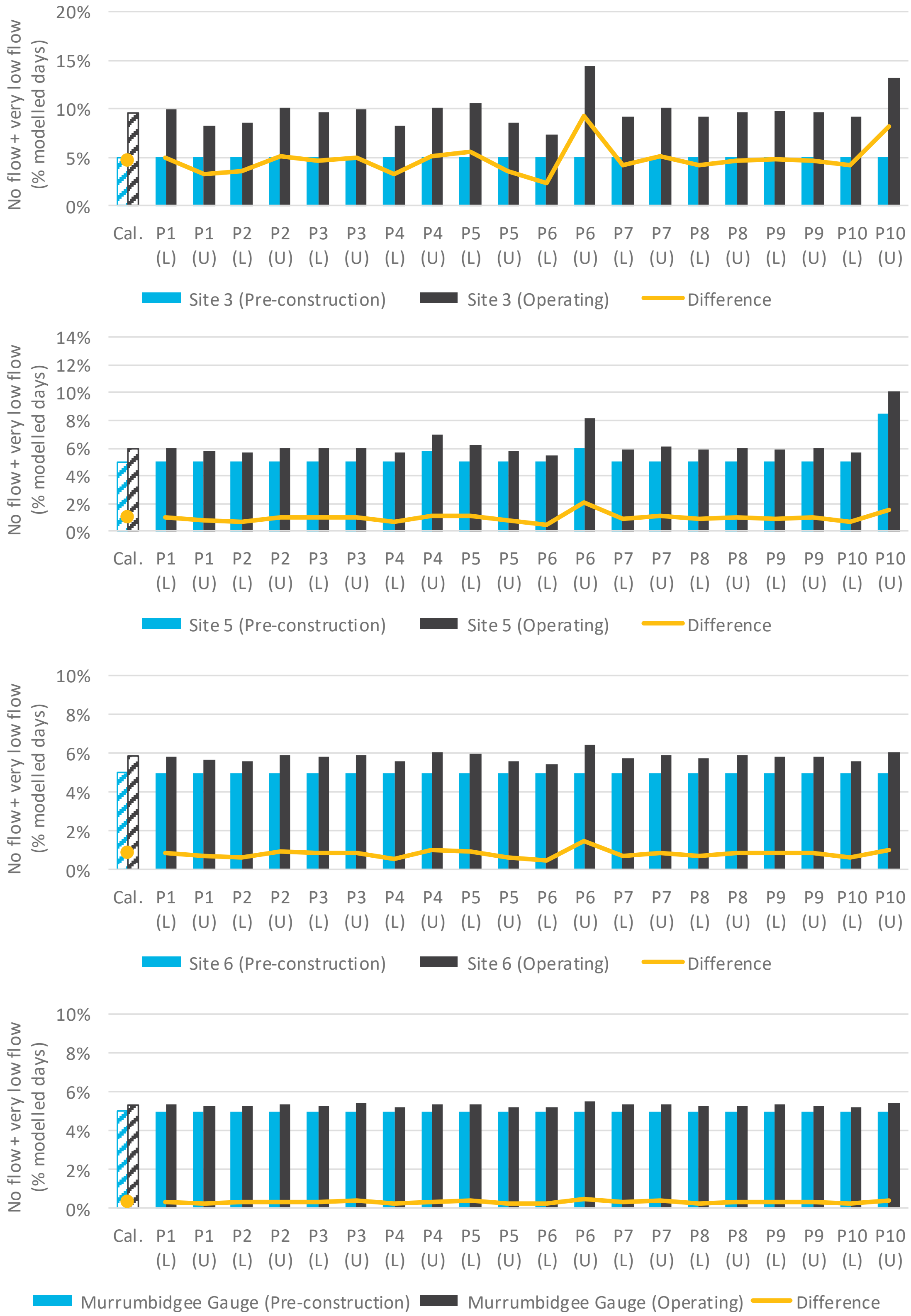


Figure 2.84 Modelled results across alternative model parameter sets (Gooandra Creek reporting sites)

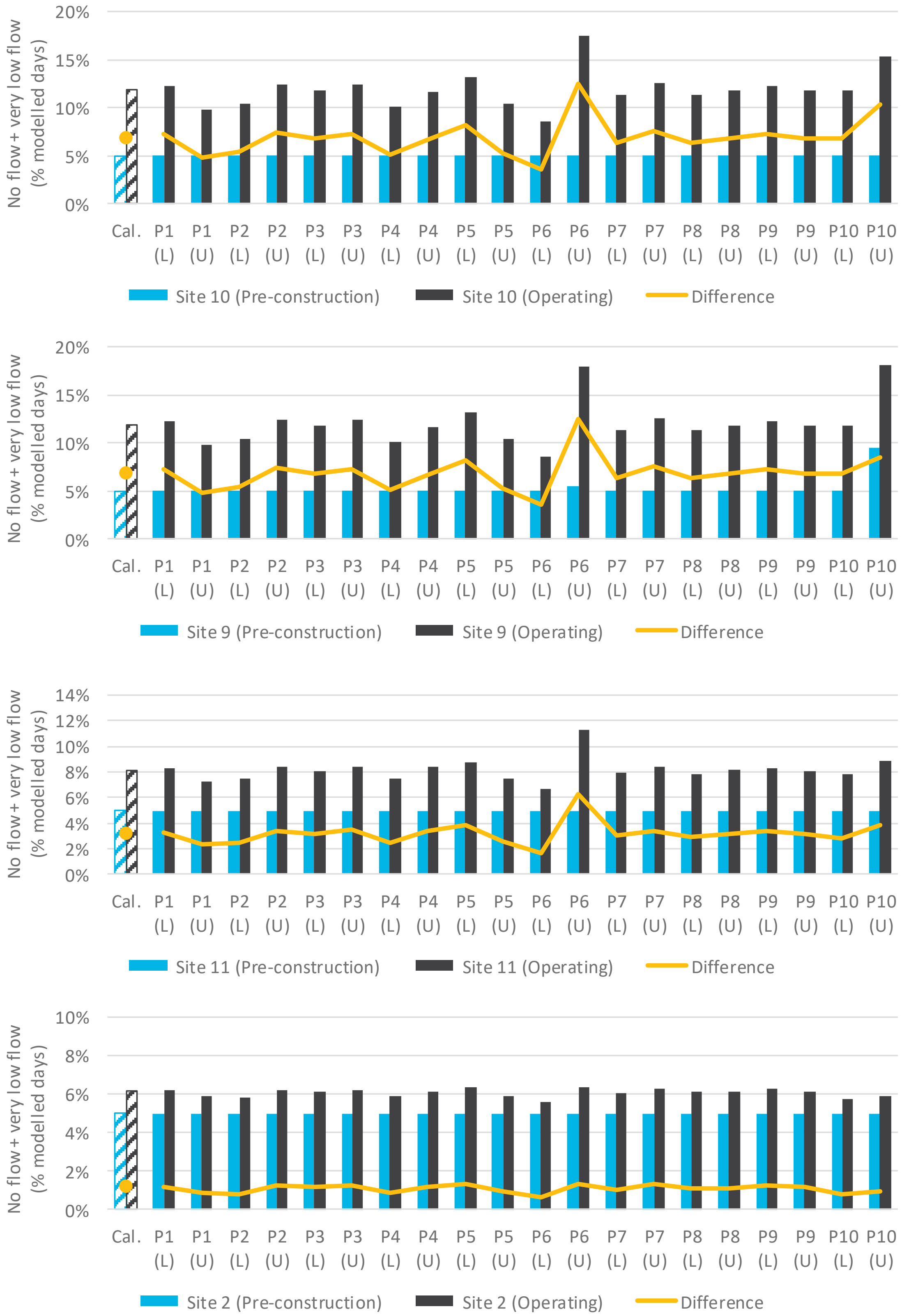


Figure 2.85 Modelled results across alternative model parameter sets (Eucumbene River reporting sites)

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 (11.1% reduction in baseflow) results in 9% 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 (11.1% reduction in baseflow within the Gooandra Creek catchment) results in 5% of days falling within the very low or no flow category.

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).

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 3.43 to Figure 3.45), and downstream river reaches.

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

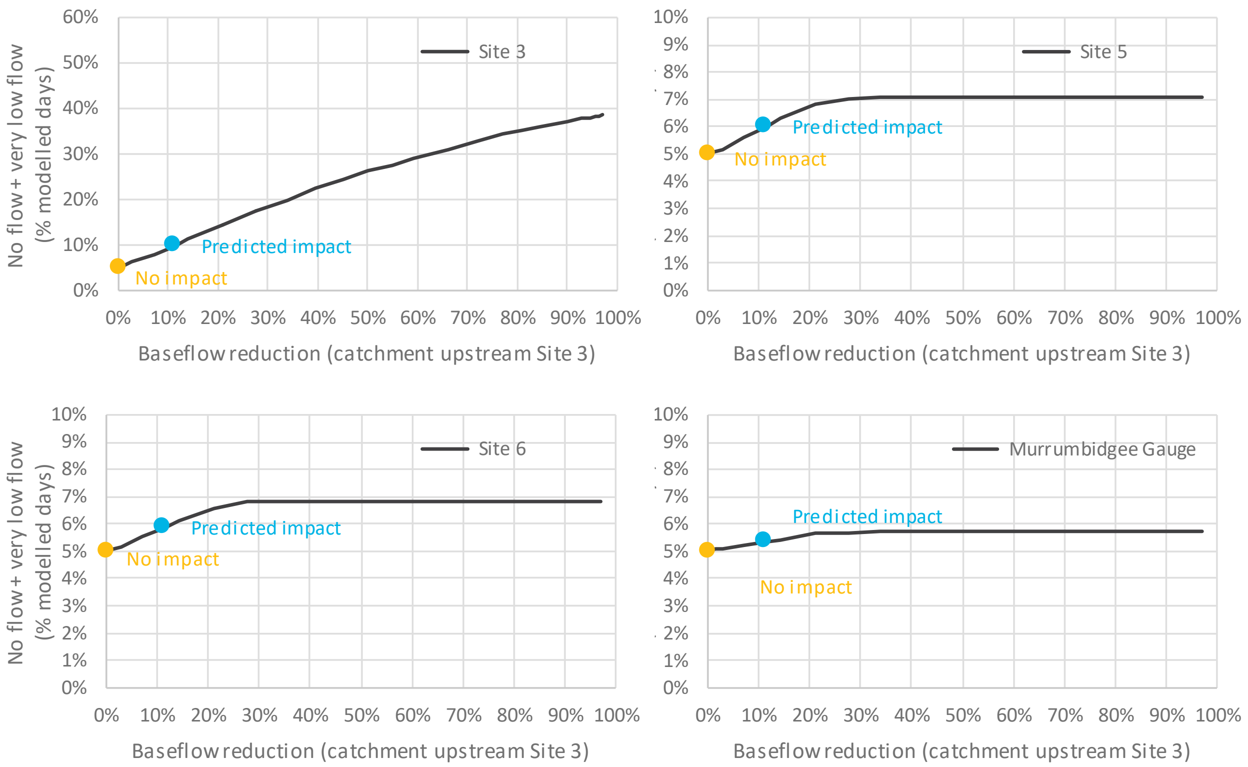


Figure 2.86 Modelled results across a range of baseflow reduction rates (Gooandra Creek reporting sites)

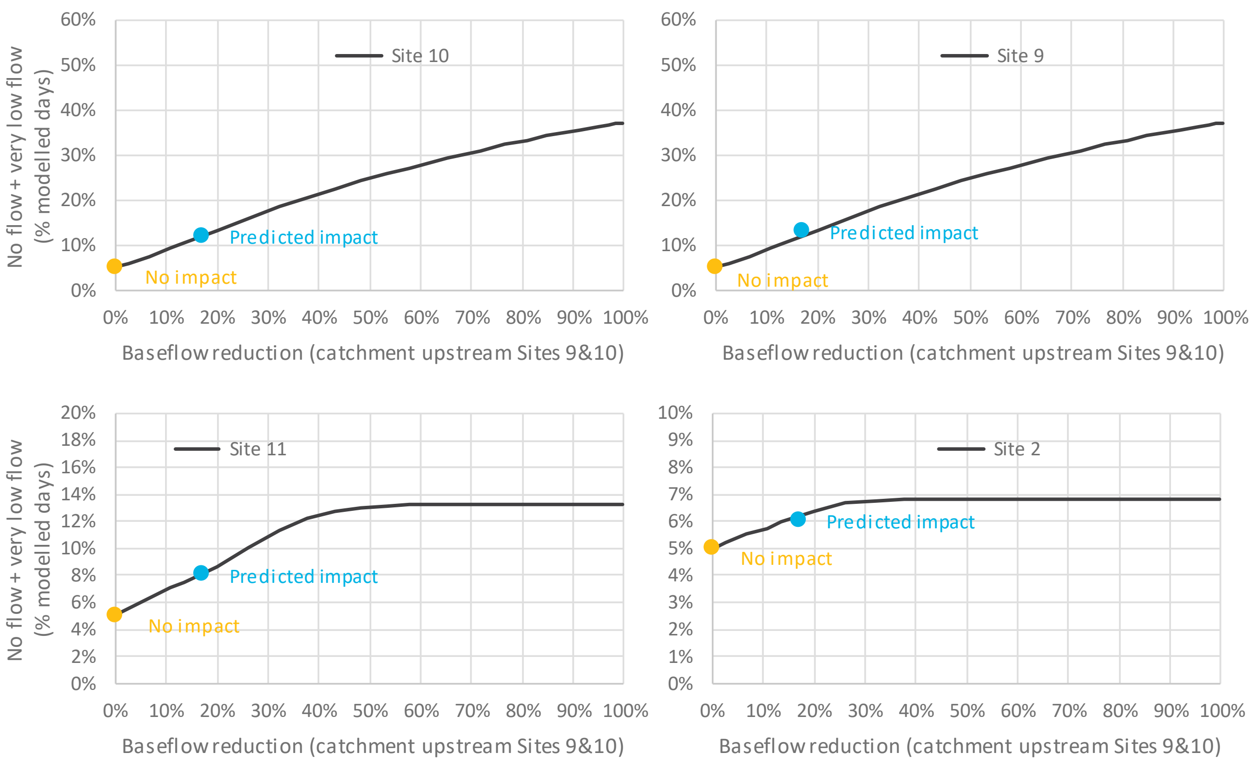


Figure 2.87 Modelled results across a range of baseflow reduction rates (Eucumbene River reporting sites)

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, 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 are 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 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 flow 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) was consulted during the development of the numerical groundwater model.

3.1.3 Peer review

The numerical model was 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, 42 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 represents the more permeable weathered geology, tertiary basalt, alluvium and colluvium. A LiDAR derived digital elevation model was used to define the top of the 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, 12.5 m thick model layers were 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, cells were refined 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.

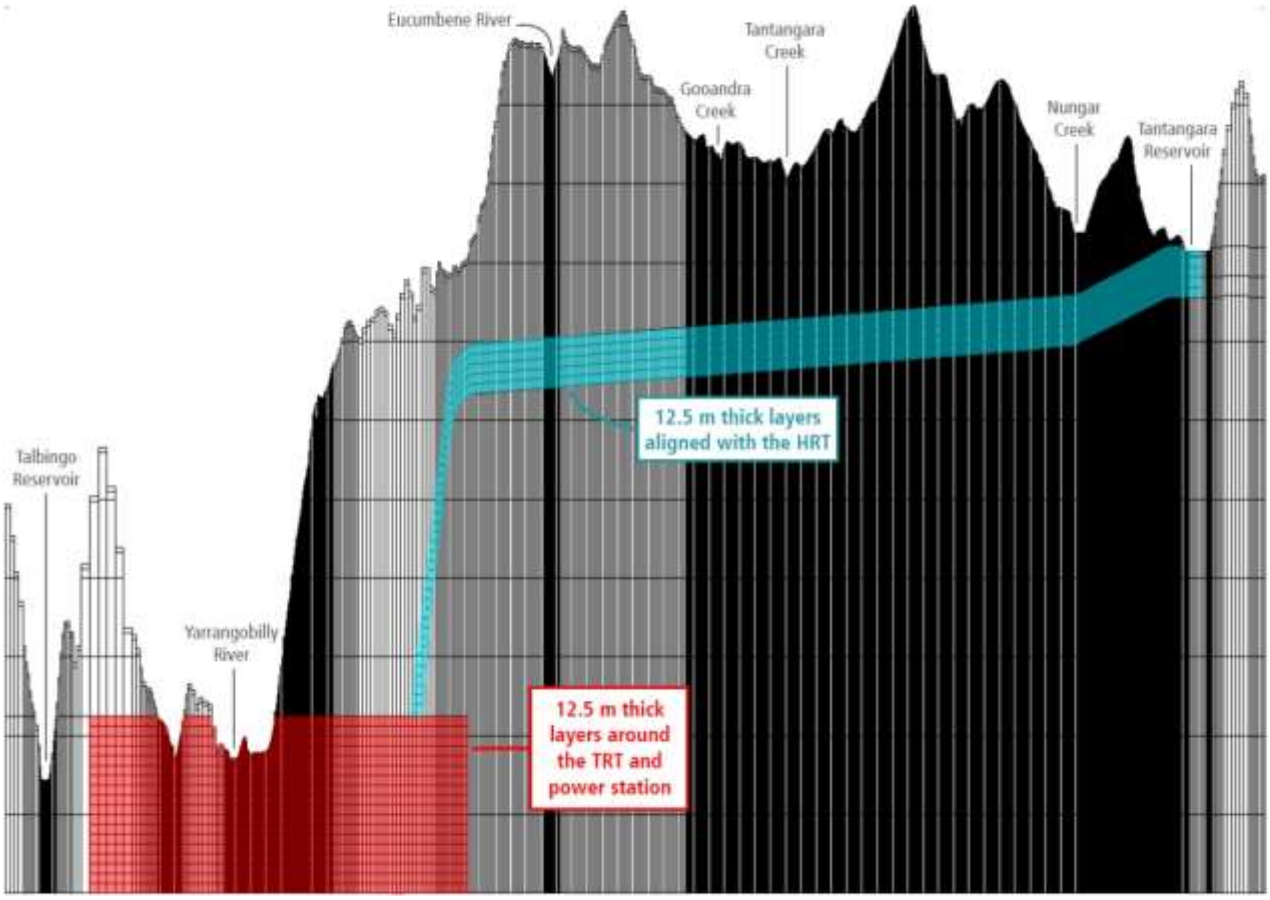


Figure 3.1 West-east cross section through model layers at 6,038,100 m N

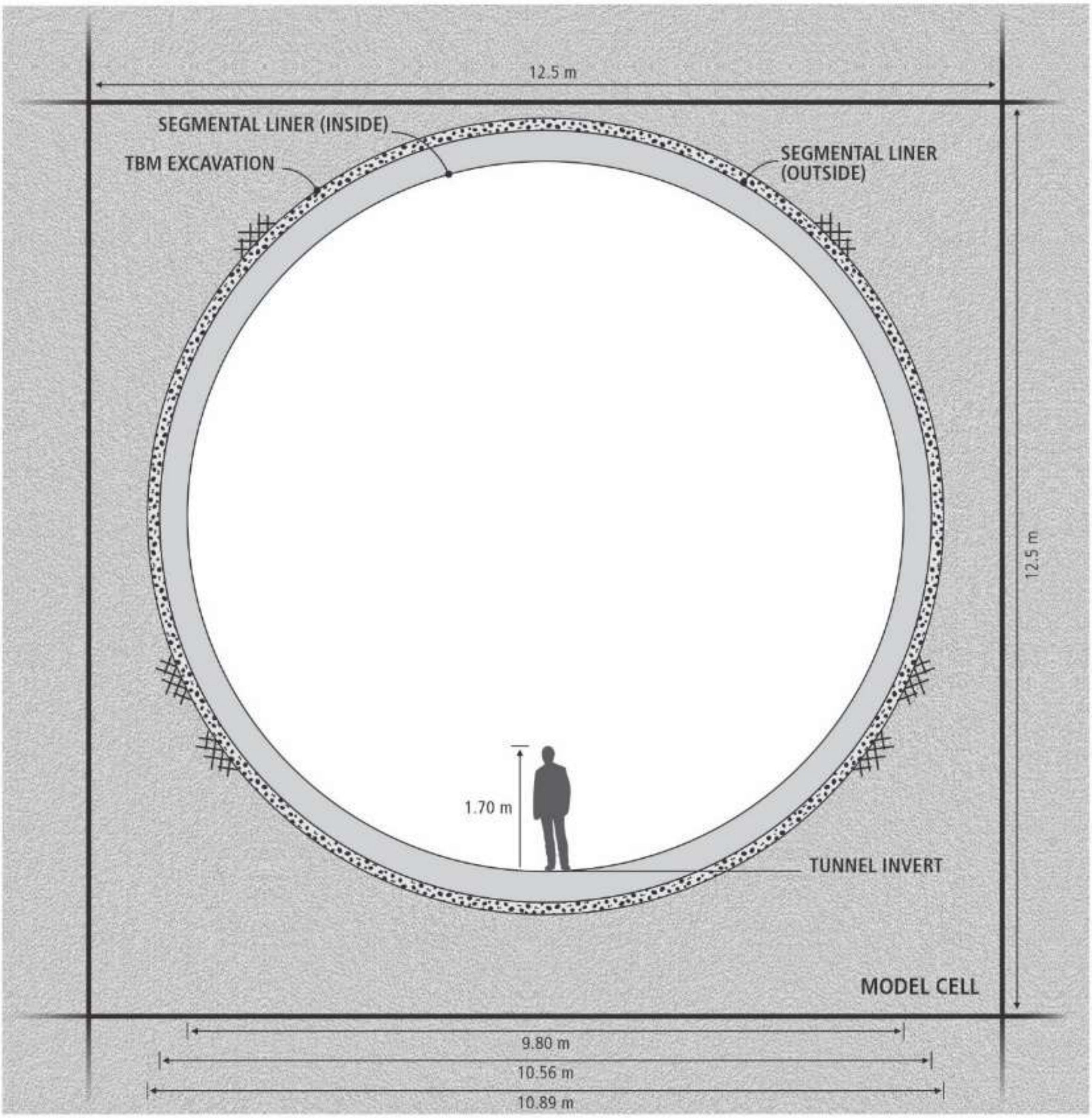
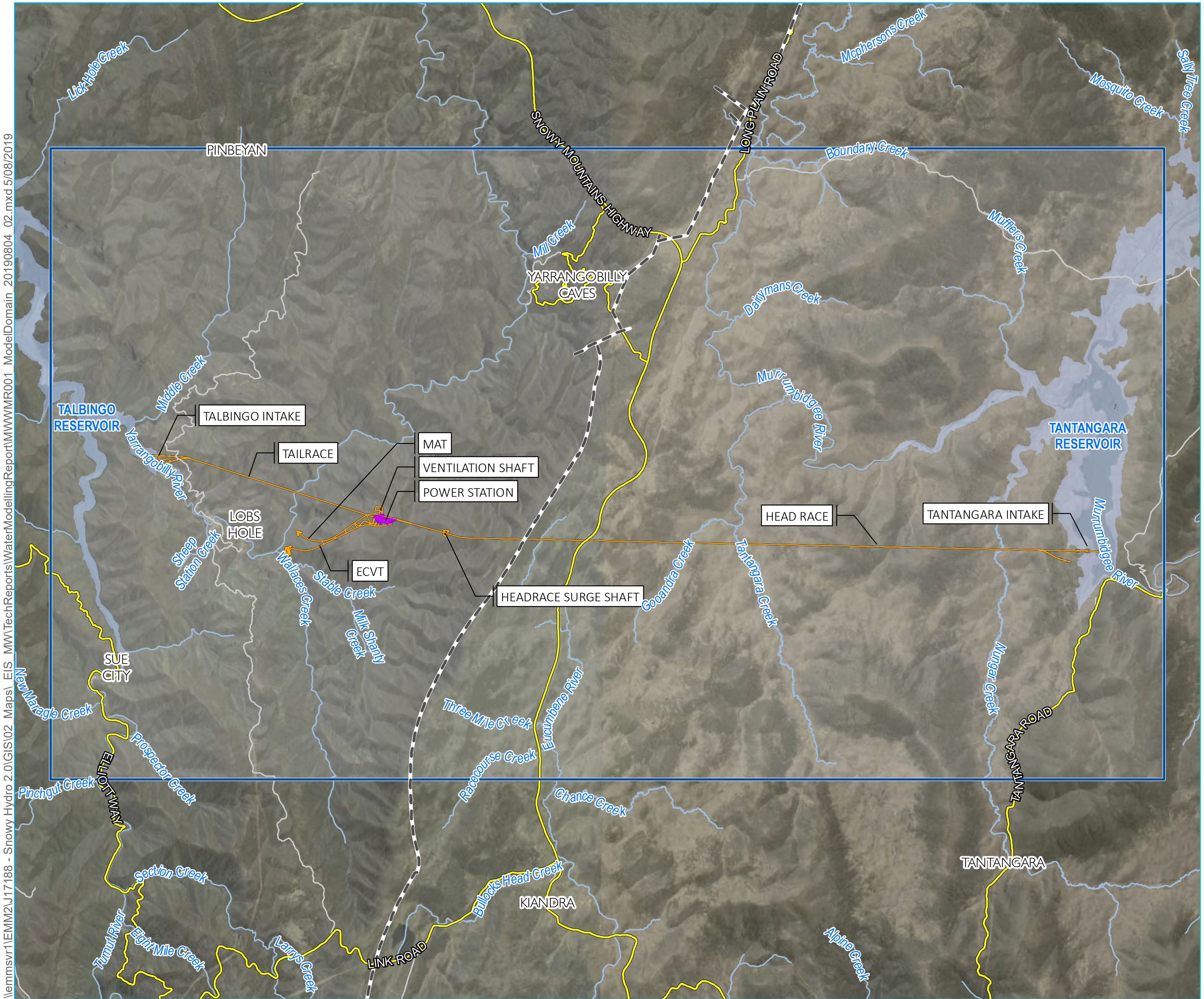


Figure 3.2 Spatial discretisation of the Head Race Tunnel



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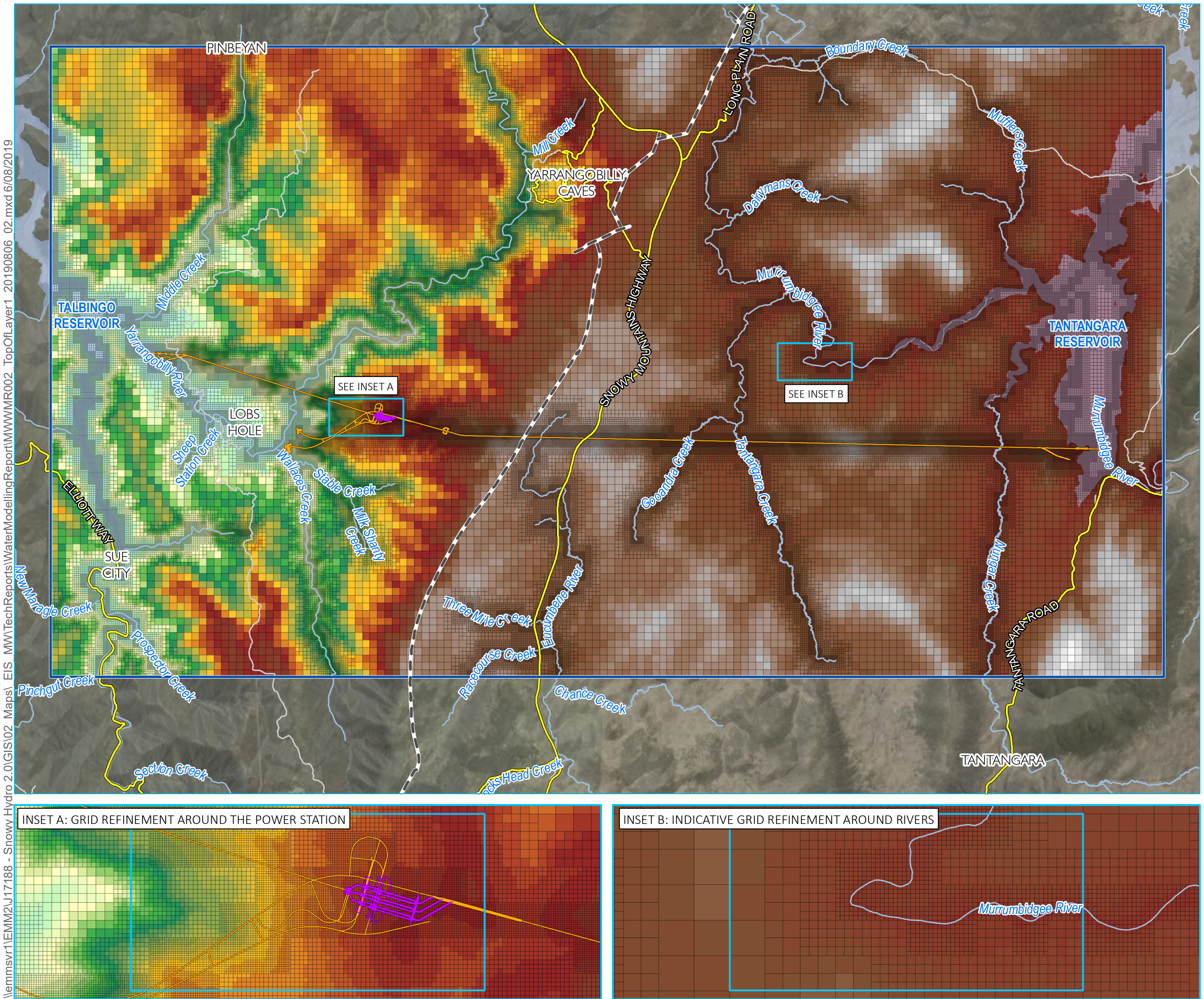
Source: EMM (2019); Snowy Hydro (2019); DFSI (2017); LPMA (2011)

SH4.0 model domain and major features

Snowy 2.0
Modelling Report
Main Works
Figure 3.3



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:

$$C = K L W / D$$

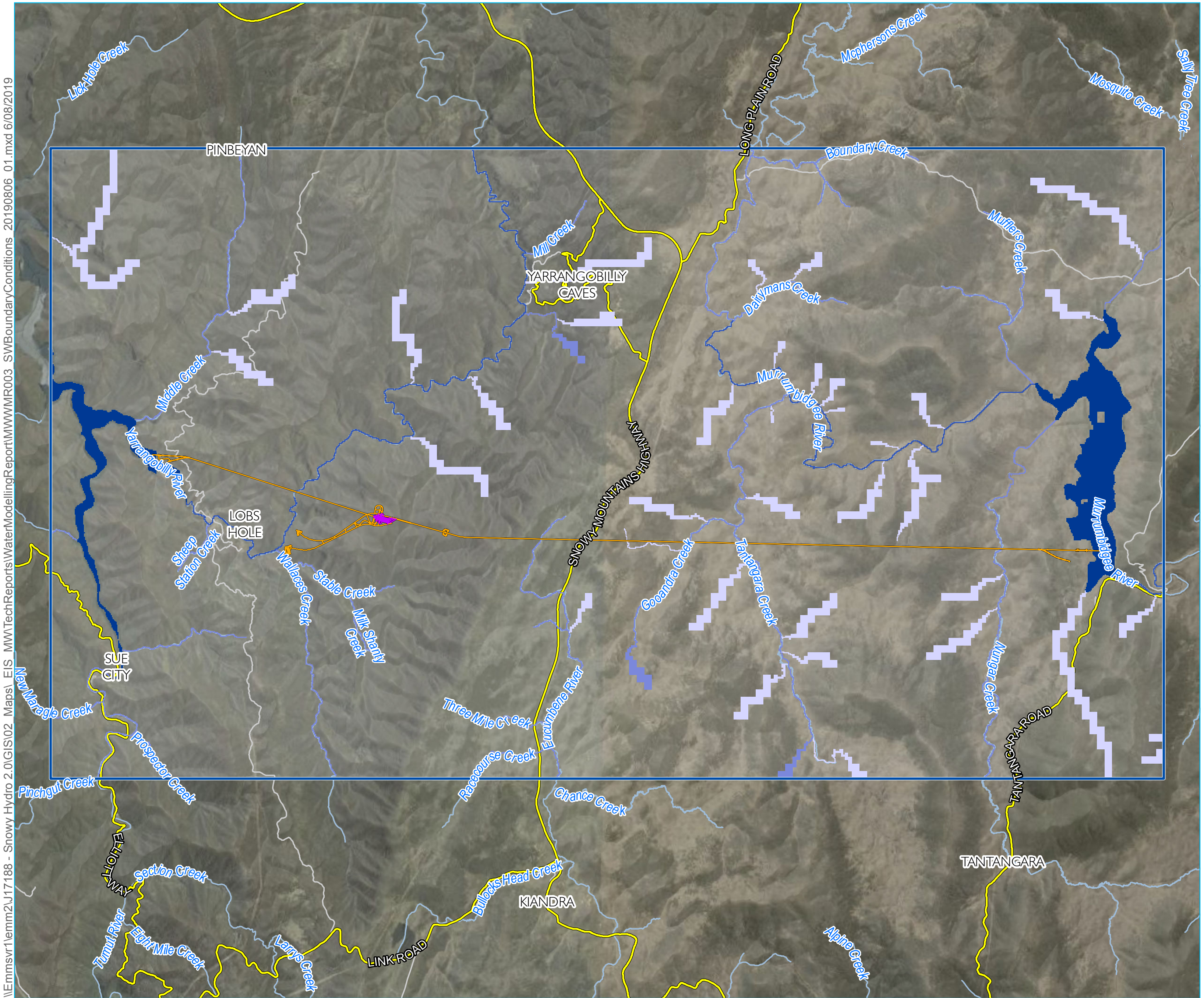
where: K = hydraulic conductivity of the river bed, L = length of the river in the cell, W = width of the river and D = thickness of the river bed material.

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.



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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

snowy 2.0

EMM creating opportunities

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.

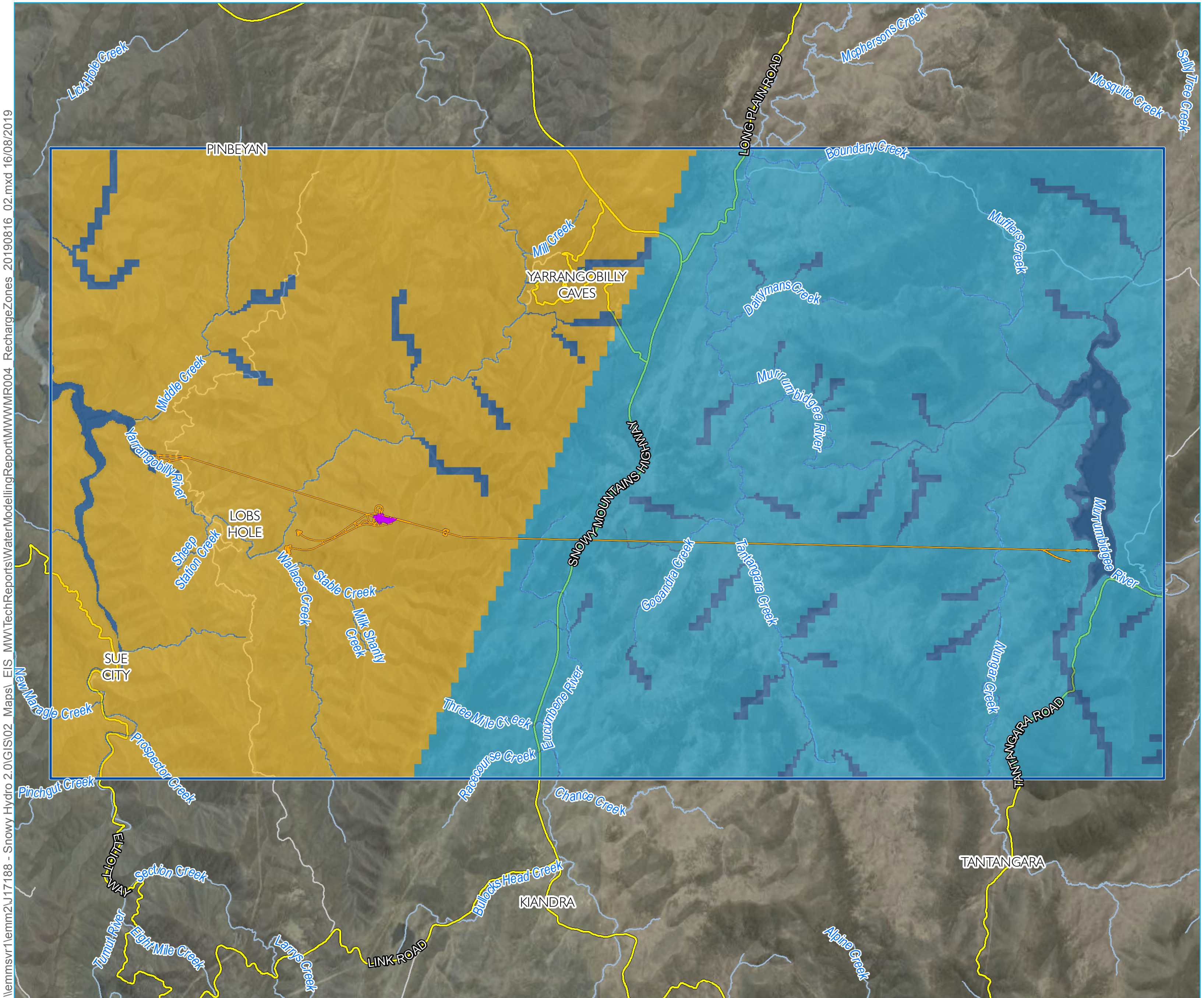
The plateau area is characterised by low relief, mostly has elevation between around 1,200 m AHD and 1,700 m AHD and is largely covered with grasses, marshes and only small stands of tree coverage. As a result of its higher elevation the plateau area is colder than the ravine area and therefore receives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

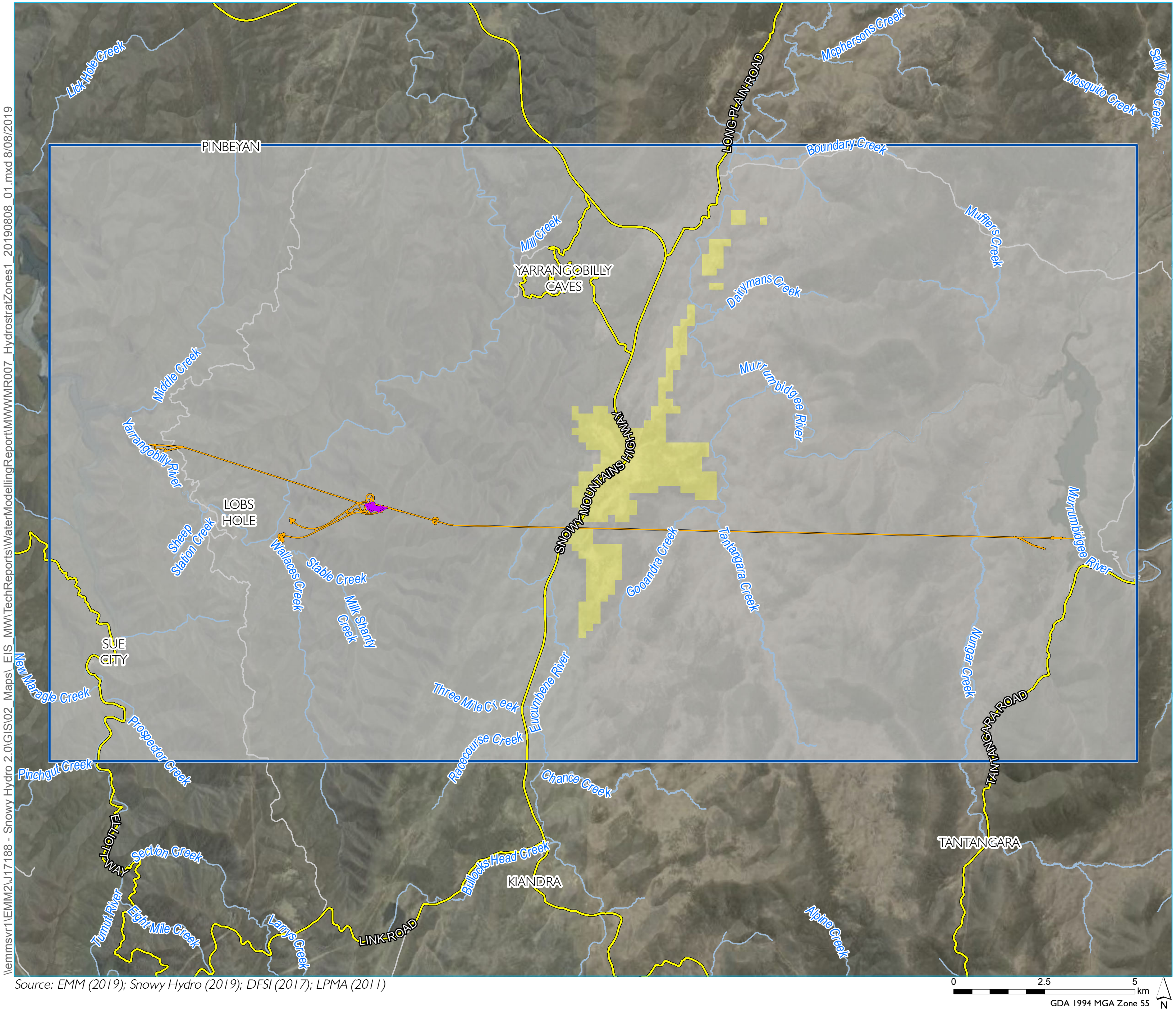
3.2.7 Hydrostratigraphy

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 are focussed around the proposed power waterway alignment, and do 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 propagate at sufficient levels to impact the Yarrangobilly Caves.



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

KEY

Hydrostratigraphic unit
- Weathered/Alluvium
- Tertiary Basalt
- Model domain

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

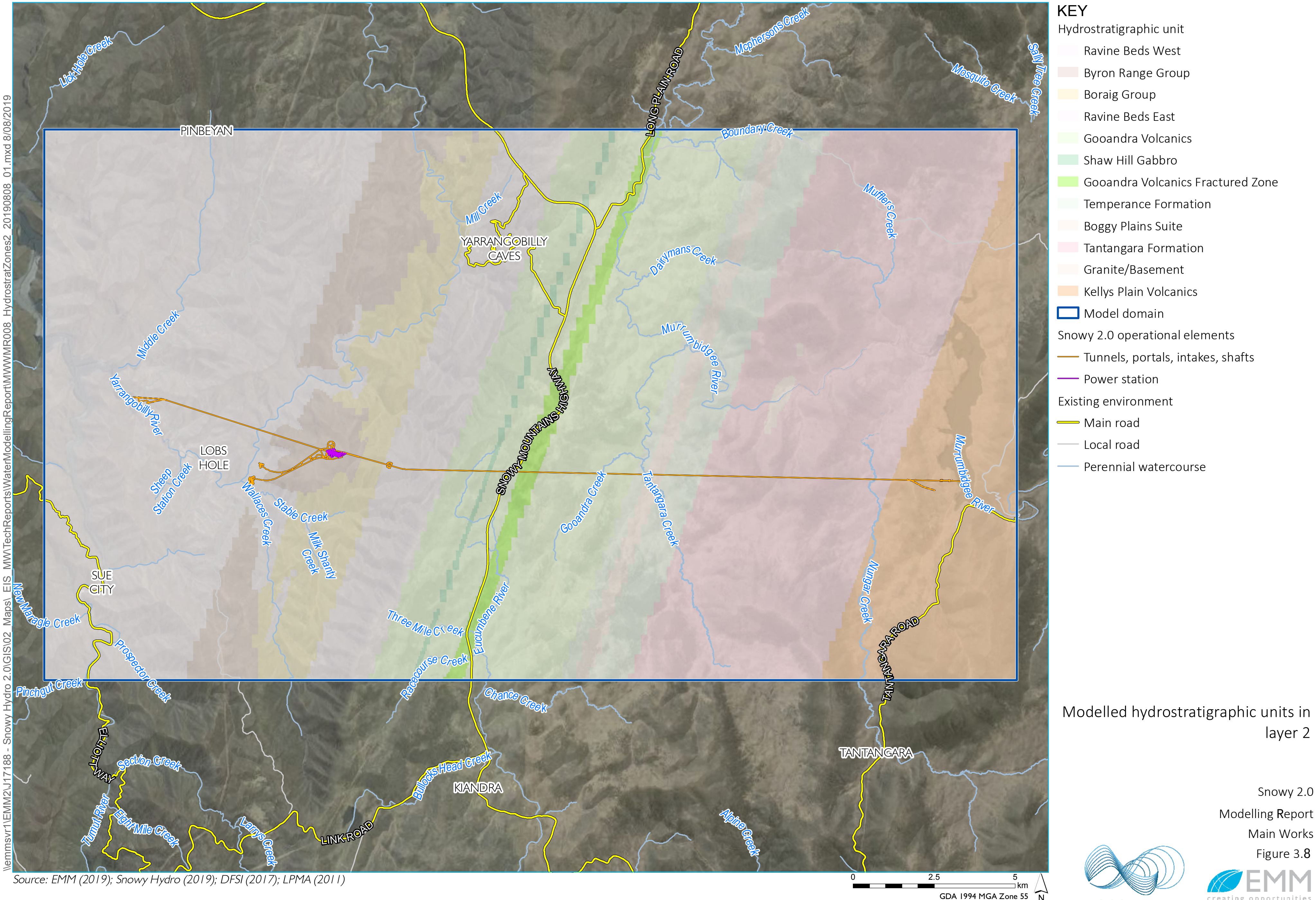
Existing environment
- Main road
- Local road
- Perennial watercourse

Modelled hydrostratigraphic units in layer 1

Snowy 2.0
Modelling Report
Main Works
Figure 3.7

snowy 2.0

EMM
creating opportunities



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

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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 head 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 magnitudes 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.

Several 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.

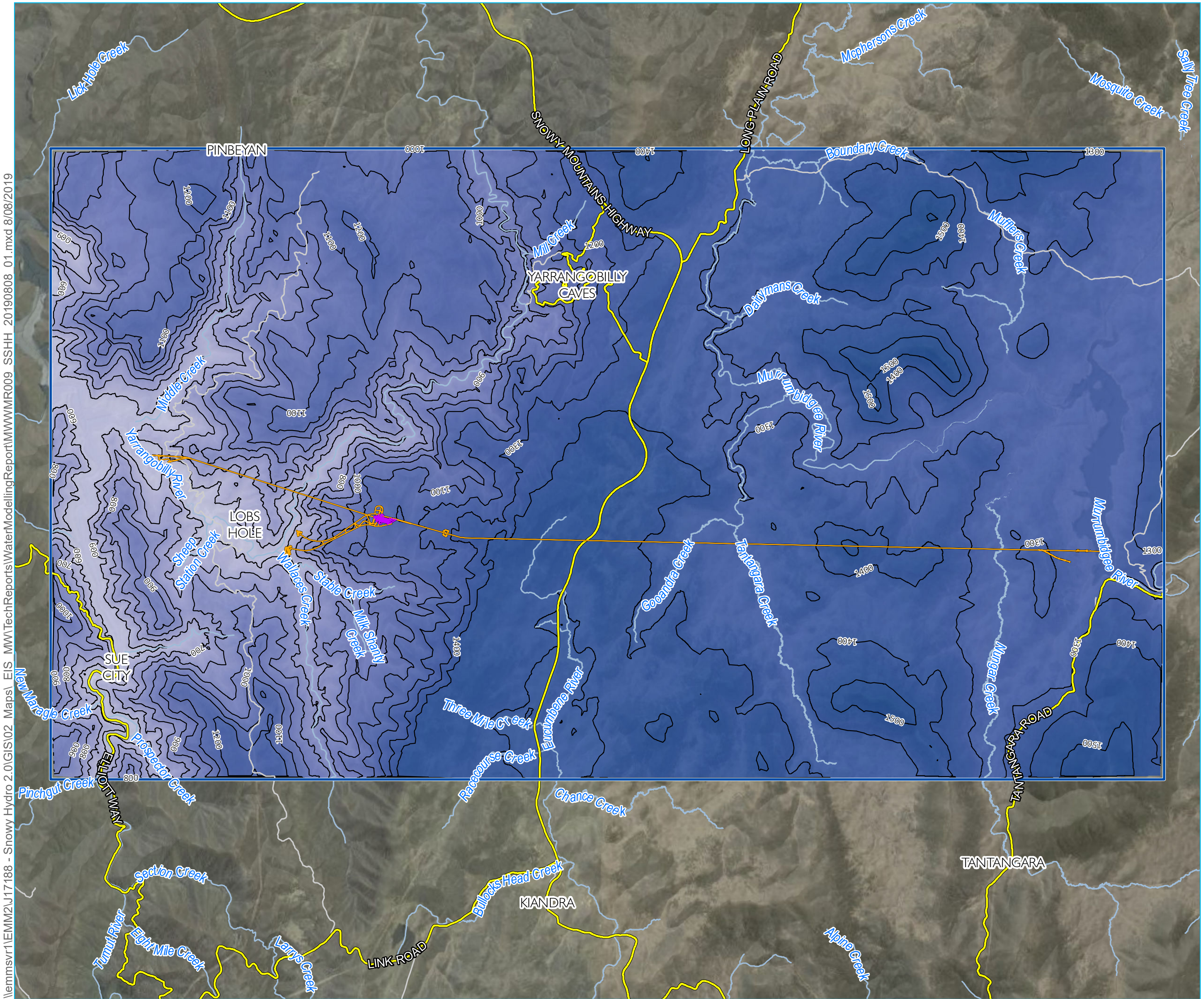
Due to the computational duration of model runs, automated calibration software was not employed. A manual calibration and sensitivity analysis process, constrained by the conceptual model, was undertaken to identify appropriate parameter values and bounds for predictive modelling.

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 AHD to 1,613 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.



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

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

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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 modelled period, consistent with observations that rivers and creeks in the project area continue to flow through summer. Diffuse baseflow discharge varied seasonally, with 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%.

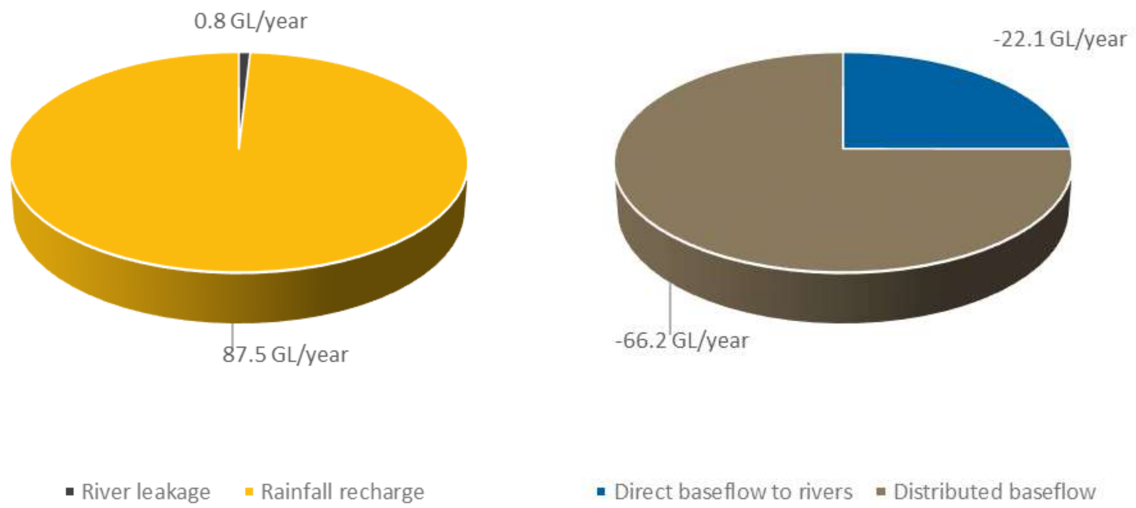


Figure 3.11 Modelled steady state water balance (ML/year) (Dec 2007-Dec 2012 climate)

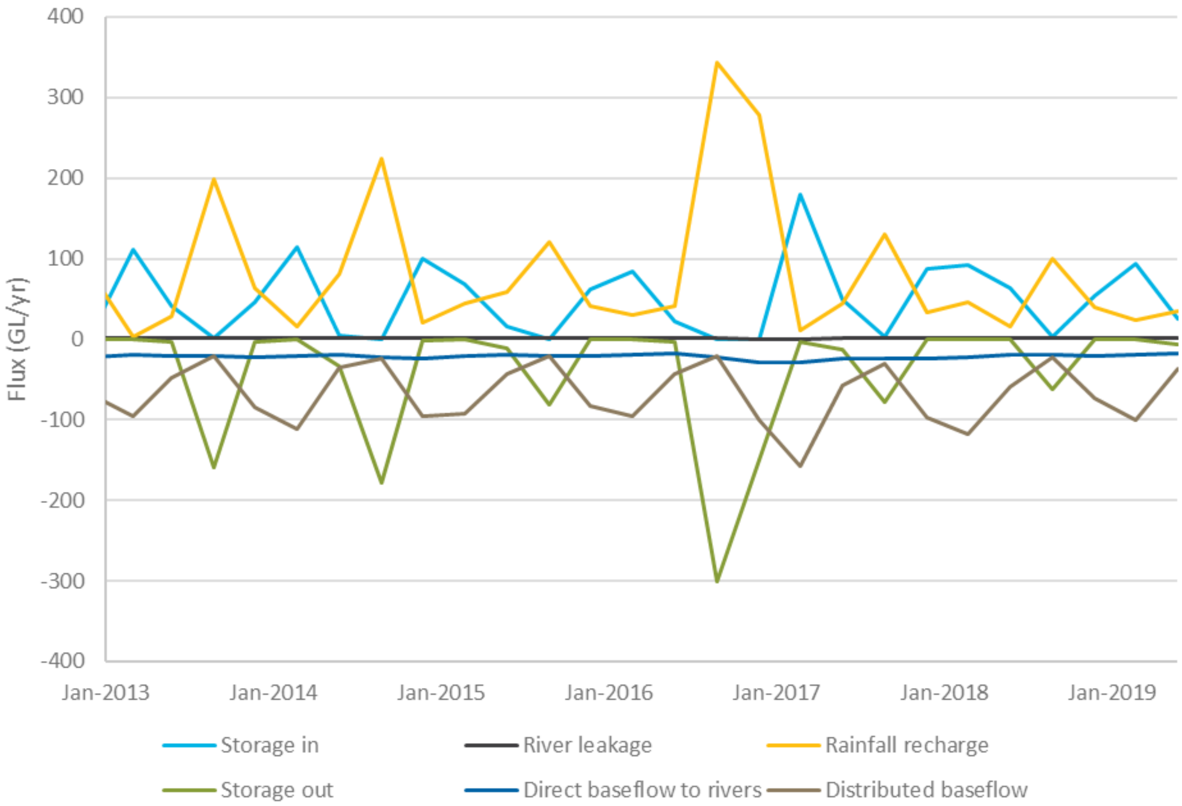


Figure 3.12 Modelled transient history matching period (calibration) water balance

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 1,479 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.

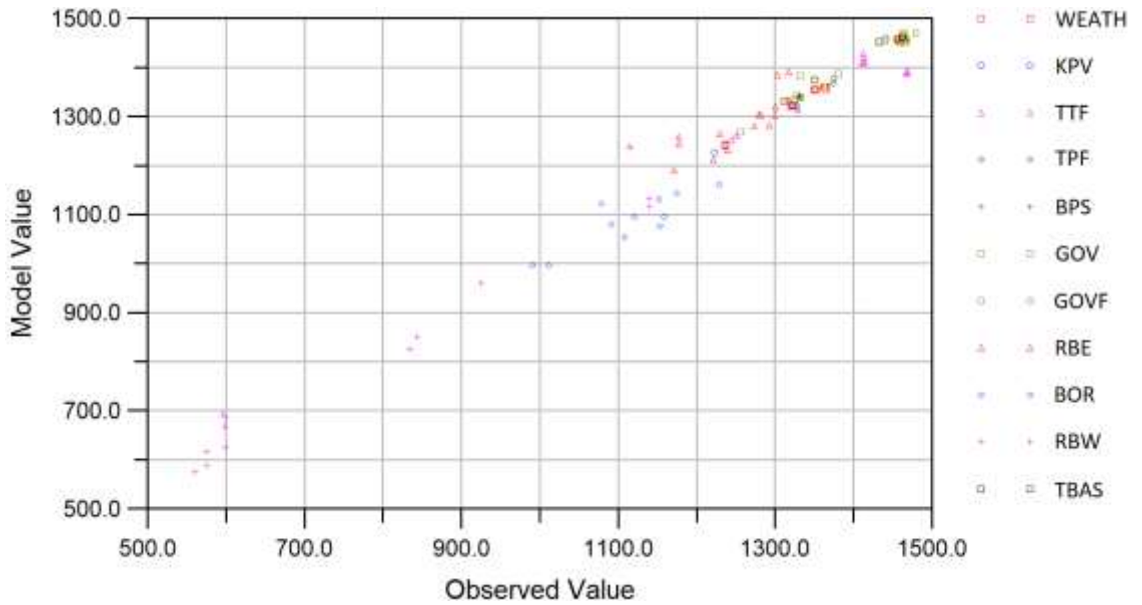


Figure 3.13 Scatter plot of steady state modelled vs measured hydraulic head

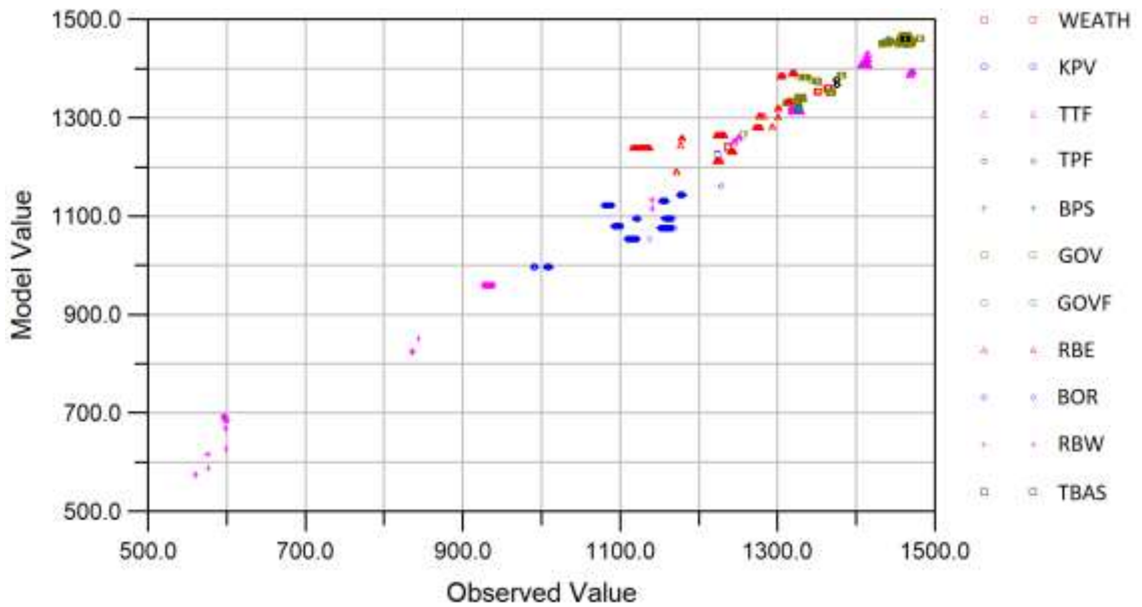
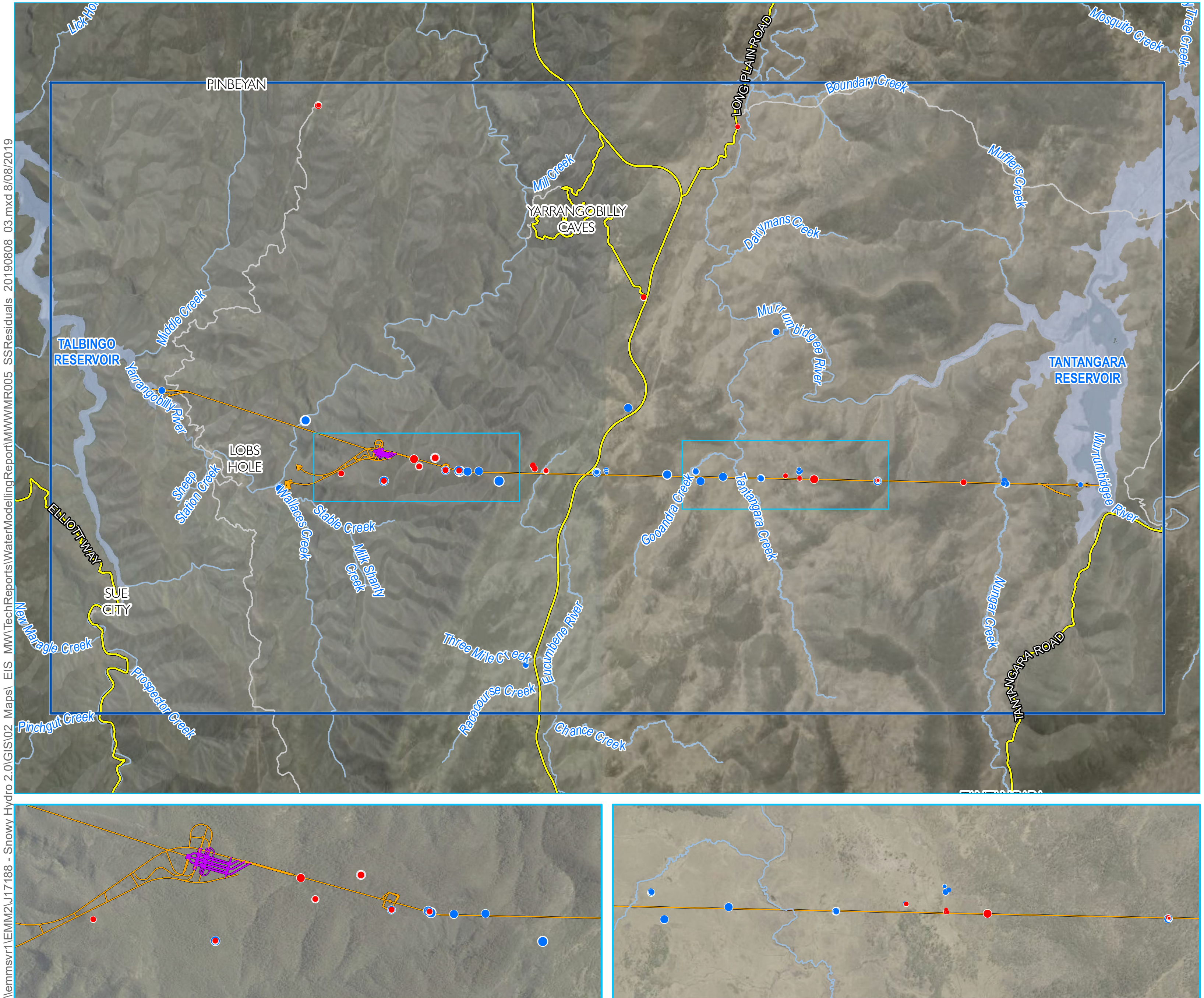


Figure 3.14 Scatter plot of transient modelled vs measured hydraulic head



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)

0 2.5 5 km
GDA 1994 MGA Zone 55

snowy 2.0

EMM creating opportunities

\\emmsvr1\EMM2\J17188 - Snowy Hydro 2.0\GIS\02_Maps_EIS_MW\TechReports\WaterModellingReport\MWWMR005_SSResiduals_20190808_03.mxd 8/08/2019

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 model 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.

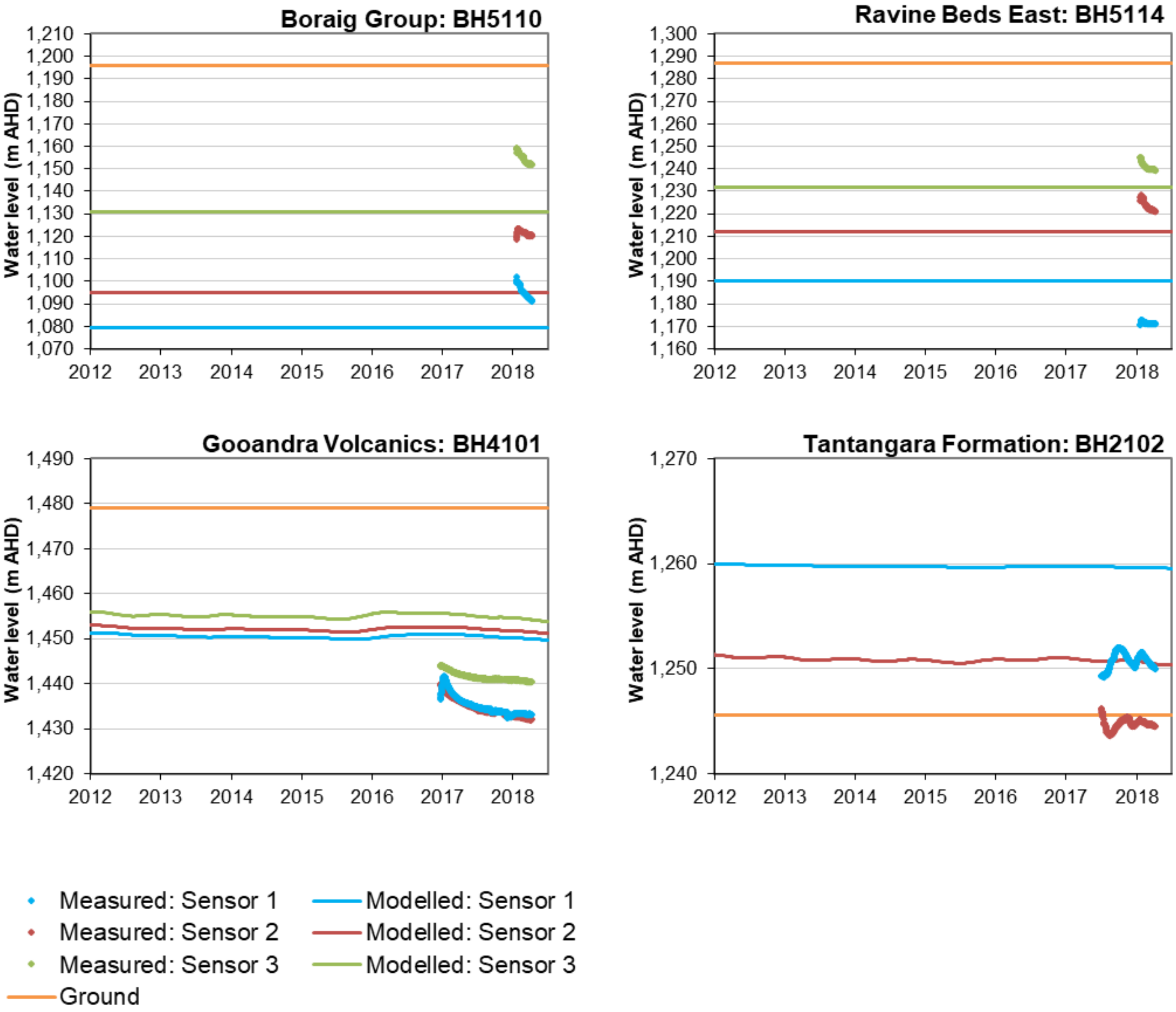


Figure 3.16 Selected measured and modelled groundwater hydrographs

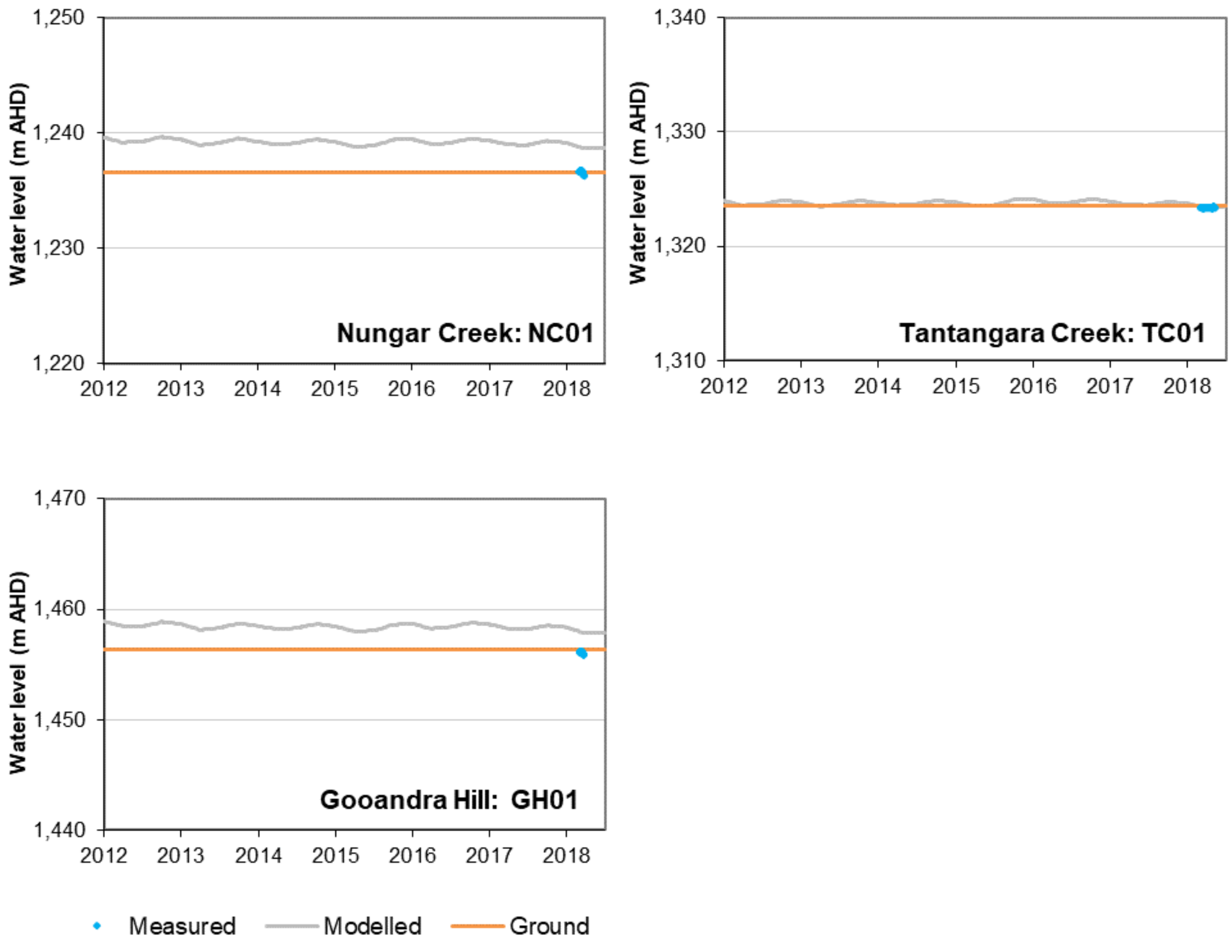


Figure 3.17 Selected measured and modelled groundwater hydrographs for weathered/alluvial material

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.

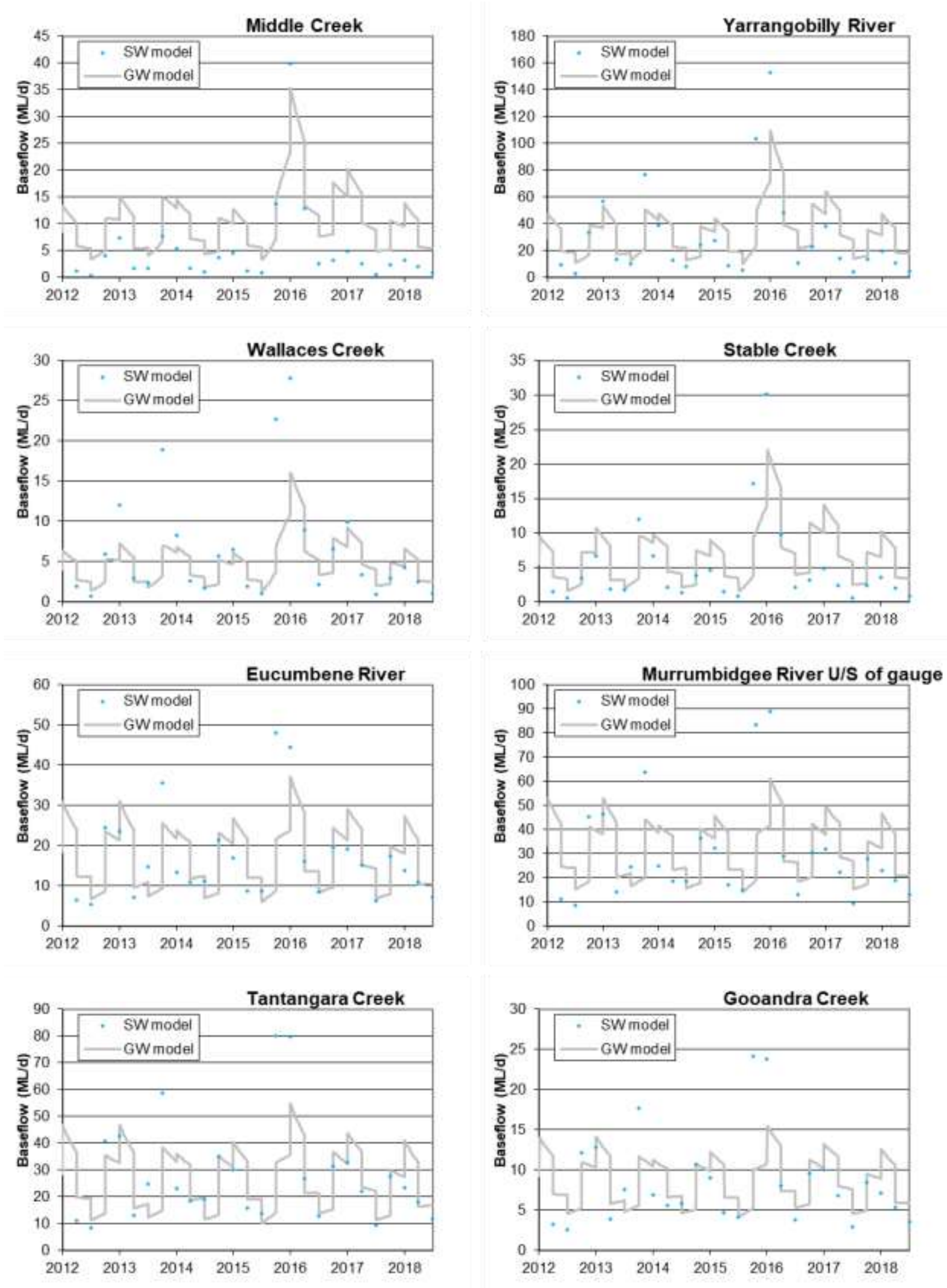


Figure 3.18 Comparison of groundwater and surface water modelled baseflow

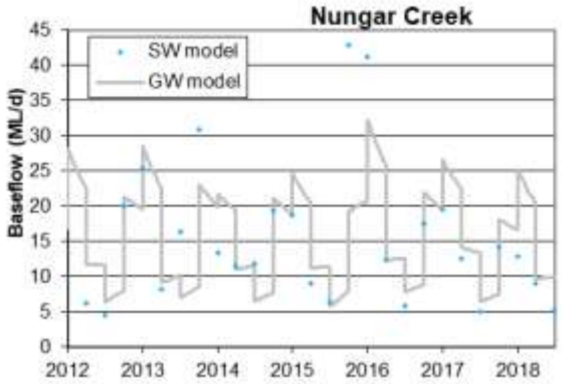


Figure 3.19 Comparison of groundwater and surface water modelled baseflow (Cont.)

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 values 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 were obtained during pumping tests to test this theory, and so isotropic assumptions were applied to most geological units in the model. If hydraulic conductivity in the east-west direction is lower than modelled, impacts of inflows to excavations will propagate ahead of 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 on 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 were 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.

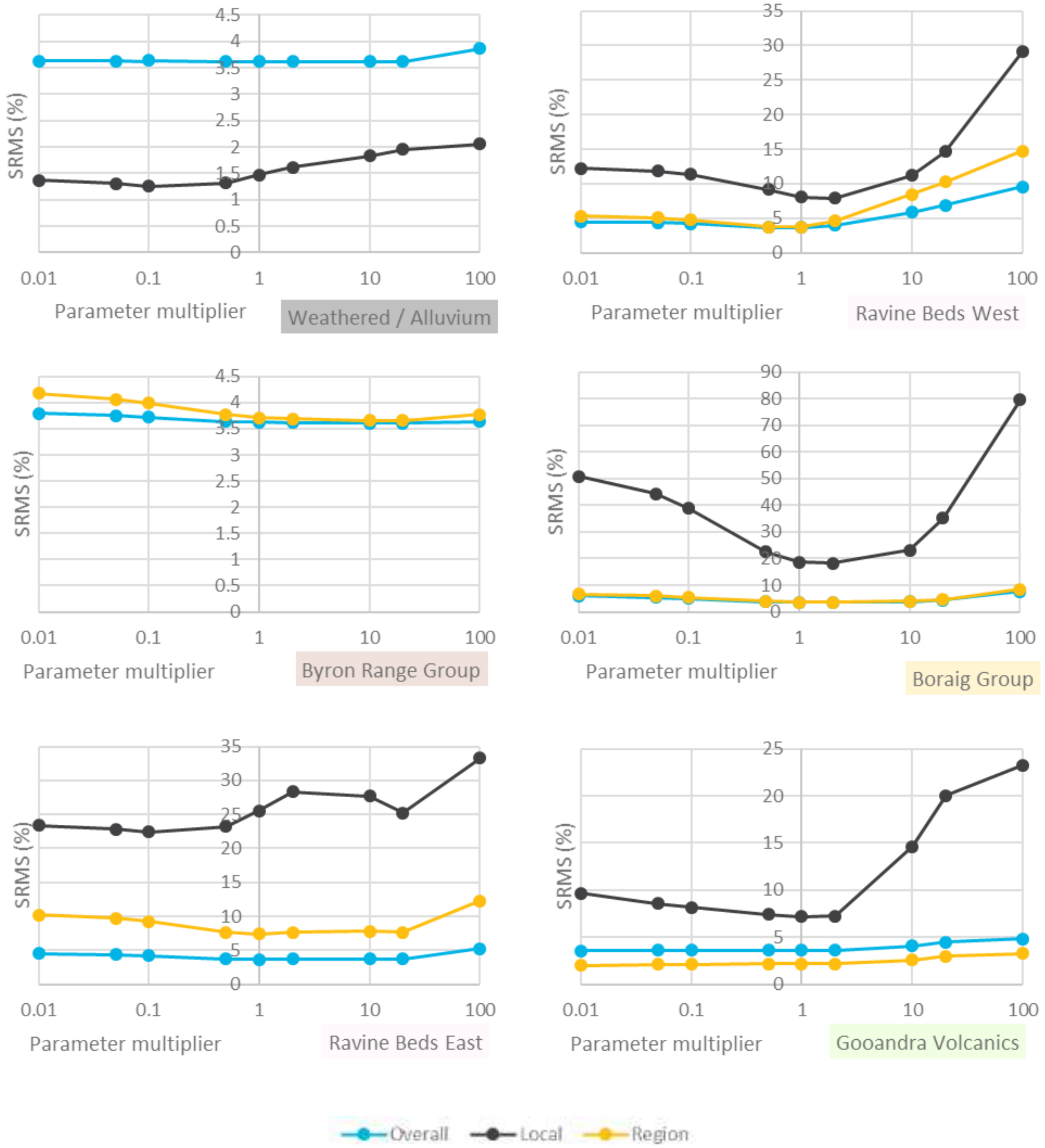


Figure 3.20 Calibration sensitivity to hydraulic conductivity (K_h and K_v)

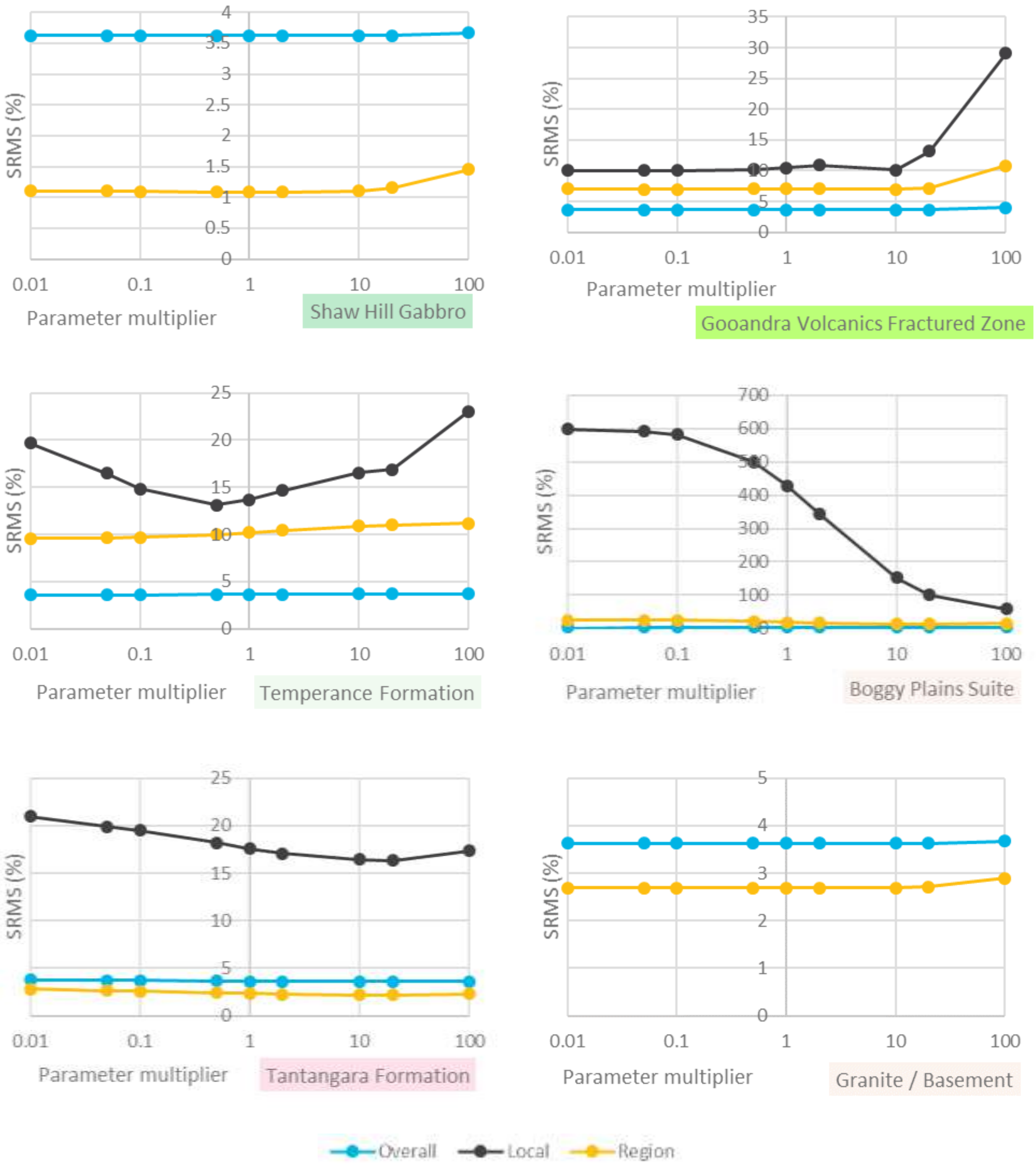


Figure 3.21 Calibration sensitivity to hydraulic conductivity (K_h and K_v) (Cont.)

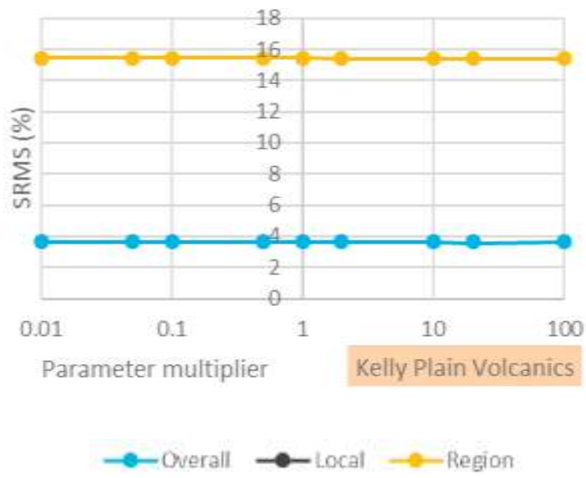


Figure 3.22 **Calibration sensitivity to hydraulic conductivity (K_h and K_v) (Cont.)**

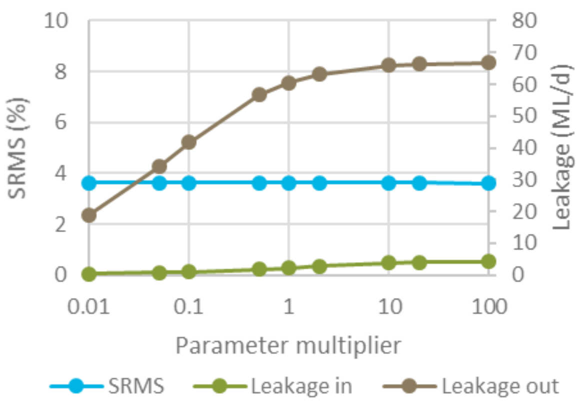


Figure 3.23 **Calibration sensitivity to river bed conductance**

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 Groundwater management measures

Groundwater is expected to enter the underground excavations during construction. This has the potential to cause drawdown of groundwater near surface. To mitigate impacts this a number of controls may be initiated. These include:

- excavation sequencing;
- pre-grouting;
- post-grouting; and
- segmental lining.

a 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.

b Pre-grouting

Pre-grouting will be conducted to reduce the hydraulic conductivity of the rock mass. It is undertaken ahead of the excavation face. This will generally be carried out by:

- drilling and testing a probe hole;
- drilling and installing a crown of groutable pipes;
- injecting grout through the pipes; and
- drilling a verification probe hole.

Probe holes are drilled up to 40 m in front of the working face. Water flow through the initial holes is measured and a decision is made on the need to grout.

In both 'traditional tunnels' and TBM tunnels, pressure grouting (or injection) in rock is carried out by drilling boreholes of a suitable diameter, length and direction into the rock material (Figure 3.24 and Figure 3.25). The boreholes will be drilled in rotary percussion mode using the hydraulic head top hammer or a Water ('down the hole') DTH hammer. The number and location of the holes will depend on rock mass condition and, in cases of work performed by a TBM, on the specific configuration of the excavation head. The boreholes will be made with a protective steel casing (with normal diameter of Ø114 mm) to avoid the hole collapsing. Ported PVC pipes will be inserted before removing the steel casing.

To perform pre-grouting injection, special PVC pipes will be installed inside holes. Packers are placed at openings within the PVC pipes, connecting via a hose to a pump. Then a prepared grout is pumped into the cracks and joints of the rock surrounding the boreholes.

The grouting of soil or rock masses with cement slurries or chemical mixtures to improve their mechanical and hydraulic properties is a well-established practice in engineering. Several kinds of grout are available and each has characteristics that make it suitable for a variety of uses. The most common are cement, sodium silicate, acrylate and urethane grouts.

Verification of the grout effectiveness is made by comparing inflow rates in the original probe hole to those in verification holes.

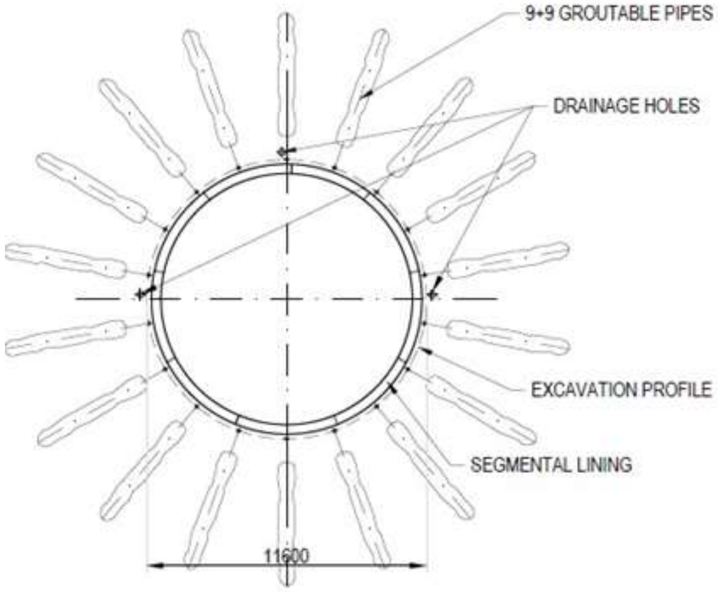


Figure 3.24 Grouting cross section

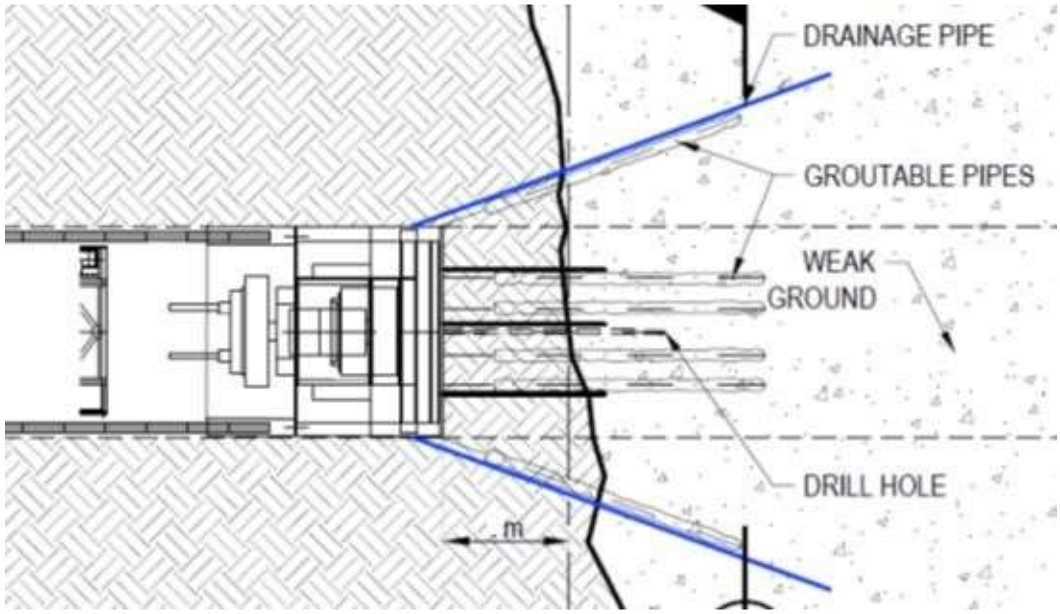


Figure 3.25 Grouting long section

c Post-grouting

Post-grouting will be conducted to reduce the hydraulic conductivity of the rock mass. It is undertaken within the constructed underground excavation. This will generally be carried out by:

- measuring inflows;
- drilling; and
- installing surface packers and injecting grout.

Tunnel water inflow will be measured using v-notch weirs along the constructed tunnel. If inflow criteria are exceeded post-grouting is initiated. Post grouting includes drilling sets of holes perpendicular to the tunnel, in a fan of 9 holes around the tunnel. The holes are generally drilled at even spacing from a jumbo with hydraulic top hammer. Mechanical packers are installed (shown in Figure 3.26) and connected to a pump via hoses. Grout is then injected to achieve a reduced permeability of the rock mass. Several kinds of grout are available and each has characteristics that make it suitable for a variety of uses.

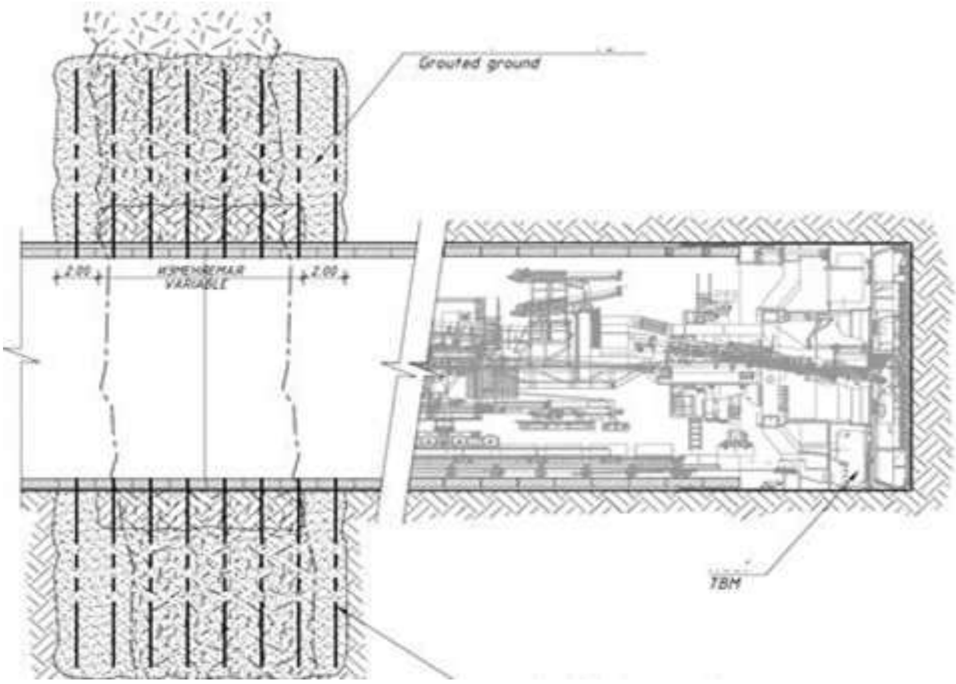


Figure 3.26 Post grouting

d Segmental lining

Concrete segmental lining is used to:

- achieve acceptable head loss in the conduit;
- prevent hydraulic jacking; and
- prevent excessive leakage by seepage.

The universal ring is a method of segmental lining for TBMs. The ring is composed of nine segments which form each ring (eight segments, one 'large size' key-segment), is 2 m wide and has no bolts along the longitudinal joints.

One drainage relief hole will be provided in each segment to guarantee the 'drainage effect' and the water pressure re-equilibrium.

Segmental lining is expected to reduce permeability.

The exact locations and extent of mitigation strategies are not yet known and, hence, the groundwater modelling adopted a conservative approach of simulating all excavations as non-mitigated with pre- or post-grouting.

iii Representation of project components

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 a combination of MODFLOW well (WEL) package and MODFLOW drain (DRN) package boundary conditions. In any stress period, all underground excavations in progress were assigned as dewatered features for the entire stress period.

a Power waterway and TBM-excavations

Table 3.4 presents inflow rates provided by the construction contractor for the TBM-excavated tunnels covering three phases of construction and operation for four scenarios. The four scenarios cover "Low", "Medium" and "High" inflow scenarios, based on experience of the contractor and taking into account the project setting, construction schedule and construction methods as well as a "Maximum capacity" scenario which represents the maximum inflow that can be handled by the TBM design. It should be noted that because the "Maximum capacity" scenario presents an upper limit to groundwater extraction from TBM-excavated project components it does not represent an anticipated outcome.

Inflow at the face relates to groundwater intercepted in the front 15 m of the TBM, which is exposed rock prior to installation of the segmental lining. The two other phases relate to the tunnel once the segmental liner and annulus grouting are installed a) when dry/drained during construction and b) once filled with water in the operational stage.

All four scenarios relate to a lined but non-mitigated construction. They do not account for the reductions in inflow that can be achieved by pre-grouting and post-grouting management actions. Therefore, the Medium inflow scenario was adopted as the base case for impact assessment. It is anticipated that this scenario will represent a conservative estimate of inflows and that actual inflows can be reduced from these values. The "Low", "High" and "Maximum capacity" inflow scenarios were also simulated to quantify sensitivity of modelled impacts to tunnel inflows but, unless indicated, from hereon in results relate to the "Medium" inflow scenario.

Table 3.4 Inflow scenarios

	Face (front 15 m)	Lined (dry/construction)	Lined (wet/operational)
Low inflow	0.25 L/s	1.5 L/s/km	1 L/s/km
Medium inflow	1 L/s	5 L/s/km	4 L/s/km
High inflow	10 L/s	11 L/s/km	8 L/s/km
Max capacity	70 L/s	11 L/s/km	8 L/s/km

The power waterway and tunnels to be excavated by TBMs were assigned well boundary conditions. The implementation of the well package employed the optional MODFLOW-USG control such that it extracts groundwater at the assigned rate unless this rate would cause reduction of the head in the cell such that the saturated thickness in the cell is less than 1% of the cell thickness. Therefore, assigned inflow rates effectively act as maximum inflow constraints beyond which the wells act like drains.

The regional numerical groundwater flow model employs stress periods of one quarter of a year, aligned with the seasons. The scheduled TBM advance rates are such that no section of tunnel maintains an open face at a given location for an entire stress period. Therefore, in the first stress period in which any given power waterway/TBM section is excavated, the inflow rates provided by the contractor (Table 3.4) were converted to average inflow per quarter using a pro-rata of the time as open face and the time as lined tunnel. This approach ensures consistency between the inflow constraints and the model water balance over a quarterly stress period duration. For subsequent stress periods the lined inflow rates were applied directly to.

The power waterway/TBM excavations advance at an average of approximately 15 m/d. Therefore, any location has an unlined excavation for approximately one day. The area is lined for the remaining approximately 90 days in the first stress period when an area is first excavated. The modelled inflow constraints, using this pro-rata approach for first excavation, along with subsequent stress periods during construction and operation, are outlined in Table 3.5 and illustrated in Figure 3.27.

Table 3.5 Modelled inflow constraints

	First excavated			Lined (dry/construction)	Lined (wet/operational)
	Face (front 15 m)	Lined	Pro-rata		
Low inflow	1 d @ 17 L/s/km	90 d @ 1.5 L/s/km	1.7 L/s/km	1.5 L/s/km	1 L/s/km
Medium inflow	1 d @ 67 L/s/km	90 d @ 5 L/s/km	5.7 L/s/km	5 L/s/km	4 L/s/km
High inflow	1 d @ 667 L/s/km	90 d @ 11 L/s/km	18.2 L/s/km	11 L/s/km	8 L/s/km
Max capacity	1 d @ 4,667 L/s/km	90 d @ 11 L/s/km	62.2 L/s/km	11 L/s/km	8 L/s/km

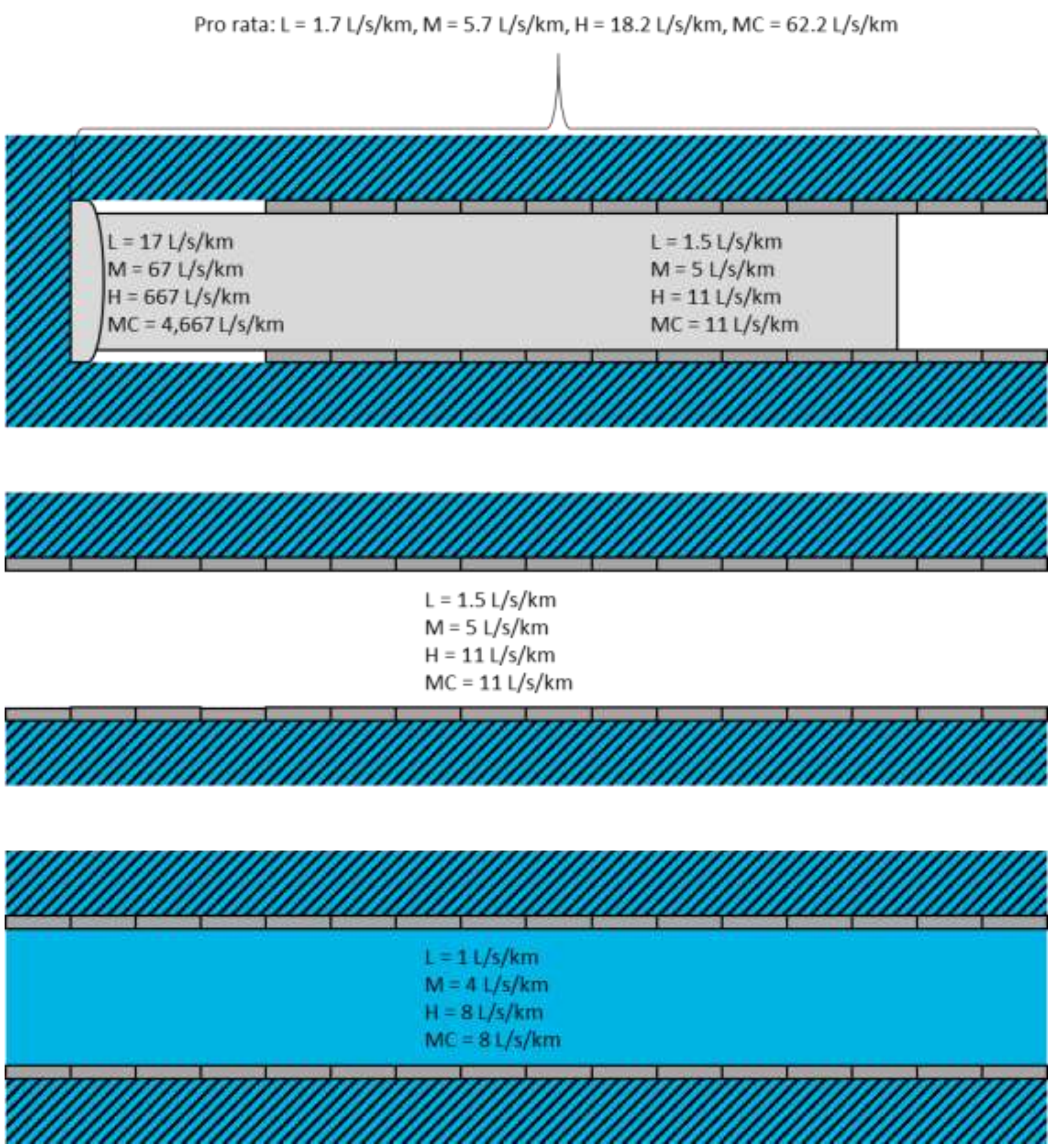


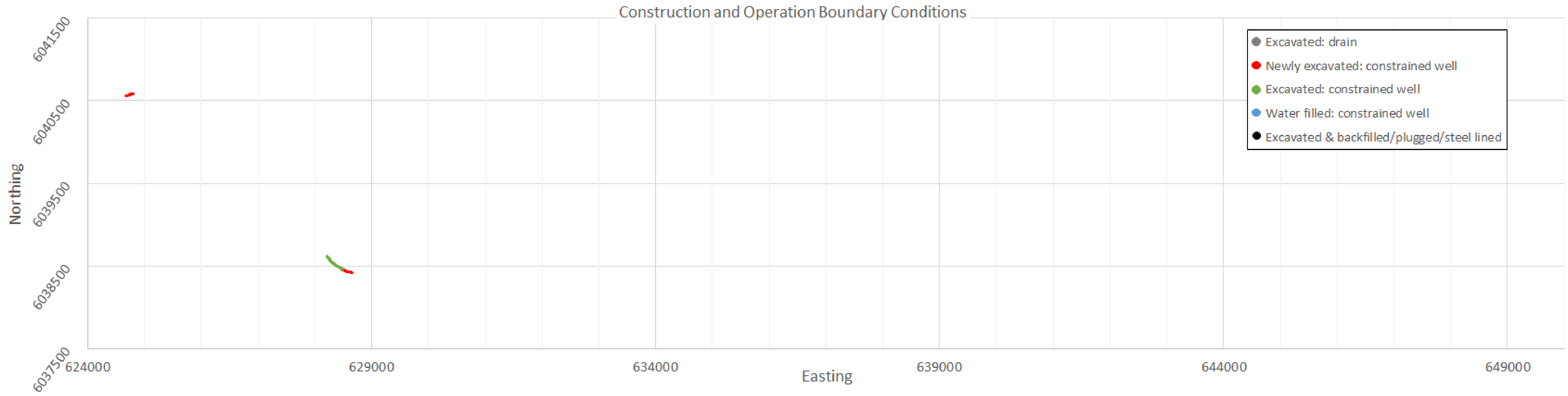
Figure 3.27 Modelled inflow constraints for a) first stress period of excavation, b) lined (dry/construction) and c) lined (wet/operational)

b Other excavations

All other excavations were assigned drain boundary conditions. Non-power waterway/TBM-excavated 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 model cells intercepted by these 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. 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.

The progression of drain and general head boundary conditions assigned within the model is presented for key times in Figure 3.28 to Figure 3.33. A series of figures presenting the full time series of excavation boundary conditions is presented in Attachment G.



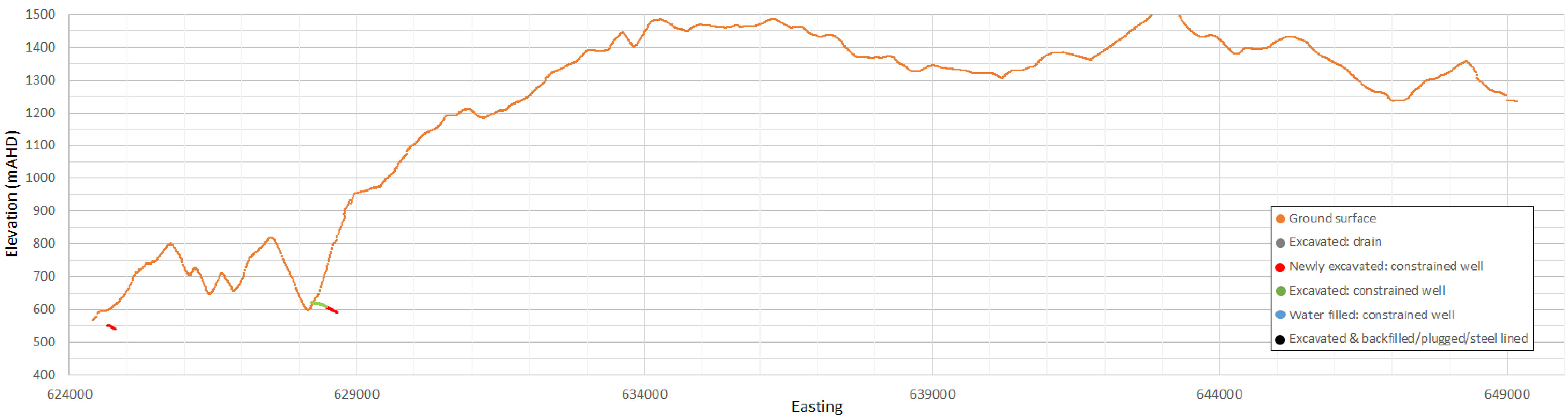
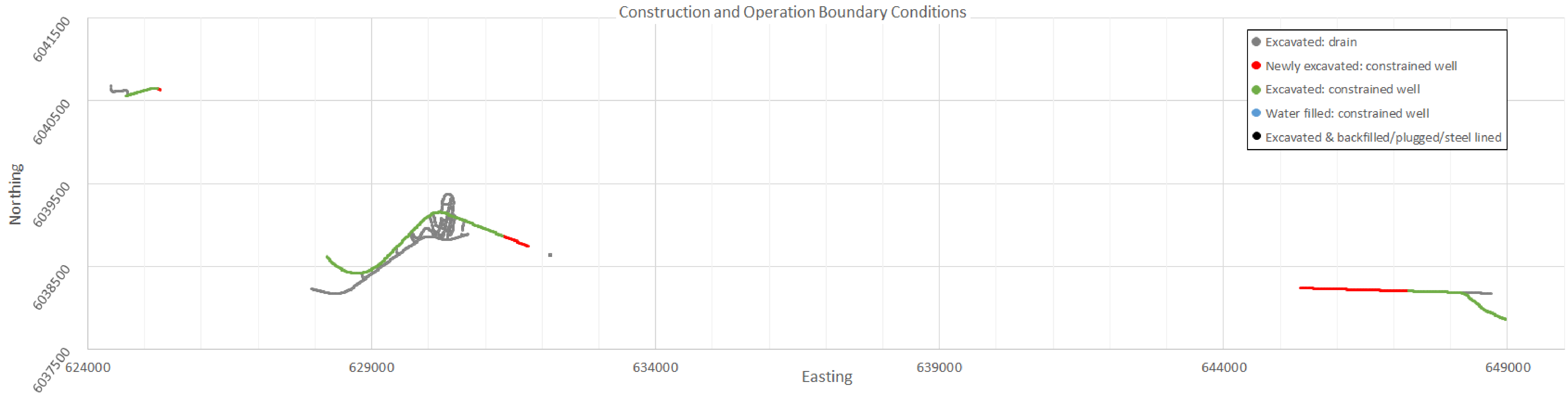


Figure 3.28 **Boundary conditions for excavations, stress period 8, ending September 2020, after 1 year of construction, plan (top) and elevation (bottom)**



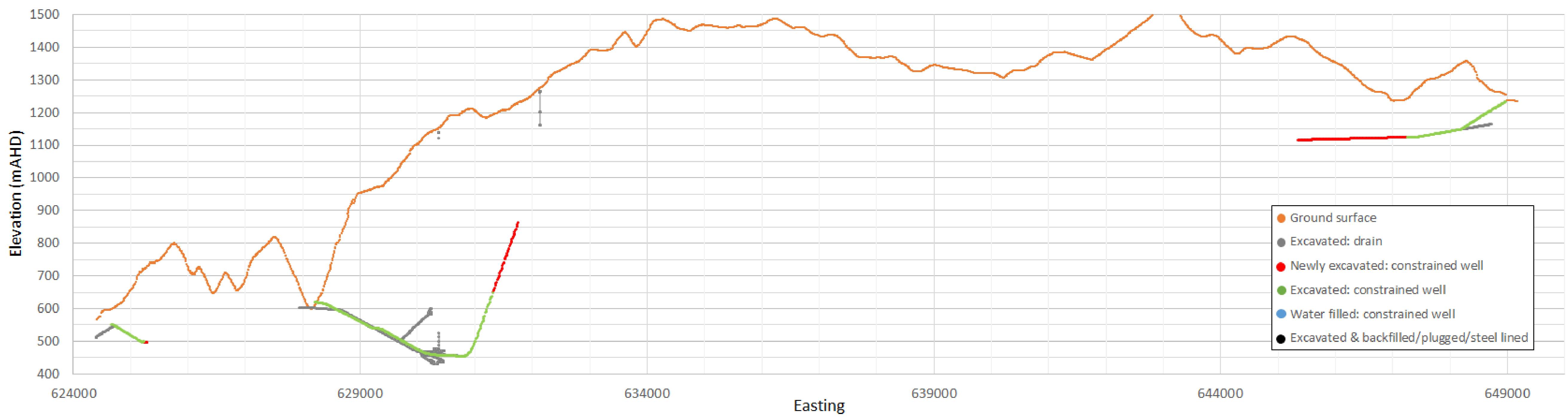


Figure 3.29 Boundary conditions for excavations, stress period 12, ending September 2021, after 2 years of construction, plan (top) and elevation (bottom)

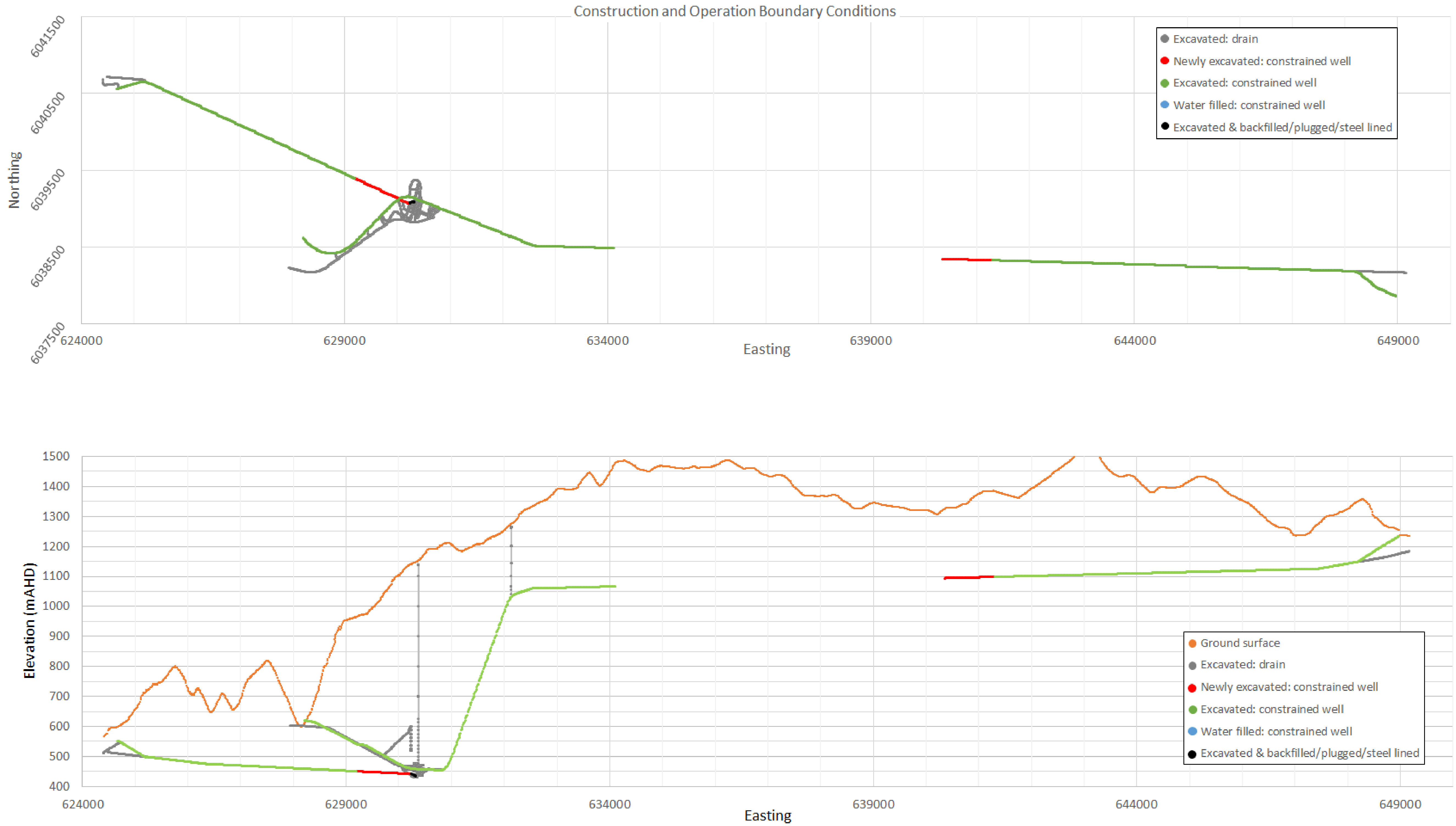


Figure 3.30 Boundary conditions for excavations, stress period 16, ending September 2022, after 3 years of construction, plan (top) and elevation (bottom)

Figure 3.31 Boundary conditions for excavations, stress period 20, ending September 2023, after 4 years of construction, plan (top) and elevation (bottom)

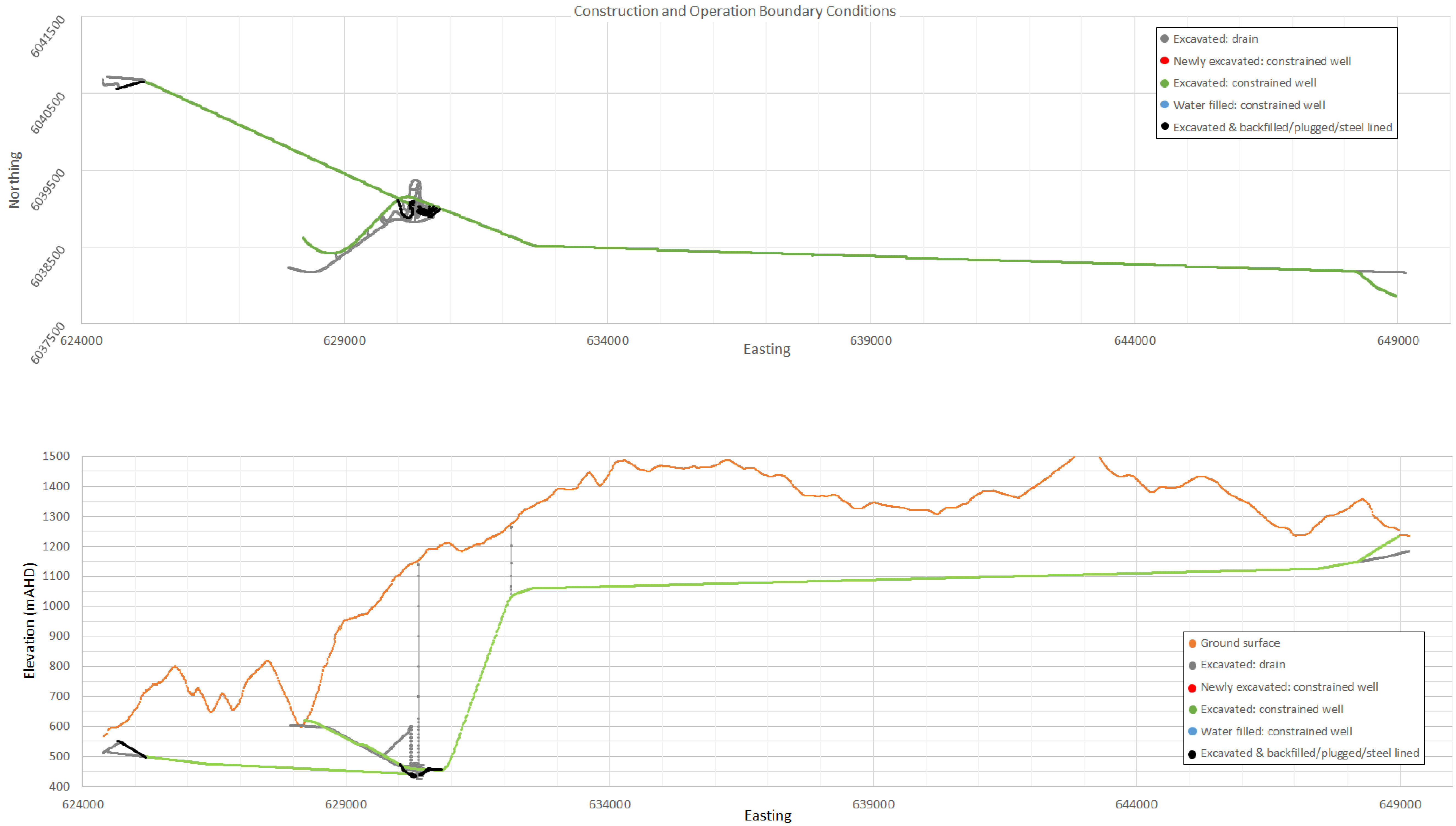
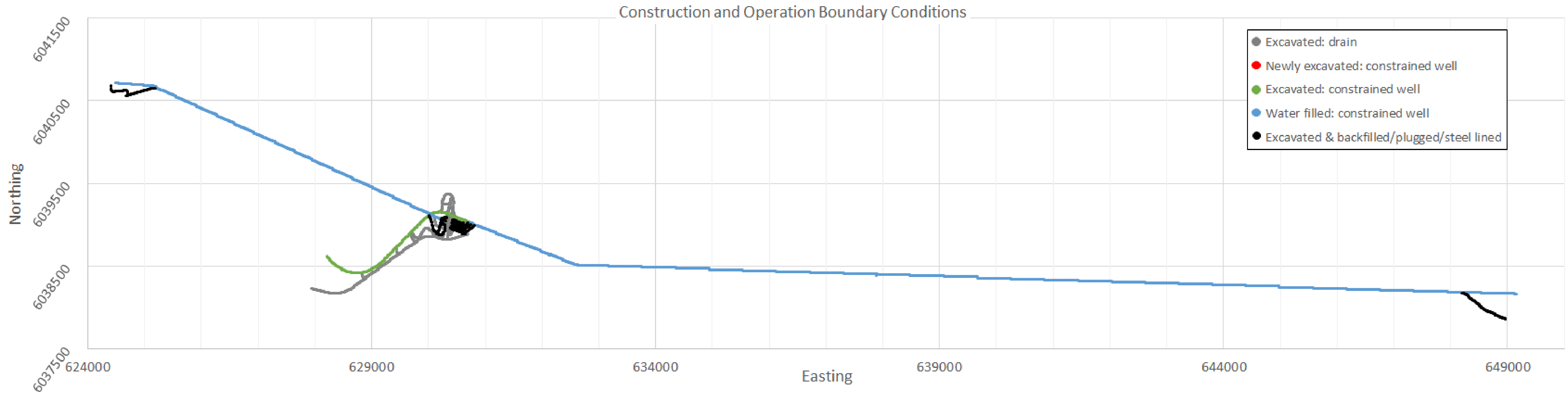


Figure 3.32 Boundary conditions for excavations, stress period 24, ending September 2024, plan (top) and elevation (bottom)



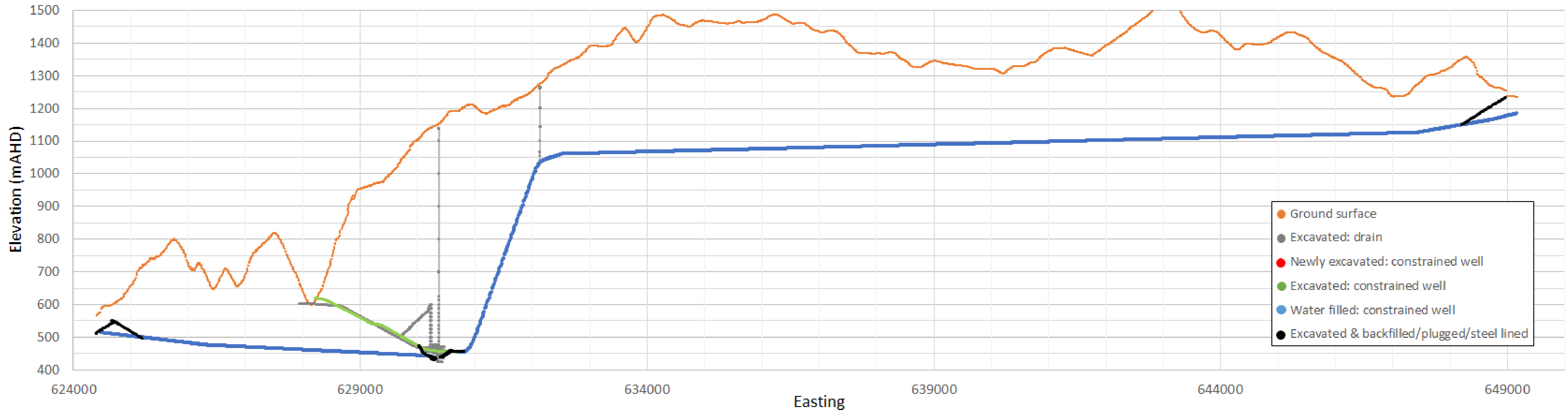


Figure 3.33 Boundary conditions for excavations, stress period 27, beginning March 2025, operation, plan (top) and elevation (bottom)

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 3.34 to Figure 3.38. 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.

After five years of construction the Kellys Plain Volcanics drawdown is predicted to further expand and a region of drawdown above the headrace tunnel in the Gooandra Volcanics region is predicted to reach magnitudes of greater than 10 m. Groundwater levels at the Yarrangobilly Caves are not predicted to be impacted during construction.

Figure 3.39 and Figure 3.40 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 but peak magnitude remains similar after 20 years of operation to that at the end of construction. Patchy, localised, drawdown above the Ravine Beds is also predicted to increase.

Figure 3.41 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 3.42). 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 20 m in a 1 km section in the Kellys Plain Volcanics and there are patches exceeding 10 m of drawdown in the Gooandra Volcanics, the predicted 0.5 m drawdown contour remains several kilometres distant from the Yarrangobilly Caves.

Predicted watertable drawdown for the “Low” inflow, “High” inflow and “Maximum capacity” inflow scenarios are provided in Attachment J. The figures illustrate the sensitivity of the predicted 0.5 m, 2 m and 5 m watertable drawdown contours after 5 years of construction, 20 years of operation and for steady state operational conditions, to the different modelled inflow constraints.