Yeodene (Big) Swamp

Groundwater and surface water modelling

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Barwon Water

Groundwater and surface water modelling for Big Swamp

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Contents

Executive Summary

This report has been prepared to fulfil the requirements of a Section 78 Ministerial Notice pursuant to Section 78 of the Water Act 1989, directing the corporation to develop and implement a Remediation Plan for the Boundary Creek, Big Swamp and the surrounding environment. The primary issue in driving the deterioration of water quality of the swamp and in the downstream reaches is the oxidation of acid sulfate soils present in the swamp as a result of declining groundwater levels and catchment runoff. Management options to remediate the swamp were investigated in a loosely coupled groundwater surface water modelling framework.

The management options investigated aimed to increase the area of inundation and raise groundwater levels to limit the future production of acid. Specifically, these options involve providing supplementary flow to Boundary Creek, the introduction of a hydraulic barrier to the downstream end of the swamp as well as a combination of both of these. The loosely coupled groundwater surface water model was calibrated to available surface water and groundwater data and was used to investigate these options.

The modelling approach integrated surface water accumulation and flow in Boundary Creek with an unsaturated/saturated zone groundwater flow model of the underlying aquifer system with Boundary Creek as a boundary condition. The surface water modelling calculated the inundation extents and water level (stage) throughout Boundary Creek and the swamp and these model outputs were applied as boundary conditions to the groundwater model. The groundwater model simulates exchange fluxes (the transfer of water between Boundary Creek and the underlying aquifer system) and quantifies groundwater levels throughout the swamp. This approach provided quantitative estimates of stream flow through Boundary Creek and Big Swamp together with estimates of the exchange fluxes and resultant changes in groundwater levels throughout the swamp.

Calibration of the individual component surface water and groundwater models has been limited by the quality and length of the available stream flow and groundwater head monitoring data. In particular, the available groundwater level records for bores in the swamp (June to September 2019) is of insufficient duration to allow a robust transient calibration that tests the model over a range of climatic and surface water hydrological conditions.

The exchange of data between the surface water inundation model and groundwater model provides a significant challenge for the transient models required to fully characterise groundwater responses to changes in river conditions. These problems largely revolve around the difference in response times in the hydraulic model and groundwater model. Simulation of surface water flow in the swamp requires a calculation time step of about one second while the groundwater model is required to run over periods of months or years to fully characterise the groundwater response to a change in river flow conditions. While these difficulties have hindered the development of a fully coupled model, simplifications have been introduced to the representation of surface water boundary conditions in the groundwater model and have enabled the generation of appropriate predictive outcomes for this investigation.

The modelling results indicate that a supplementary flow of 2 ML/d with no other interventions such as hydraulic barrier is not effective in increasing the inundated area or raising groundwater levels above those typically experienced at the end of winter (nominally September). However, the modelling suggests that this level of flow release will ensure flows through the swamp through all seasons and hence represents an improvement in historic groundwater levels throughout the swamp. While this scenario is conservative, in that no additional flows (from runoff or interflow) to the system were modelled, it is not unrealistic over the summer where extended periods of low flow are experienced. Increasing the supplementary flow to 20 ML/d was shown to be effective in increasing both the area inundated and groundwater levels; however, the flow rates represents the average high winter flows in recent years and its continuous delivery is not feasible. These results indicate that supplementary flows, with no other intervention, are not feasible to achieve the necessary increases in inundation extent and raising groundwater levels required to manage acid export.

The hydraulic barrier scenarios have demonstrated significant increase in the extent of inundation as well as increases in groundwater levels although these benefits were limited to immediate surrounds. Further, the surface water results of a barrier with different supplementary flows found that there were diminishing returns with higher flows, that is, increased flow rates did not result is a significantly larger area inundated behind the barrier.

The modelling suggests that a modest supplementary flow with multiple hydraulic barriers within the swamp would provide the greatest benefit and limit the export of acid water. While it has not been possible to model additional hydraulic barriers within the available time for this investigation, it is recommended that the location of additional barriers be investigated and modelled in the future with suitable locations selected on the basis of topography to assess the expected beneficial impacts on vegetation and the predicted reduction in acid generation and export.

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to assess the feasibility of the proposed remediation option for Yeodene Swamp using an integrated groundwater and surface water modelling approach. These works have been carried out in accordance with the scope of services as set out in Barwon Water's Request for proposal (contract no: 001291), and the proposal for groundwater and surface water modelling for Big Swamp submitted to Barwon Water by Jacobs in August 2019.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by Barwon Water and/or from other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and concludes as expressed in this report may change.

Jacobs derived the data in this report from information sourced from Barwon Water, the Bureau of Meteorology and DELWP as outlined in this report.

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1. Introduction

This report has been prepared to fulfil the requirements of a Section 78 Ministerial Notice pursuant to Section 78 of the Water Act 1989, directing the corporation to develop and implement a Remediation Plan for the Boundary Creek, Big Swamp and the surrounding environment.

The Section 78 covers Boundary Creek, Big Swamp and the surrounding environment. A loosely coupled groundwater surface water model was developed to inform the remediation plan for Boundary Creek and Big Swamp. The models are described as being loosely coupled as they do not run concurrently, rather the models are run one after the other with results from a surface water model run transferred to the groundwater model as an input data set. The coupling is not dynamic in that the models do not simultaneously transfer data between models at every calculation time step.

Areas outside the Boundary Creek catchment that may also have been impacted by historic borefield pumping will be considered in a separate investigation plan. This report documents the development, calibration and results obtained from the coupled groundwater surface water model specifically to assess remediation options for Boundary Creek & Big Swamp.

1.1 Background

Big Swamp is a peat swamp located on Boundary Creek, upstream of the confluence with the Barwon River. The peat swamp contains acid sulfate soils that have dried out, resulting in the release of acidic water to the lower reach of Boundary Creek and ultimately, to the Barwon River.

The current state of the swamp reflects the culmination of numerous events throughout the catchment’s history. This includes:

- The initial deposition of acid sulfate soils in the swamp
- The construction of nearby agricultural drains and farming in the area over 100 years ago
- Step changes in climate (including the Millennium Drought)
- The construction of an on-stream dam (McDonalds Dam) upstream of the swamp
- Groundwater extraction by Barwon Water and the release of supplementary flows to Boundary Creek, and
- Peat fires in the swamp and the excavation of trenches by CFA to control these fires.

Until recently, there has been limited understanding of the relative contributions of each of these factors to the generation and release of acidic waters in Big Swamp. There have also been limited scientific studies focussing on characterising the lower reaches of Boundary Creek.

Consultation with the community resulted in Barwon Water’s commitment to develop and implement a remediation plan for Boundary Creek. The intention of this plan is to improve streamflow and water quality within Boundary Creek and Big Swamp, with the ultimate goal of improving ecological function of Big Swamp and water quality in Boundary Creek. The 2017-2018 Technical Works Program resulted in an improved conceptual understanding of the local hydrology, hydrogeology and interaction between the surface water and groundwater systems. A high-level assessment of six remediation options found that inundating the swamp would likely prove to be the most technically feasible.

Although Barwon Water had committed to remediation of the swamp, this was formalised when Barwon Water received a Ministerial Notice pursuant to Section 78 of the Water Act 1989 in September 2018. The Section 78 Notice directs the corporation (Barwon Water) to develop and implement a Remediation Plan for the Boundary Creek and Big Swamp environments.

The scope of works developed to meet the requirements of the Section 78 notice outlines a detailed program of works required to inform the remediation of the swamp, including an extensive field program to collect soil and groundwater data and subsequent analysis, collection of LiDAR data, installation of additional monitoring assets as well as groundwater and surface water modelling and hydro-geochemistry modelling.

Previous investigations undertaken by Jacobs concluded that the management of the acid sulfate soils in Big Swamp would require the management of both the surface water system and groundwater system, as well as the interaction between the two. In response to this, Jacobs has developed a loosely coupled groundwater-surface water model scheme to help inform the assessment of remediation options for Boundary Creek and Big Swamp.

2. Catchment description

Boundary Creek is located in south-west Victoria and originates south of Colac and flows in an easterly direction for approximately 18km discharging to the Barwon River. There are a number of streamflow gauges upstream of Yeodene as discussed in Section 4.1.

The Boundary Creek catchment was delineated using the Statewide 10 m resolution DEM and terrain analysis tools available within ESRI ArcGIS. Catchments were calculated for four streamflow gauging locations as indicated in Figure 2-1. Table 2.1 presents a summary of each of the sub catchments.

Table 2.1: Summary of subcatchments adopted for this investigation

Catchment Name	Area (km^2)	Description	Geology
Upstream of Barongarook (233273)	18.7	• Extends from the origin of Boundary Creek (south of Colac) to Barongarook, just downstream of where Boundary Creek meets Gardiners Road.	• Boundary Creek flows over outcropping bedrock characterised by impermeable Palaeozoic sandstone, siltstone and mudstone.
Barongarook (233273) to upstream McDonalds Dam (233231)	5.4	• Extends from Boundary Creek at Barongarook, downstream of where Boundary Creek meets Gardiners Road, to the streamflow gauge upstream of McDonalds Dam.	• Boundary Creek flows over outcropping bedrock characterised by impermeable Palaeozoic sandstone, siltstone and mudstone.
Upstream McDonalds Dam (233231) to downstream McDonalds Dam (233229)	2.7	• Extends from the streamflow gauge upstream of McDonalds Dam to the gauge downstream of McDonalds Dam • Contains McDonalds Dam, a privately-owned on-stream dam which was constructed in 1979	• Boundary Creek flows over alluvial sediments overlying Lower Teritary Aquifer characterised by permeable sands of the Mepunga, Dilwyn and Pebble point formations and Mid Tertiary Aquatard comprising marls and clays associated with Gellibrand Marl
Downstream McDonalds Dam (233229) to Yeodene (233228)	12.6	• Extends from the streamflow gauge downstream of McDonalds Dam down to Yeodene, where Boundary Creek intersects with Colac-Forest Road. • This catchment contains Big Swamp, a peat swamp. Upstream of Big Swamp the flow path of Boundary Creek is disperse, forming marshes and deeper pools.	• Boundary Creek flows over alluvial sediments overlying Mid Tertiary Aquatard comprising marls and clays associated with Gellibrand Marl

Figure 2.1: Topographic map showing the subcatchment boundaries and other key hydrological features along Boundary Creek, upstream of the Yeodene township

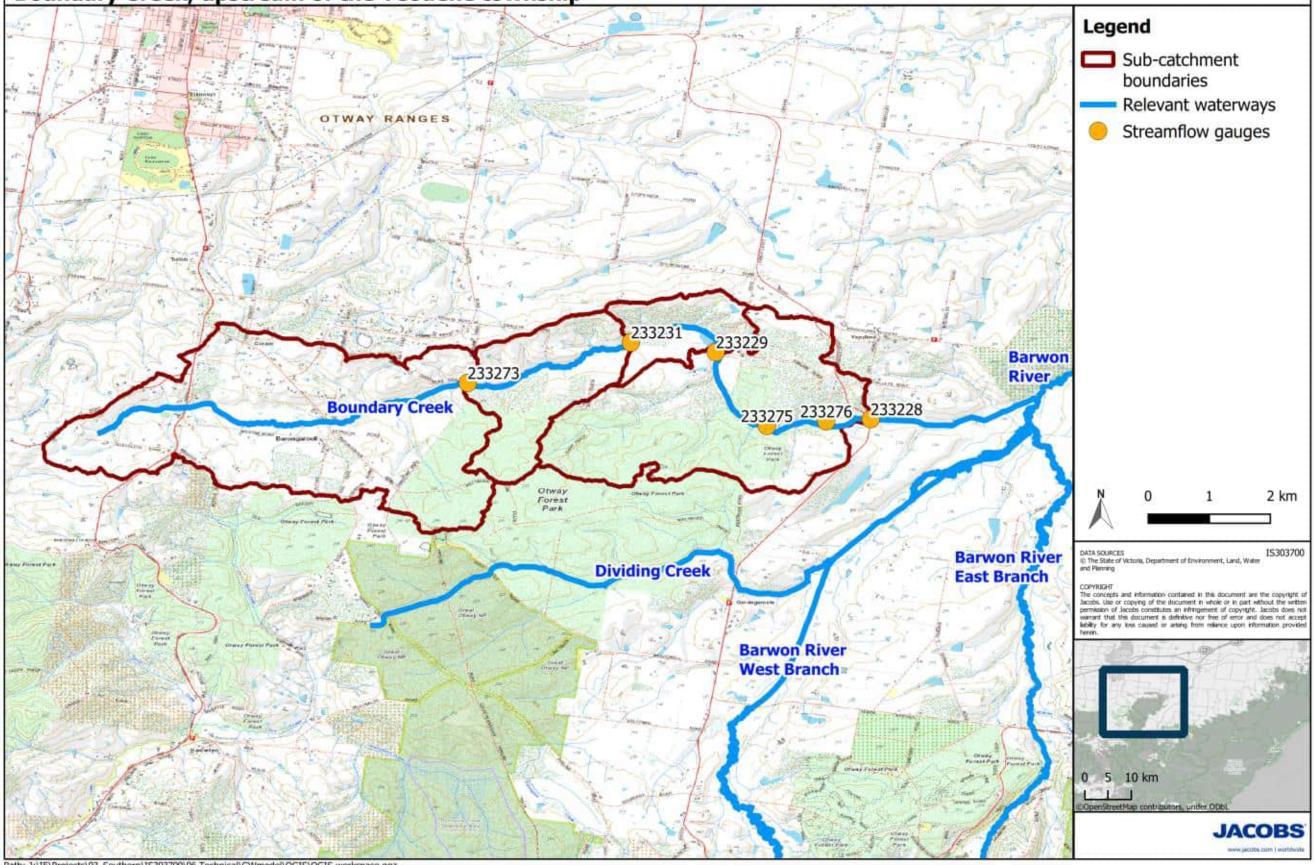

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Figure 2-1: Topographic map showing the subcatchment boundaries and other key hydrological features along Boundary Creek, upstream of the Yeodene township

3. Approach to coupled groundwater surface water model

Previous groundwater modelling and subsequent detailed site investigations at Big Swamp and Boundary Creek in general has highlighted the fact that the regional groundwater flow model does not provide the spatial refinement required to represent the detailed system geometry important in simulating the local hydrogeology of the swamp. This is most graphically illustrated in the fact that the regional model does not include alluvial sediments that bound the creek and that dominate the surface geology through the swamp. While the alluvial sediments are not significant to the regional scale groundwater model, they are of particular significance when it comes to assessing groundwater behaviour in the swamp.

It is also recognised that the interaction between groundwater and surface water in Boundary Creek is of critical importance when assessing historic behaviour of the swamp and in considering the future condition of the swamp. An approach to modelling has been proposed that integrates surface water accumulation and flow in Boundary Creek with an unsaturated/saturated zone groundwater flow model of the underlying aquifer system in which Boundary Creek is represented as a boundary condition. The intention is that the surface water modelling will produce estimates of the wetted area and water level (stage) throughout Boundary Creek and the swamp and that these model outputs will be used as boundary conditions for the groundwater model. The groundwater model will simulate exchange fluxes (the transfer of water between Boundary Creek and the underlying aquifer system) and will also quantify groundwater levels throughout the swamp. The integrated model will, in theory provide quantitative estimates of stream flow through Boundary Creek and Big Swamp together with estimates of the exchange fluxes and resultant changes in groundwater levels throughout the swamp and investigate management scenarios.

Details of the surface water and groundwater models are provided in Sections 5 to 8 below.

A limited amount of historic river gauging and groundwater level measurements are available and have been used to help calibrate both the surface water and groundwater models. The duration and quality of the available groundwater data have provided challenges for the calibration process and currently limit the confidence with which the groundwater modelling results can be used to predict future aquifer behaviour.

Perhaps the biggest challenge in integrating the models is the different time scales that are of relevance. A groundwater model is typically required to consider behaviour over a period of months and years as the response times in groundwater can be slow. On the other hand, water flow in the creek is extremely dynamic and requires a fine time scale (in the order of seconds) to be able to capture the processes of importance. Linking models of this type is challenging and a significant level of simplification has been necessary to achieve modelling outcomes within the available time for this project. While a more rigorous coupling of the models may help to provide more accurate transient groundwater behaviour in the hours following a significant flow event, it is unlikely that this level of precision is required to assess the longer term impacts of long term flow releases in Boundary Creek.

4. Data review

4.1 Streamflow

Streamflow data was sourced from the Bureau of Meteorology's Water Data Online (2019) or provided by Barwon Water. The location of these streamflow gauges is shown in Figure 2-1. Table 4.1 below presents a summary of the available streamflow data acquired for this investigation. These streamflow gauges are situated along Boundary Creek, upstream of the Yeodene township. The record lengths of available daily data are presented in Figure 4-1. Note that daily flow is representative of the average daily flow over the 24-hour period to 0900 local time.

Table 4.1: Summary of available streamflow data

Gauge No	Gauge Description	Data Provider	Data frequency	Period of record	% Missing [1]	Notes [1]
233273	Boundary Creek at Barongarook	BoM	Daily / Irregular	Jul 2014 – Current	10%	57% of available data is best quality
233231	Boundary Creek at Upstream McDonalds Dam	BoM	Daily / Irregular	Dec 1989 – Current	72%	100% of available data is best quality
233229	Boundary Creek Downstream at Downstream McDonalds Dam	BoM	Daily / Irregular	Dec 1989 – Current	72%	[2 80% of available data is best quality; In 2019, data was missing for all flows greater than approx. 0.13 m^3/s (12ML/d)
233275A	Boundary Creek Upstream Big Swamp	Barwon Water	Predominately 15min intervals	Jun 2019 – Current	34%	[2 Missing data up to 10-days at a time; Available data is good quality; Data was missing for flows greater than approx. 0.13 m^3/s (12ML/d)
233276A	Boundary Creek Downstream Big Swamp	Barwon Water	Predominately 15min intervals	Jun 2019 – Current	32%	[2 Missing data up to 10-days at a time; Available data is good quality; Data was missing for flows greater than approx. 0.13 m^3/s (12ML/d)
233228	Boundary Creek at Yeodene	BoM	Daily / Irregular	Mar 1985 – Current	1%	90% of available data is best quality
ME763	Boundary Creek at Yeodene	Barwon Water / BoM	Daily / Irregular	Dec 2015 – Current	0%	100% of available data is best quality

[1] Where data were acquired as both a daily average or as all available points, the percentage of missing data and quality assessment was based on the daily timeseries.

[2] The gauge was installed to capture flows of 0 to 12 ML/day accurately and flows above this were not reported.

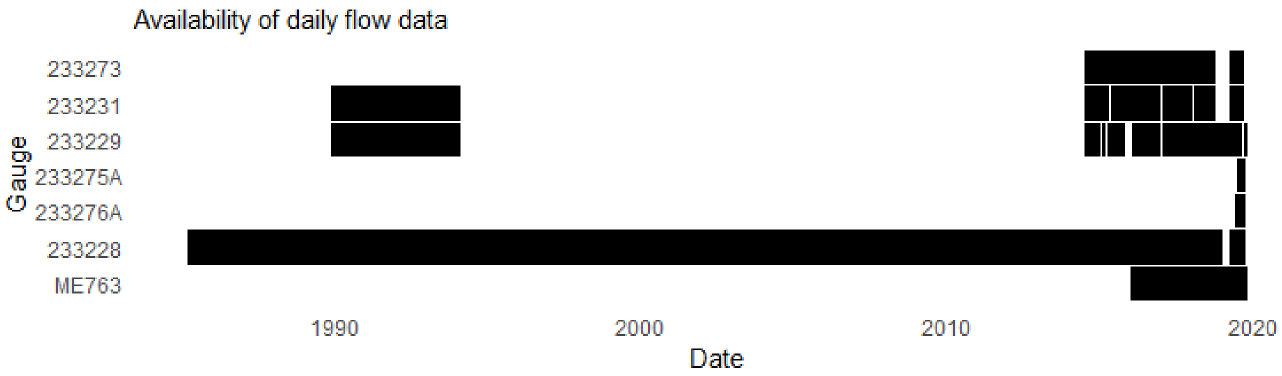

Figure 4-1: Timeline of available streamflow data

4.2 Climate

Gridded data of rainfall and Morton's wet areal potential evapotranspiration (PET) was sourced from SILO (Department of Environment and Science, 2019). SILO is a database of Australian climate data from 1889 to the present. Data are provided on a continuous, daily time-step and are constructed from observed data. Rainfall data was downloaded to the end of September 2019 while PET data was only available until the end of June 2019.

Subcatchment average rainfall and Morton's wet areal potential evapotranspiration was calculated using geospatial packages compatible with the Python 3 programming language. The average monthly evapotranspiration (expressed in units of mm/d) was derived and used to infill the missing data between July and September of 2019. Figure 4-2 presents the resulting catchment average monthly rainfall and evapotranspiration over the Boundary Creek at Yeodene catchment over the period 1990 – September 2019.

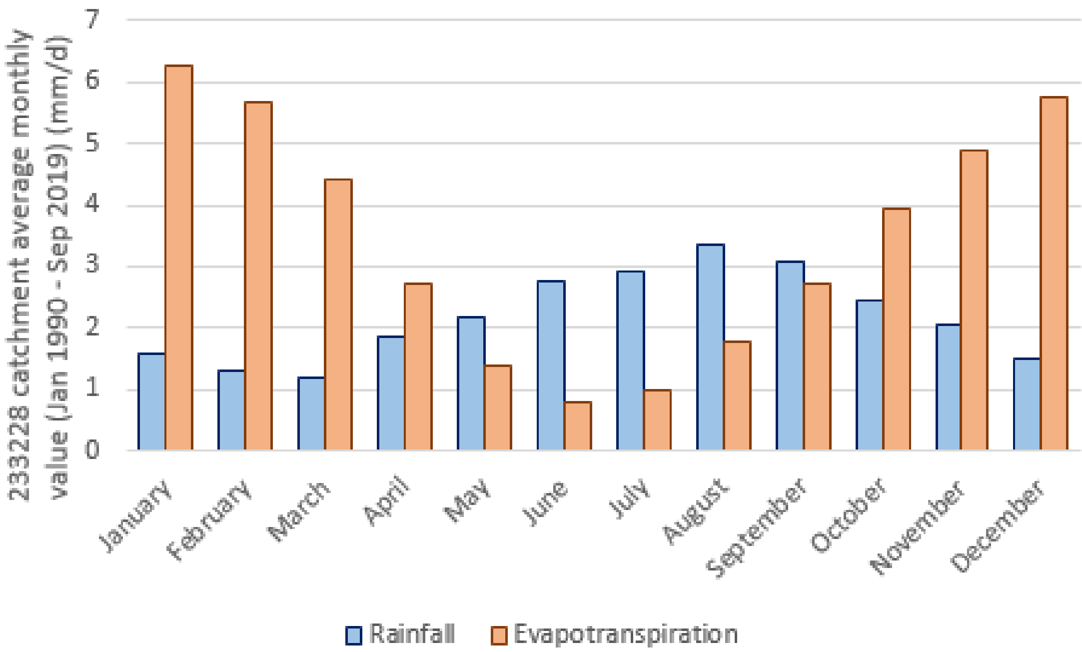

Figure 4-2: Monthly average rainfall and evapotranspiration (mm/d) which falls over the Boundary Creek catchment upstream of the Yeodene township (233229) between 1990 – Sep 2019.

4.3 Elevation

A number of topographic elevation datasets were obtained as part of the project, including:

- A 1 m gridded DEM of LiDAR captured in May 2019 provided by Barwon Water; and
- Statewide 10 m DEM (VICMAP Elevation DTM 10 m, (DSE, 2008))

4.4 Aerial photography

Aerial photography of the Swamp and immediate surround was captured as part of the LiDAR survey which was undertaken in May 2019 and represents the current catchment conditions. The resolution of the photography was 70mm. Lower resolution images for areas beyond the recent LIDAR data were sourced from Google Maps (Google Maps, 2019). All sources of aerial imagery were of sufficient quality and accuracy for modelling purposes.

5. Surface water models

The surface water modelling involved two modelling approaches – rainfall runoff modelling and hydraulic modelling. These are discussed in the following sections.

5.1 Objectives

The surface water models, rainfall runoff and hydraulic, were developed for the following purposes:

- The rainfall-runoff model objectives are to:
  - Calculate information on the streamflow in Boundary Creek downstream of McDonalds Dam and at Yeodene to infill missing gauged data;
  - Determine the catchment runoff for the intermediate catchment between McDonalds Dam and Yeodene;
  - Undertake streamflow loss analysis; and
  - Determine monthly flow patterns to help develop transient data sets for the groundwater model.
- The hydraulic model objectives are to:
  - Provide surface water level conditions (both the inundated area and levels or stage) for inputs to the groundwater model.
  - Assess different management scenarios by determining the extent of inundation and losses from the surface water system.

5.2 Rainfall runoff model

In order to understand the hydrological characteristics of the catchment, a rainfall-runoff model was developed. In addition to characterising the catchment in terms of hydrology, the model was used to infill missing streamflow data and estimate runoff from the subcatchment between McDonalds Dam and Yeodene.

A continuous daily GR4J rainfall-runoff model was created to produce an estimate of the surface runoff in response to input climate conditions (represented by a timeseries of both rainfall and potential evapotranspiration). The transformation of climate inputs into runoff is controlled by the model structure and parameters. The GR4J sub-catchment breakup is shown in Figure 5-1. More detail on the GR4J model is provided in Appendix A.

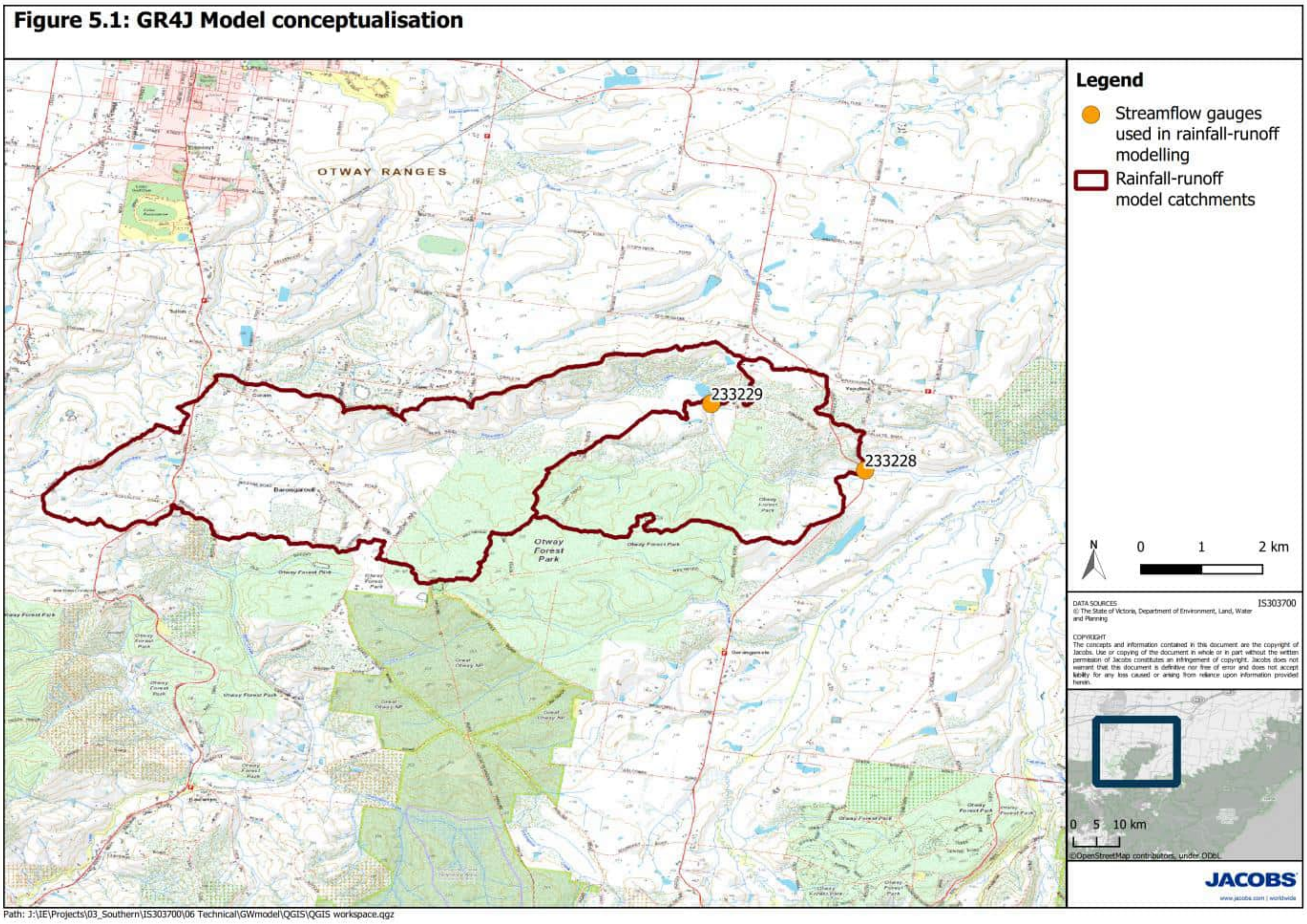

Figure 5-1: GR4J Model conceptualisation

The rainfall-runoff model was calibrated to the most relevant gauge with an acceptable length of record namely; the gauge downstream of McDonalds Dam (233229) and the Yeodene (233228) gauge. The two had a period of concurrent data from 01/01/2015 – 30/09/2019 which was used for calibration and validation as set out in Table 5.1. Initial results indicated that data and model setup did not support two parameter sets; one for the upstream catchment to the gauge downstream of McDonalds Dam and another set to the Yeodene gauge. The model was therefore calibrated to the Yeodene gauge only.

The resulting calibration together with diagnostic plots is shown in Figure 5-2 with further details in Appendix A. These results demonstrate that the model is able to replicate the rainfall-runoff response of the catchment.

Table 5.1: Rainfall Runoff model calibration and validation periods

Model period	Calibration	Validation
Warm-up period	01/07/2014 – 31/12/2014	1/07/2017 – 31/12/2017
Simulation period	01/01/2015 – 31/12/2017	1/01/2017 – 31/12/2018

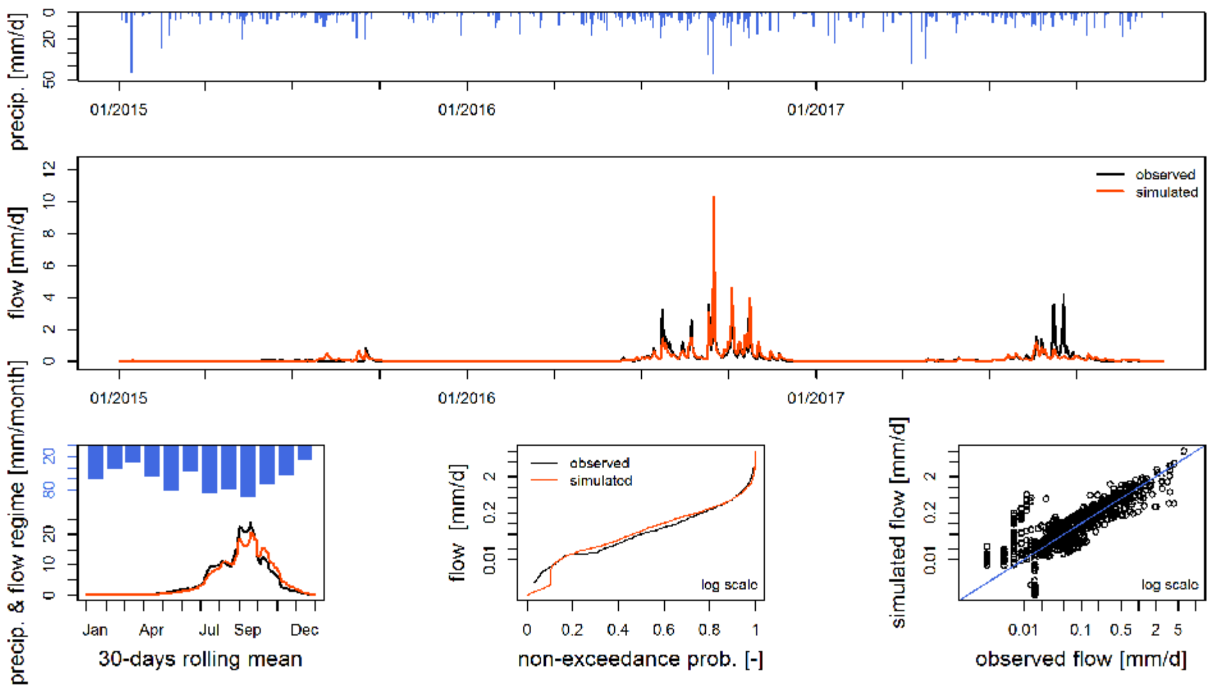

Figure 5-2 : Yeodene (233228) gauge calibration diagnostic plots

The rainfall-runoff model was run over the full simulation period (01/01/2015 – 30/09/2019). Figure 5-3 presents a flow duration curve of the timeseries outputs for the following:

- Simulated flow at the gauge location 233229: Boundary Creek at Downstream McDonalds Dam
- Simulated flow at the gauge location 233228: Boundary Creek at Yeodene
- Simulated catchment runoff between the two gauges.

A plot of average monthly flow (ML/d) is presented in Figure 5-4.

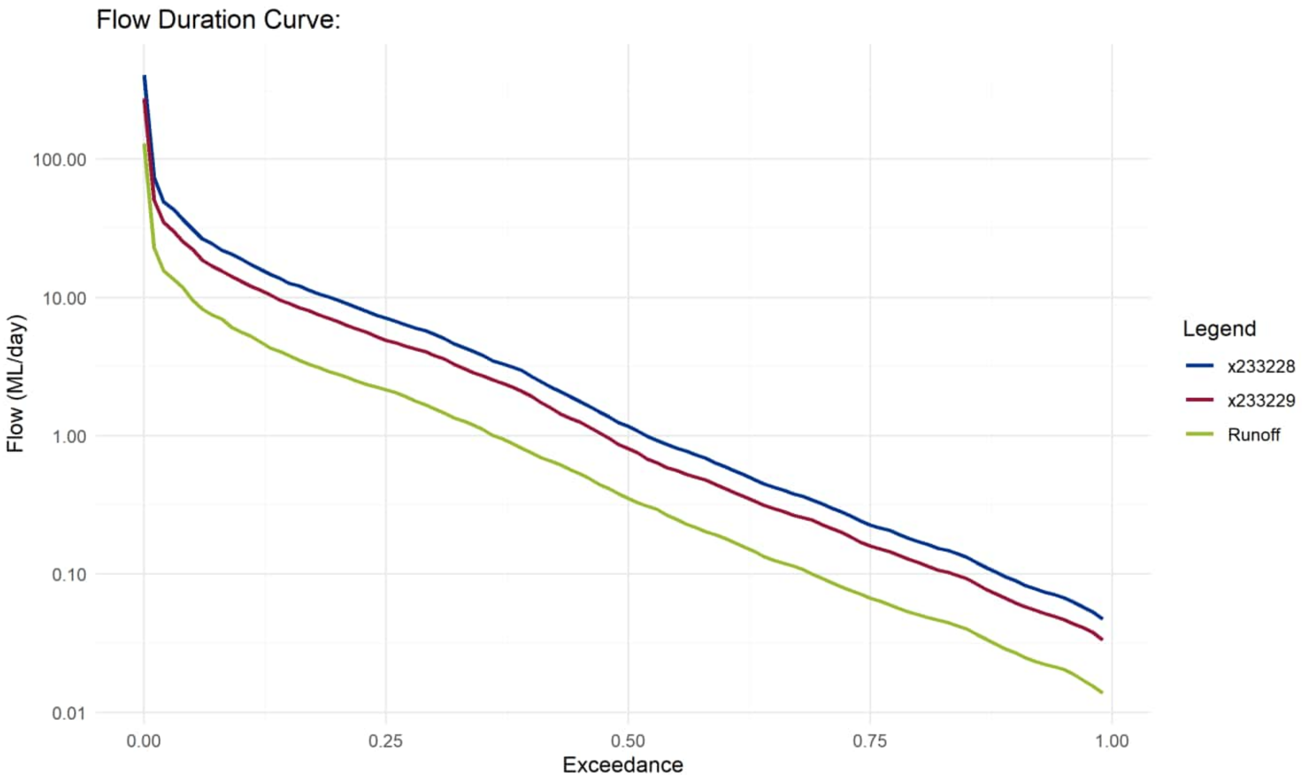

Figure 5-3: Exceedance curve of flow over the full record of simulation (1/01/2015 – 30/09/2019).

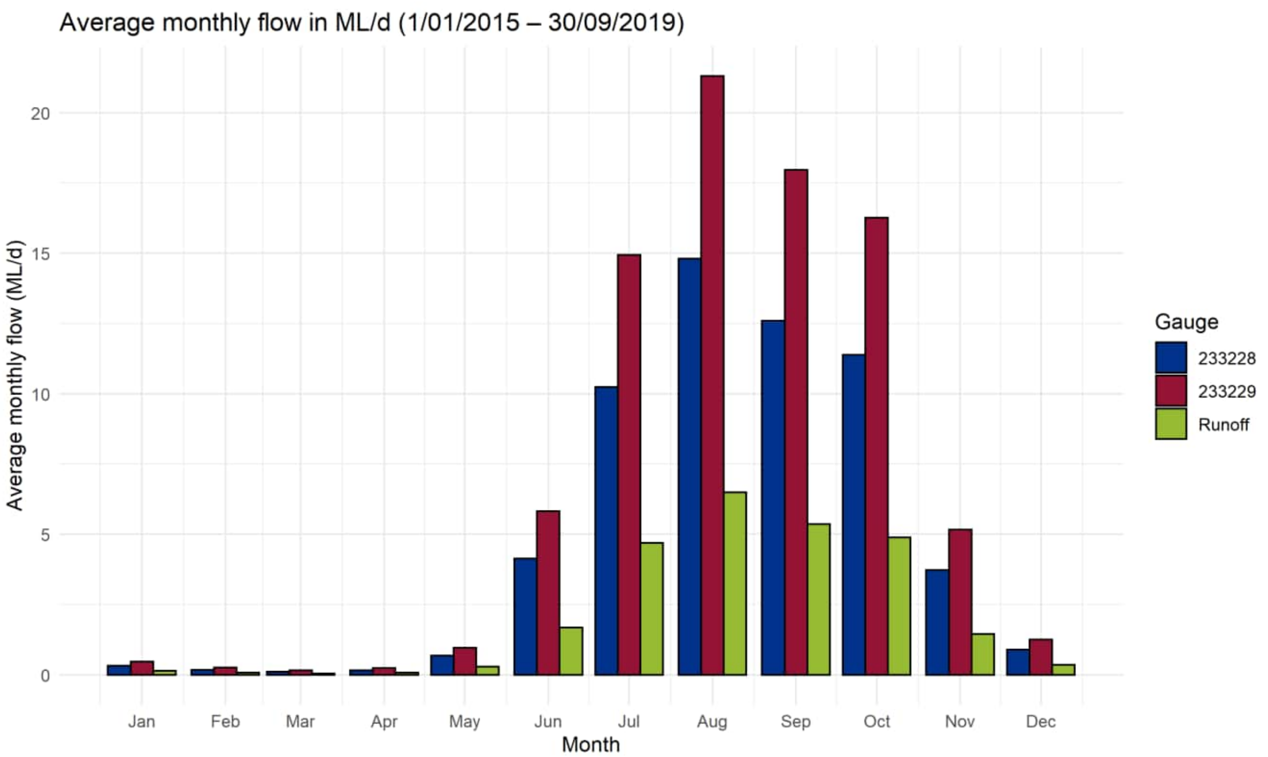

Figure 5-4: Average monthly flow (ML/d) over the full record of simulation (1/01/2015 – 30/09/2019).

5.2.1 Loss analysis

Flow losses in the downstream sub-catchment were analysed using the stream flow data with infilling of missing data from the rainfall-runoff model. The difference in flow between the gauge downstream of McDonalds Dam (233229) and the Yeodene (233228) gauge was computed. A negative change is indicative of losses from the surface water, while a positive change indicates a gain. Note that this calculation does not explicitly account for runoff from the downstream subcatchment and hence the losses may be greater than calculated.

Figure 5-5 presents the results from the loss analysis. These results indicate that on average, between September and October catchment runoff (for the catchment bounded by the streamflow gauges 233229 and 233228) results in a net gain in streamflow to Boundary Creek. From November through to August however the system appears to result in a net loss of streamflow, with the magnitude of losses greatest in April through to August. The losses, assumed to represent seepage to groundwater, range from 0.5 ML/day to 2.5 ML/day.

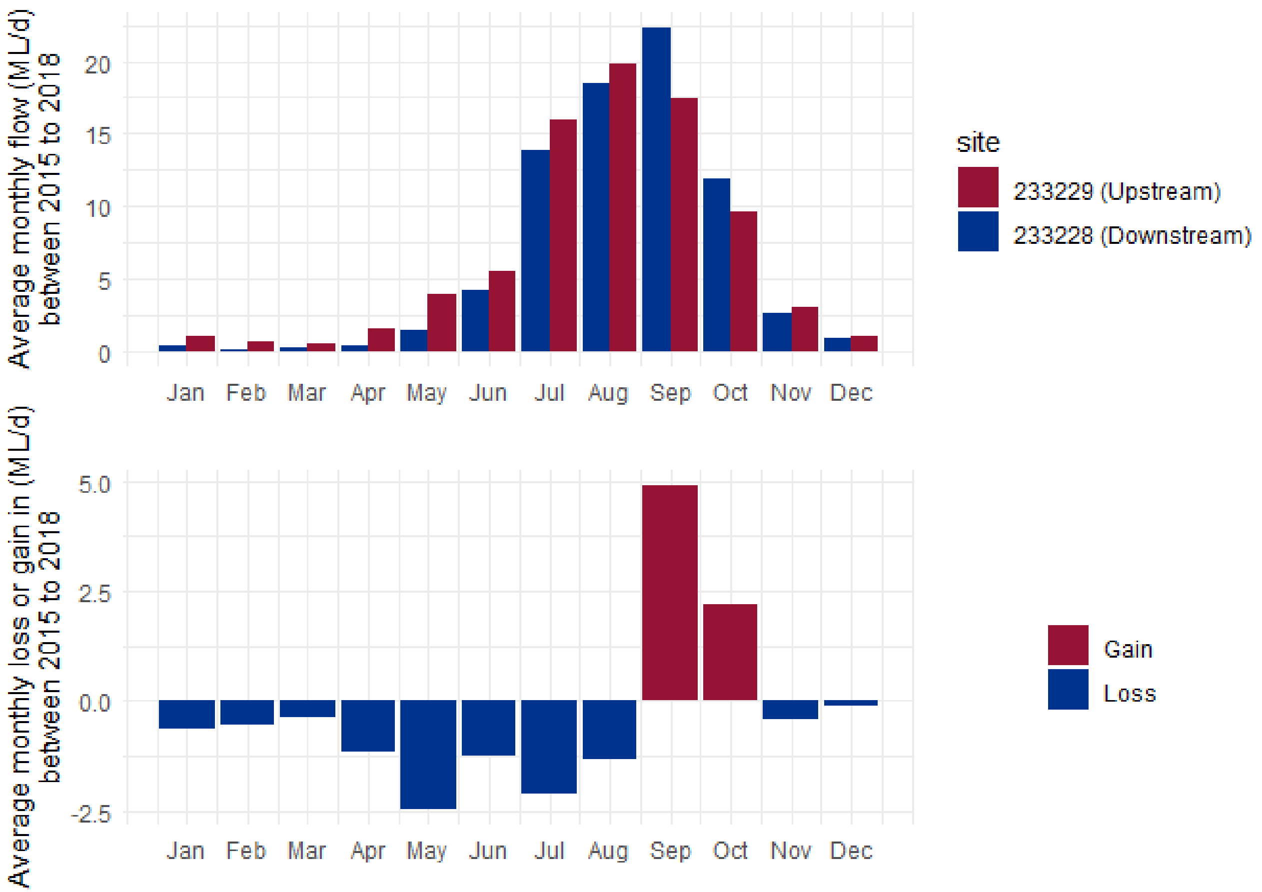

Figure 5-5: Average monthly flow the key streamflow gauges (233229 and 233228) and average monthly loss/gain to Boundary Creek occurring between these two gauges.

5.2.2 Discussion and recommendations

The daily rainfall-runoff model was able to reasonably replicate the hydrological characteristics of Boundary Creek; however, the model has been calibrated (and validated) over a relatively short period due to limited available data. There are a number of recommendations to improve the calibration for potential future assessments.

Suggested model improvements:

- At present the model assumes that McDonalds dam was full and did not affect runoff as sufficient data to characterise the dam were not available (stage-storage-elevation data, usage data, etc). It is recommended that the dam be included in future revisions of the model. It is expected that the inclusion of this information will improve the model calibration.
- Presently Barwon Water releases 2 ML/d into the Boundary Creek system and it is recommended that this inflow be considered explicitly rather than implicitly in the rainfall-runoff model. This will allow transparent assessment of supplementary flows.
- As additional streamflow data becomes available it is recommended that the rainfall runoff model be re-calibrated (and validated) against this additional information. Further, once the newly installed gauges immediately upstream and downstream of Big Swamp have an adequate period of good quality record, the rainfall runoff model should be validated against this data. This could then allow for an analysis of the losses over the swamp and upstream of the swamp to McDonalds Dam separately.
- Once the additional data and the model is updated to incorporate the changes above, it should be calibrated with two sets of parameters for each sub-catchment. This would provide a better understanding of losses in the downstream catchment.

Additionally, the rainfall-runoff model could also be used to:

- Simulate longer timeseries of streamflow records and catchment runoff.
- Investigate the expected impact of climate change on runoff using, for instance, the DELWP Climate Change Guidelines (DELWP, 2016).
- Generate a drought sequence, such as the Millennium Drought (which is largely missing from the available streamflow records).

These assessments could provide insights into drying characteristics in the swamp under different climatic conditions and provide an understand of the continued effectiveness of management scenarios.

5.3 Hydraulic modelling

The surface water flow paths in Big Swamp are complex with flow breaking out of the watercourses to form dynamic overland flow paths that lead to ponding and inundation across the swamp. To investigate and map the extent of surface water in Big Swamp a hydraulic model was developed. Given the nature of the inundation, TUFLOW, a fully 2D hydraulic modelling package, was adopted for this study. TUFLOW calculates the movement of water across a regular grid that represents the topography of the area being modelled.

The TUFLOW hydraulic model to calculate the extent, depth and level of surface water in Big Swamp for a variety of historic and future management flows. The model provides an understanding of the way water moves through the swamp, including an understanding of the inundation extent, levels and water depths. In addition, the hydraulic model has been built to be loosely coupled with the groundwater model, through the provision of a level timeseries to characterise head dependent boundary conditions included in the groundwater model. By way of feedback, the groundwater model is able to inform the loss parameters included in the surface water model.

The following sections provides details of the hydraulic modelling, including model schematisation, inputs and results.

5.3.1 Model conceptualisation

The model is required to simulate the surface water movement within Big Swamp and the conceptual representation of the major hydrologic features are shown in Figure 5-6. The physical extent of the model was designed to cover the entire area of the swamp as shown in Figure 5-7.

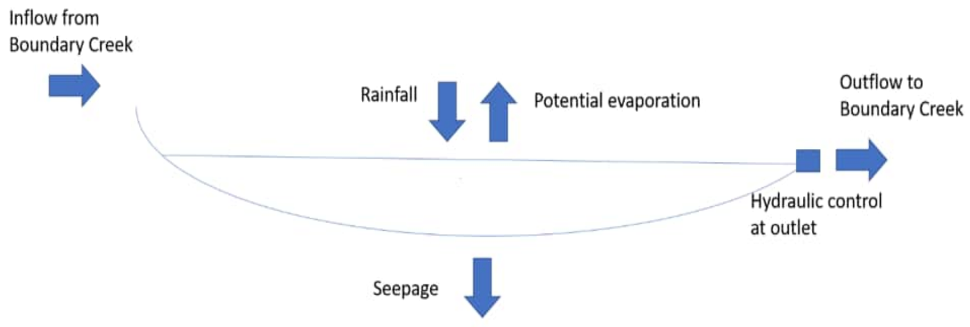

Figure 5-6: Conceptual model of the major hydrologic features included in the hydraulic model

Inflows to the model occur at the upstream boundary and through catchment runoff, while outflows occur at the downstream boundary and through losses to evapotranspiration and to groundwater. In addition to these, the TUFLOW model incorporates culverts and channels, used to modify the topography, to satisfy the conceptual understanding of the systems flow path. Each of these concepts are explored in further detail below.

The hydraulic model covers an area of approximately 1.3 km^2, extending from the streamflow gauge south of McDonalds Dam, 233229, to the gauge on Boundary Creek at Yeodene, 233228, which is adjacent to the intersection of Colac-Forest Road with Boundary Creek.

The topography of the area was represented by a Digital Elevation Model (DEM) developed from the LiDAR data.

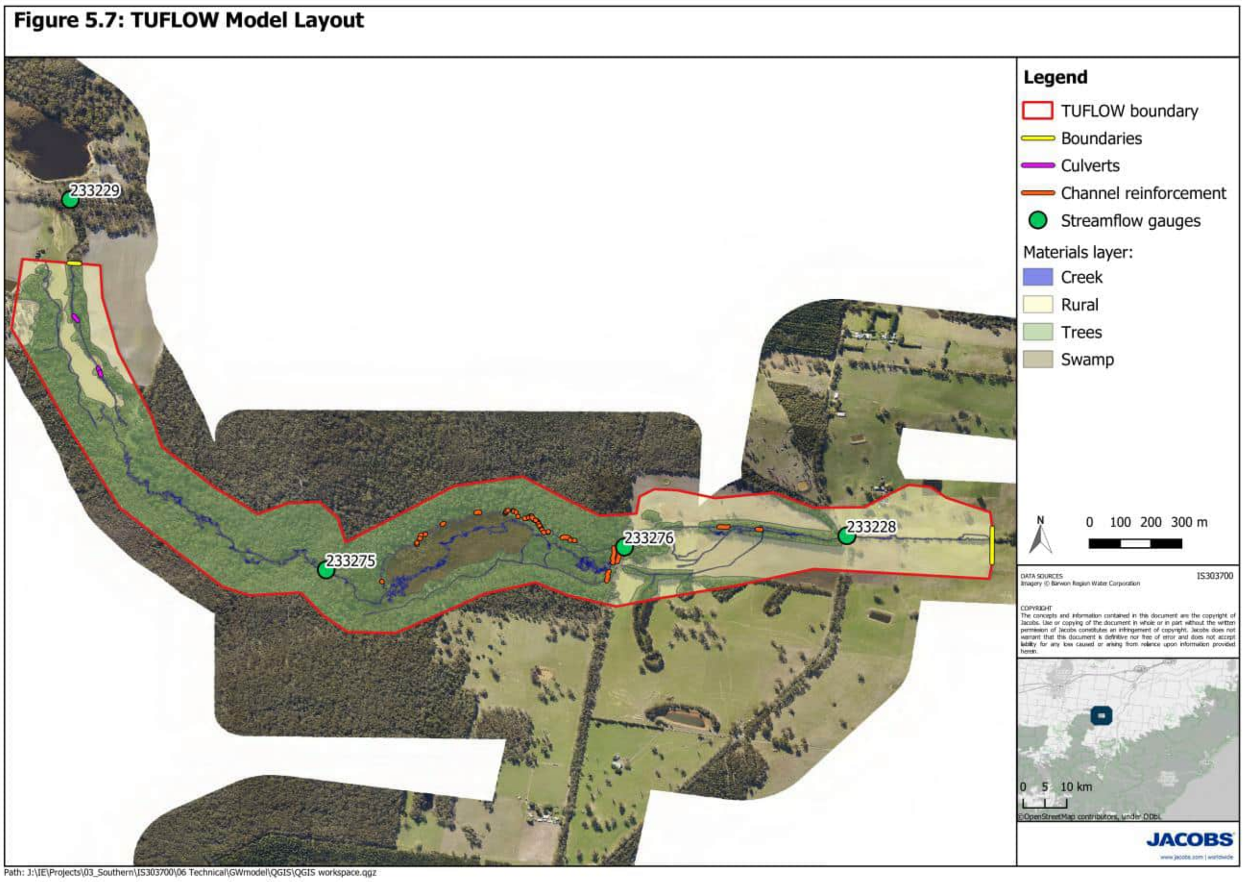

Figure 5-7: TUFLOW Model Layout

TUFLOW version 2018-03-AD-iSP-w64 was used for this assessment and was run using TUFLOW HPC computational scheme.

5.3.2 Topography

The topography of the model is based on the LiDAR data. The resolution of the DEM is an important part of the model that dictates its accuracy; however, model runtimes are directly proportional to the DEM resolution. To balance the model run times whilst still providing an accurate representation of the creek channels, a 2 m grid resolution was selected. Each square grid element contains information on ground topography and surface resistance to flow (Manning's n value) sampled from the DEM and aerial photography at 1 m spacing. This DEM is considered to be a high-resolution model.

The topography was modified in a number of cases to better represent actual ground levels and to reproduce observed flow. The following topography modifications were undertaken in order to force water to flow along known flow paths:

- TUFLOW terrain modifications for sections of Boundary Creek, especially along the Northern Channel
- TUFLOW terrain modifications for flow along the agricultural drain and fire trench where it meets with Boundary Creek

Figure 5-7 shows the locations of channels and culverts and terrain modifications to represent existing conditions over the study location.

5.3.3 Boundary conditions

Boundary conditions in the TUFLOW model add or remove water from the model, as illustrated in Figure 5-6 the following boundary conditions were incorporated into the model:

- Upstream inflow – An external inflow was applied to the TUFLOW model at the upstream boundary to represent flows in Boundary Creek. The location of this boundary is shown in Figure 5-7.
- Swamp catchment inflow – Flows generated from the catchment below the dam were applied to the model. These flows were applied as a flow timeseries and distributed along the channel.
- Downstream outlet – Flow at the downstream boundary was represented by a rating curve or discharge – level boundary. This downstream boundary is located sufficiently downstream of the Site (Figure 5-7), to minimise the influence of boundary assumptions on the flood model results.
- Loss or seepage to groundwater – The Green-Ampt infiltration losses were used to calculate the losses from the surface water. The Green-Ampt parameters were taken from the USDA soil types classification (Rawls, et al. 1983) for a 'Sandy Clay' type soil, presented in Table 5.2.
- Evapotranspiration / Rainfall – An internal rainfall boundary applies a rainfall and evapotranspiration depth to all active cells within the model domain, based on an input timeseries. For model calibration rainfall and evapotranspiration were both incorporated and applied to the model as a timeseries of effective rainfall.

Table 5.2: USDA soil types classification for Sandy Clay

USDA Soil Type	Suction (mm)	Hydraulic Conductivity (mm/hr)	Porosity (as a fraction)
Sandy Clay	239.0	0.6	0.321

5.3.4 Hydraulic structures

Three culvert structures were incorporated into the model upstream of Big Swamp, as shown in Figure 5-7. These culverts were included in the model as embedded 1D elements. The flow through the structures is assumed to be unimpeded by the presence of flood debris and therefore no blockage factors were applied to any structures. This assumption is not considered to impact results.

5.3.5 Manning's 'n' coefficients

The roughness layer, or Manning's 'n' layer, is based on areas of different land-use types, which were determined from aerial photography and site inspections. These land use types (referred to as 'materials') are presented in Figure 5-7 and the adopted coefficients are summarised in Table 5.3. The values used are based on the range of values provided in the Australian Rainfall and Runoff (ARR) (Ball et al., 2019).

Table 5.3: 2D domain Manning's 'n' Values

Land Use	Manning's 'n'
Creek	0.06
Urban	0.04
Trees	0.09
Swamp	0.10

5.3.6 Calibration

Given that the hydraulic model is to be coupled to the groundwater model it was necessary to have a common calibration period. Section 2 outlines the available streamflow data and the borehole data that is required to calibrate the groundwater model is limited to the period 12/06/2019 to 02/09/2019. The hydraulic model was calibrated for this period.

The gauge downstream of McDonalds Dam (233228) has recently been impacted by road and culvert works undertaken by Council. This resulted in the gauge being offline for a period of time and following re-instatement the site has required re-establishment of the stage-discharge relationship for monitoring of flow. Given the limited flow ranges experienced since reinstatement, the streamflow ratings have been confined to within banks flow and therefore flow above approximately 0.09 m^3/s (7.8 ML/day) has not been rated. For this reason, the available flow series monitoring is missing flow peaks above this range and therefore it was necessary to infill these gaps.

As the temporal resolution required for the hydraulic model is sub-daily it was not possible to use results of the rainfall runoff model which has a daily resolution. As a result, streamflow data for June to September 2019 was infilled through correlation with the upstream gauge at Barongarook. Flows at Barongarook were offset by 8.5 hours and increased by 22% to infill flows downstream of McDonalds Dam. This was based on a sample of 17 events which were analysed, and the mean differences calculated. Of the events analysed 13 had peak flows with a ratio of +/- 10% and 12 were within +/- 2 hours. This is considered to be of sufficient accuracy for the purposes of the modelling. Further, with these assumptions the model was able to calibrate to the downstream gauge. An example output of this infilling process is shown in Figure 5-8.

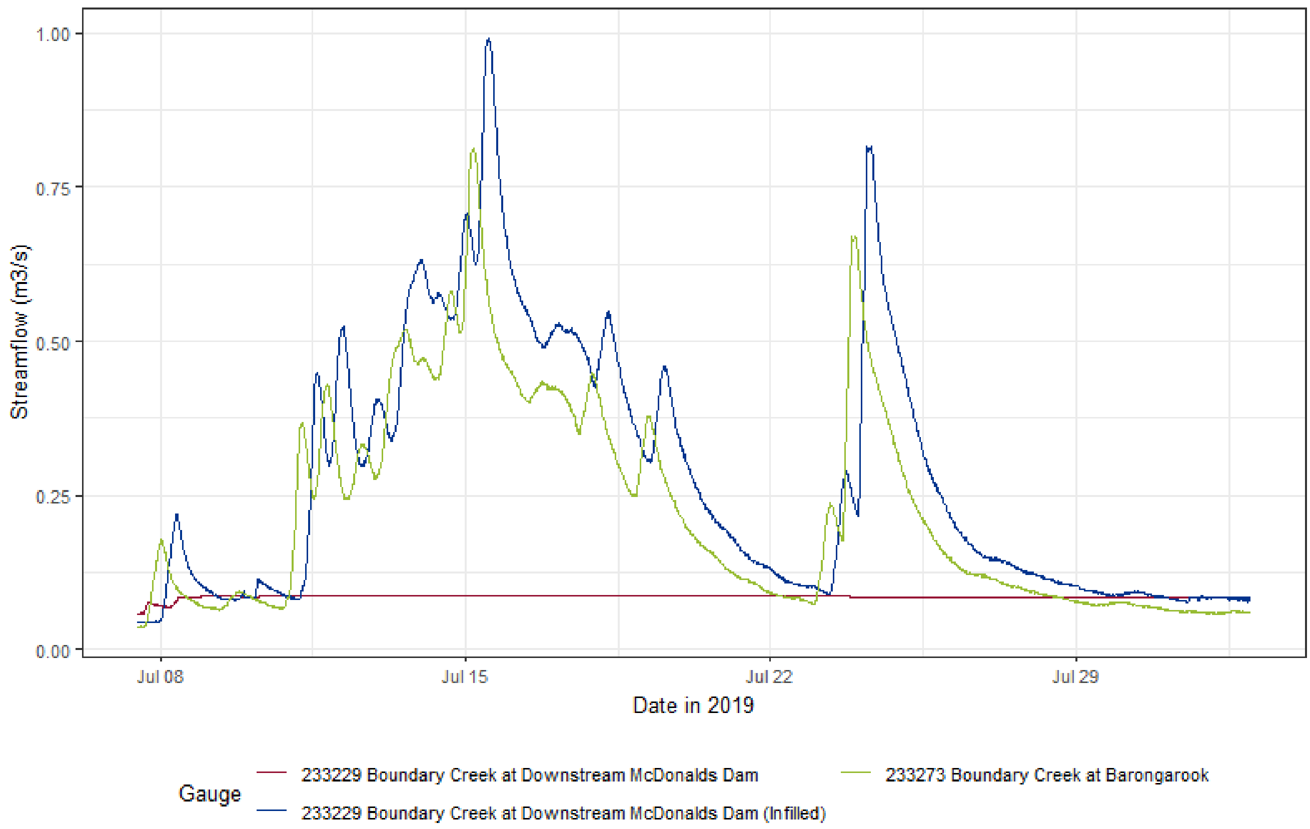

Figure 5-8: Infilling of streamflow at 233229 (Boundary Creek at downstream McDonalds Dam) through application of peak ratios with 233273 (Boundary Ck at Barongarook)

The results of calibration are presented in Figure 5-9, which shows a comparison of the observed and modelled flow at the four gauge locations within the hydraulic modelling domain (see Figure 5-7) and Figure 5-10 presents the maximum water level over the calibration record.

The results in Figure 5-9 represent an excellent fit to the data indicating that hydraulic model can appropriately predict the flow at the gauge locations. Note that for the Big Swamp gauges which had missing peaks in their records (233275A and 233276A), where there is data at these gauges for lower flows, there is a slight overestimate of discharge of around 2.5ML/s. The sensitivity of this tested by increasing losses from the surface water system and it was found that maximum water levels and extents did not significantly alter.

The calibration results at Yeodene (233228) are excellent across the full flow record indicating that the model provides an accurate simulation of flow during periods of low, peak and recession streamflow.

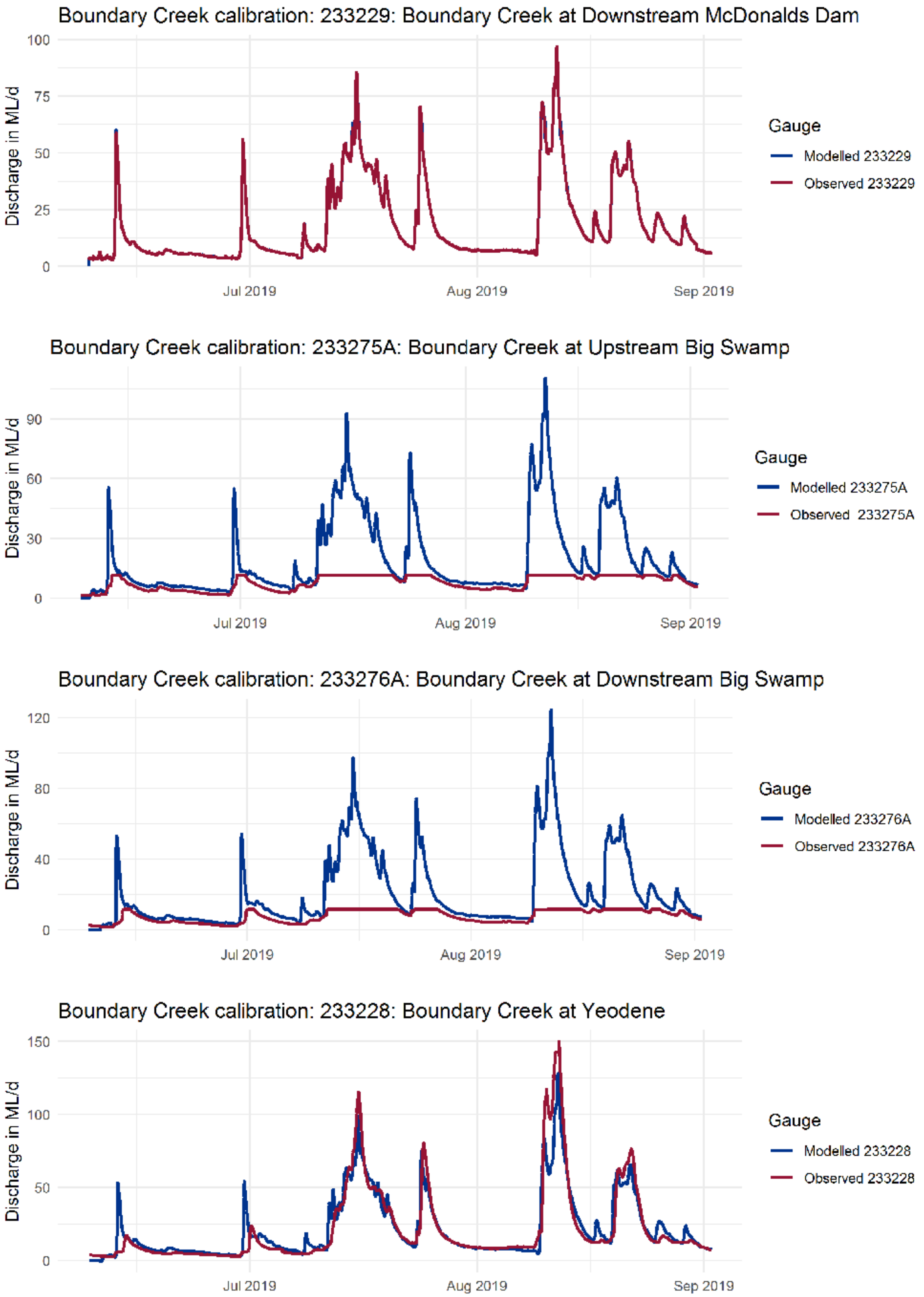

Figure 5-9: Calibration of the hydraulic model at the gauges in the modelling domain over the 2019 calibration period

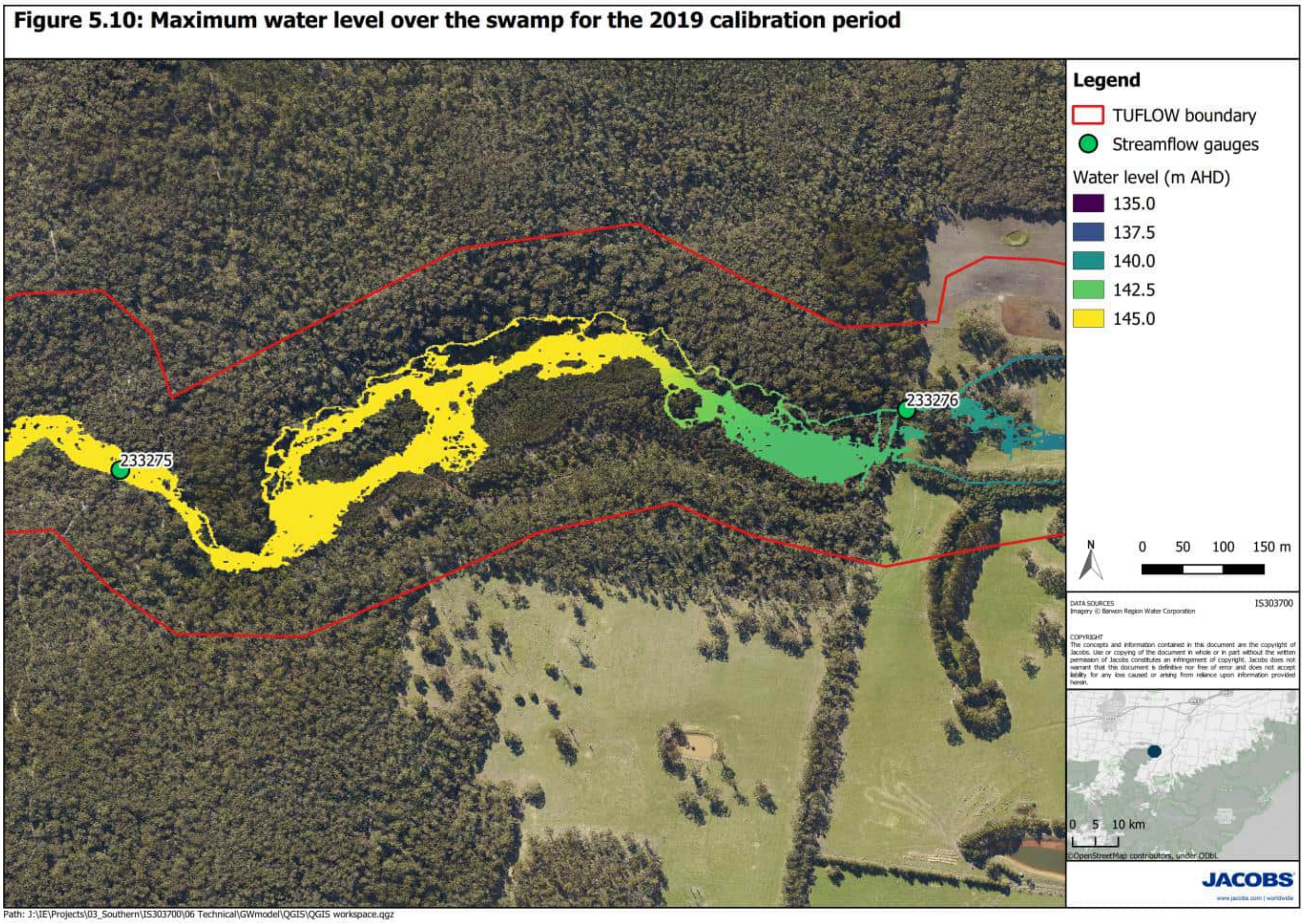

Figure 5-10: Maximum water level over the swamp for the 2019 calibration period

5.3.7 Discussion and recommendations

The hydraulic model is calibrated well to the available data, particularly at Yeodene gauge demonstrating its suitability to investigate future flow scenarios. While the model is well calibrated, there are a number of recommendations that would improve certainty in the results, in particular the interaction between surface water and groundwater, these are:

- As additional data becomes available it is recommended that the hydraulic model be calibrated or validated to additional events. This would increase confidence in the modelled outputs.
- The new streamflow ratings for the gauges upstream of the Yeodene gauge do not contain any high flow information due to limited high flow events to inform development of stage-discharge relationships and subsequent flow ratings. When this information becomes available the results of the hydraulic modelling should be compared to this information.
- The modelled hydraulic water levels should be compared to the borehole monitoring records where these have recorded water levels above the ground surface.
- Due to time limitations only one iteration between the hydraulic model and the groundwater model was possible and this has not allowed an update of the hydraulic model loss parameters (Green & Ampt) based on the groundwater model results. It is expected that further iteration with the groundwater model will improve loss estimates and potentially improve the low flow calibration in the swamp where modelled results were noted to be slightly higher than the recorded flows.
- The results from the hydraulic model are used to inform future data collection programs to demonstrate the effectiveness of any management plan. This additional data will also increase the understanding of the system and can be used to improve the numerical models.

6. Surface water scenario modelling

Six scenarios have been developed for the coupled surface water groundwater model to investigate a variety of management options. These scenarios were designed to replicate conditions under low and high flow over short periods of time (6 months) and a longer term scenario with typical average flows. All scenarios were run with and without a hydraulic barrier at the eastern end of the swamp to determine the influence of the barrier on inundation areas and groundwater levels.

These scenarios have been designed to increase the area inundated in the swamp and to raise groundwater levels. This section presents the surface water results for these scenarios as well as for additional scenarios that assume flows that are intermediate between the maximum and minimum flow releases.

All scenarios assume dry conditions with creek flow entirely supported by supplementary flow released immediately downstream of the dam. That is, they represent worst case conditions for flow in the creek and swamp. The scenarios have been designed to include an upper (20 ML/d) and lower estimate (2 ML/d) of the supplementary flow that may be required and hence provide limits within which results can be interpolated for intermediate rates of supplementary flow.

The additional intermediate scenarios have been completed to allow interpolation of results between the 2 ML/d and 20 ML/d extremes of flow releases.

Scenarios 5 and 6 are transient groundwater model scenarios run over a ten-year period using a repeating sequence of assumed monthly flows where the boundary conditions for the creek are obtained from the Scenario and Intermediate runs as described below. In this instance, Scenarios 5 and 6 were not run explicitly through the hydraulic model as the model runtime would have been infeasible (more than 2 months for 10 years of model time).

A consistent set of definitions for the scenarios has been determined as outlined below, together with the intermediate scenarios:

- **Scenario 1** assumes a constant release of 2 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with no hydraulic barrier.
- **Scenario 2** assumes a constant release of 2 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with a hydraulic barrier.
- **Intermediate 1** assumes a constant release of 5 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with no hydraulic barrier.
- **Intermediate 2** assumes a constant release of 5 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with a hydraulic barrier.
- **Intermediate 3** assumes a constant release of 10 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with no hydraulic barrier.
- **Intermediate 4** assumes a constant release of 10 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with a hydraulic barrier.
- **Scenario 3** assumes a constant release of 20 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with no hydraulic barrier.
- **Scenario 4** assumes a constant release of 20 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with a hydraulic barrier
- **Scenario 5** is a ten year **transient** simulation that assumes an annual cycle of flows with no hydraulic barrier. This was not assessed through a single surface water model run.
- **Scenario 6** is a ten year **transient** simulation that assumes an annual cycle of flows with a hydraulic barrier. This was not assessed through a single surface water model run.

6.1 Surface water scenario model set up

A constant supplementary flow corresponding to each scenario was applied as a steady state release to Boundary Creek with no other inflow. In all other respects the hydraulic model was setup as for the calibration run for the supplementary flow scenarios with no hydraulic barrier.

For the hydraulic barrier scenarios, a levee was applied to the downstream end of the swamp and the height of the levee was set at a level of 142.5 m AHD as shown in Figure 6-1. Over the cross-section depicted in Figure 6-1, the maximum height of the levee above the surface was 1.3m, with a typical height of 0.5m. The location of the barrier is shown in Figure 6-4

Figure 6-4. This barrier blocked the ‘agricultural drain’ and ‘fire trench’ flow paths forcing water to pond upstream of the barrier. Eventually, the water would pond to a height that would discharge to the northern channel.

6.2 Scenario results

Figure 6-4 to Figure 6-11 present the modelled extent and level of inundation across the swamp under each scenario. An increase in the volume released from McDonalds Dam from 2 ML/d to 5 ML/d causes the flow path to split and move towards the centre of Big Swamp. Further increases up to a release of 20 ML/d simply causes a buffering effect of the area inundated. Furthermore, the inclusion of the hydraulic barrier shows little effect on the extent and depth of the inundation when the flow rate is increased from 2 ML/d.

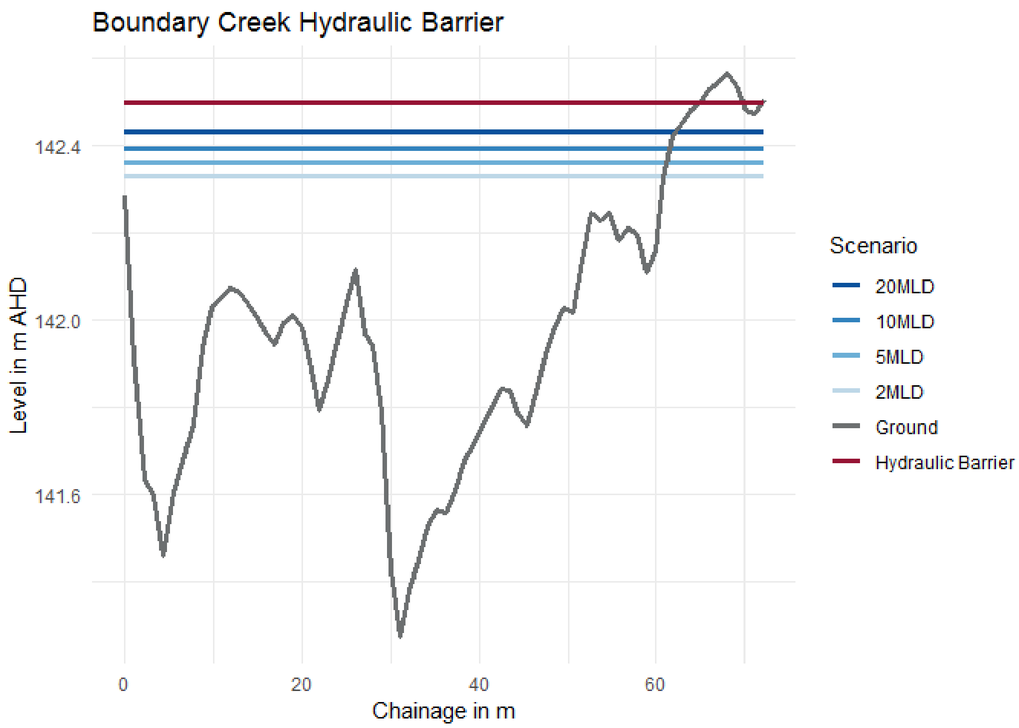

Figure 6-1: Peak water levels immediately adjacent to the hydraulic barrier for various scenarios

Figure 6-2 presents a timeseries of the modelled flow rate at the Yeodene gauge for each scenario. As expected, the system reaches steady state conditions more rapidly under the higher flow rate scenarios. The Scenario 1 (2 ML/d supplementary flow) results in a steady state flow of 1.1 ML/d at the Yeodene gauge. When the hydraulic barrier is incorporated (Scenario 2) a flow rate of 0.9 ML/d is achieved compared to the 1 ML/d requirement at this gauge. For both the 20 ML/d scenarios (Scenario 3 and Scenario 4) a steady state flow of 3.7 ML/d at Yeodene was calculated.

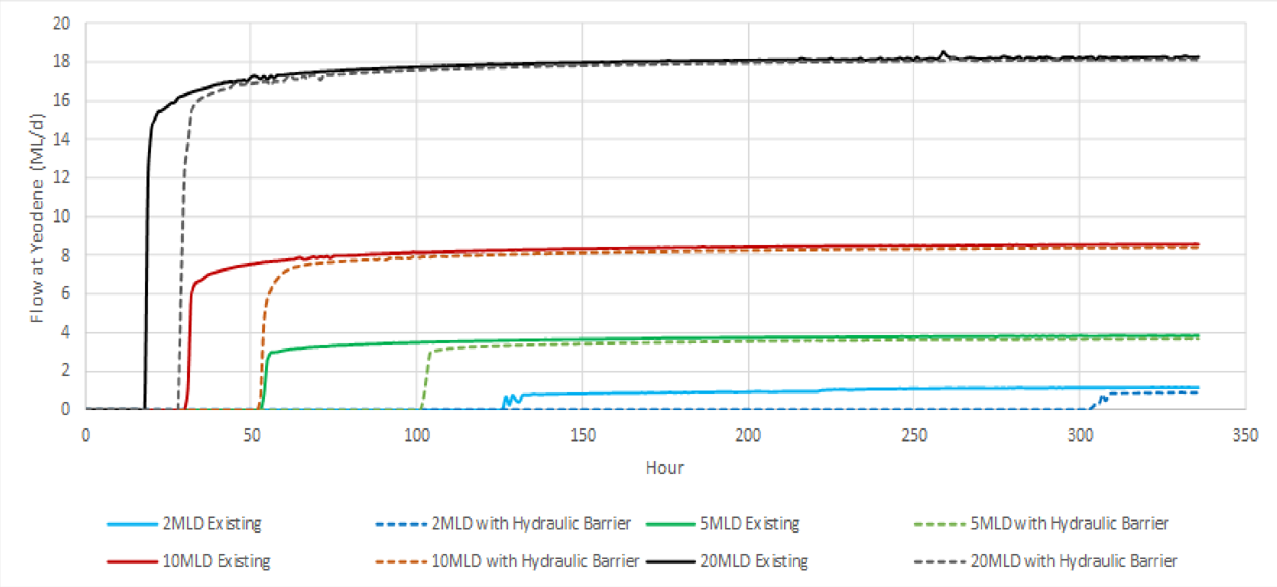

Figure 6-2: TUFLOW modelled flow under each scenario at the streamflow gauge 233228, Boundary Creek at Yeodene

For each scenario the volume of infiltration over the swamp under steady state conditions was derived, with the results presented in Figure 6-3. In order to derive this volume from the infiltration rate results at the final timestep which was at steady state (see Figure 6-2). This was calculated for the area of inundation over the swamp, which was defined as being bounded by the streamflow gauges 233275A and 233276A.

Figure 6-3 shows that an increase in the magnitude of supplementary flow results in an increased loss in Big Swamp. Similarly, the inclusion of the hydraulic barrier also increases the volume lost to infiltration (ie groundwater).

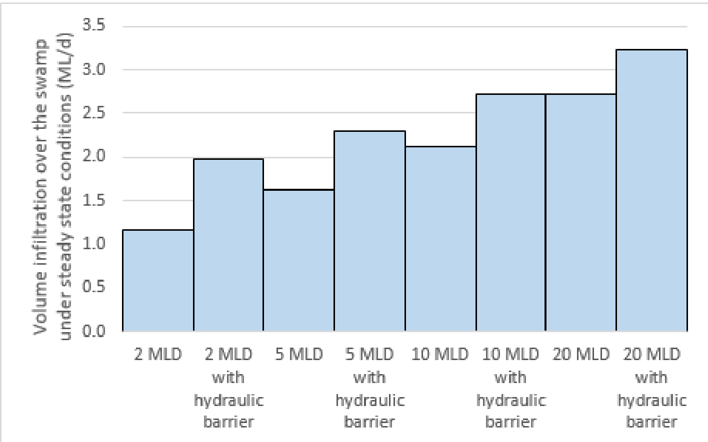

Figure 6-3: Volume of infiltration (ML/d) over the swamp under steady state conditions for each modelled scenario

The area of inundation over Big Swamp under each scenario is presented in Table 6.1 with the water levels immediately adjacent to the hydraulic barrier presented in Figure 6-1. These results show that the area of inundation in the swamp and depth adjacent to the barrier increases with an increased upstream flow rate and increases with the presence of the hydraulic barrier. Although the additional area of inundation due to the hydraulic barrier is diminished with higher supplementary flows. This is due to the relatively minor increases in inundation extent immediately behind the hydraulic barrier as illustrated in Figure 6-5, Figure 6-7, Figure 6-9 and Figure 6-11. Any increased inundation is due to the introduction of new flow paths upstream of the pool caused by the hydraulic barrier.

Table 6.1: Area of inundation over the swamp for each scenario

Flow released from McDonalds Dam (ML/d)	Area of inundation under existing model structure (m^2)		Area of inundation with the inclusion of the hydraulic barrier (m^2)	
	m^2	%	m^2	%
2 ML/d	17,800	8.5	27,500	13.0
5 ML/d	25,100	11.9	34,100	16.2
10 ML/d	33,300	15.8	41,100	19.5
20 ML/d	41,700	19.8	48,500	23.0

6.3 Discussion

The hydraulic model has been used to investigate the effectiveness of a number of scenarios designed to increase both, the surface water inundation and groundwater levels in the swamp as required to manage the production of and export of acidic water from the swamp. The effectiveness of the scenarios in increasing groundwater levels is discussed in Section 8 and a discussion of the surface water results is provided below. The hydraulic modelling has demonstrated the following:

- The introduction of supplementary flow inundates the swamp. The 2ML/d does not increase the extent of inundation beyond what is typically experienced in late winter early spring. The supplementary flow becomes more effective with increasing flow, for instance a supplementary flow of 5 ML/d results in an increase in inundation extent of 40% over the 2 ML/d supplementary flow. A supplementary flow of 10 ML/d results in an increase in inundation extent of 85% and a supplementary flow of 20 ML/d results in an increase in inundation extent of 130% compared to the 2 ML/d supplementary flow.
- The hydraulic barrier at the downstream end of the swamp was found to be effective in increasing the aerial extent of inundation compared to scenarios that simulate supplementary flows on their own. However, there are diminishing returns in terms of the area inundated with increased supplementary flows. This is due to the topographic properties of the pool immediately upstream of the hydraulic barrier. Comparing Figure 6-5, Figure 6-7, Figure 6-9 and Figure 6-11 and the results in Table 6.1, it can be seen that the extent of the pool does not significantly increase with increased flow. These results indicate that there is limited benefit in doubling the supplementary flow from 10 ML/d to 20 ML/d with the hydraulic barrier located at the end of the swamp.

While the results presented here demonstrate that the scenarios would be effective in achieving the management aims, there would be more benefit in installing multiple hydraulic barriers distributed through the swamp to increase the extent of the inundation. To maximise the benefit of additional hydraulic barriers the locations should be selected to inundate areas of potential acidity where the topography allows. This is further discussed in Section 9.

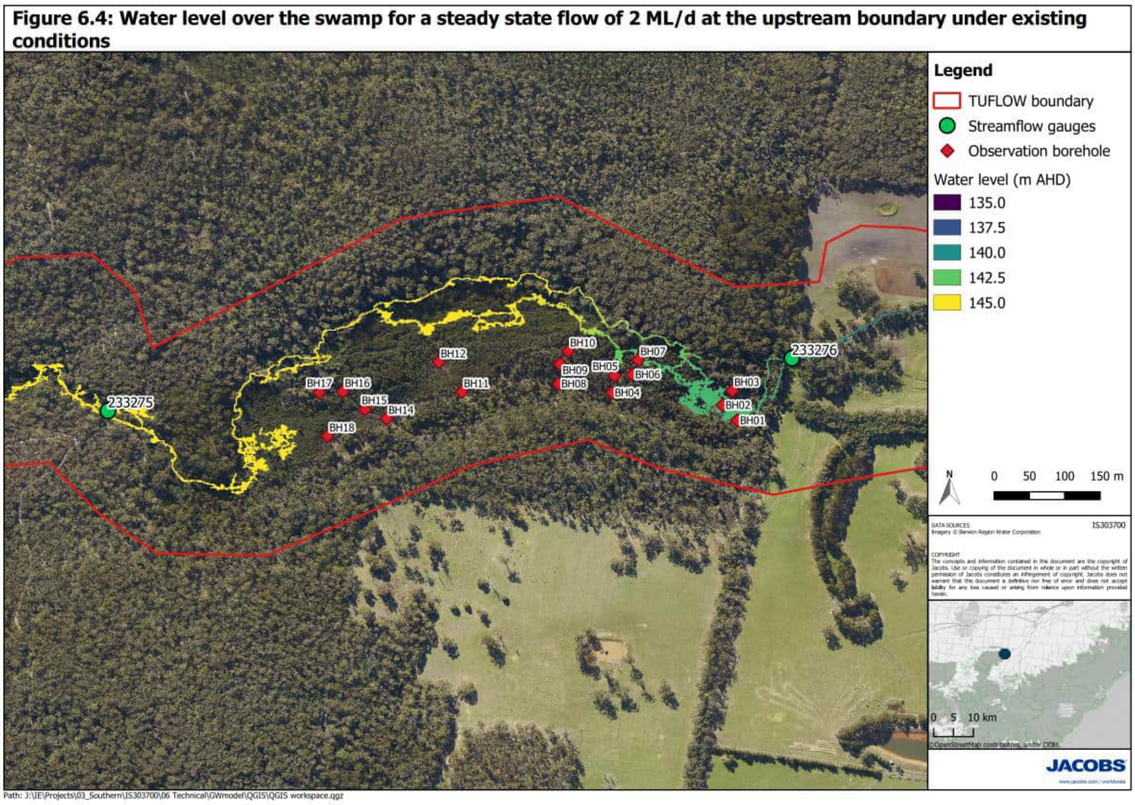

Figure 6-4: Water level over the swamp for a steady state flow of 2 ML/d at the upstream boundary under existing conditions

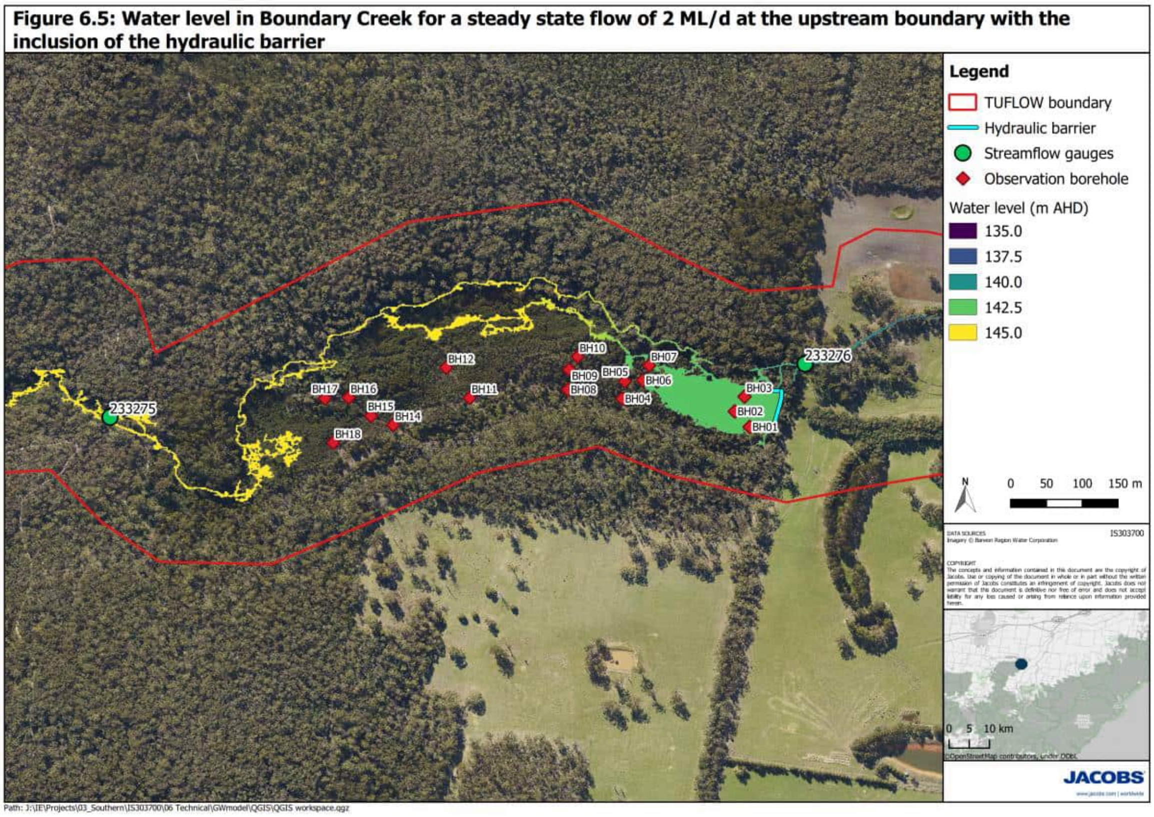

Figure 6-5: Water level in Boundary Creek for a steady state flow of 2 ML/d at the upstream boundary with the inclusion of the hydraulic barrier

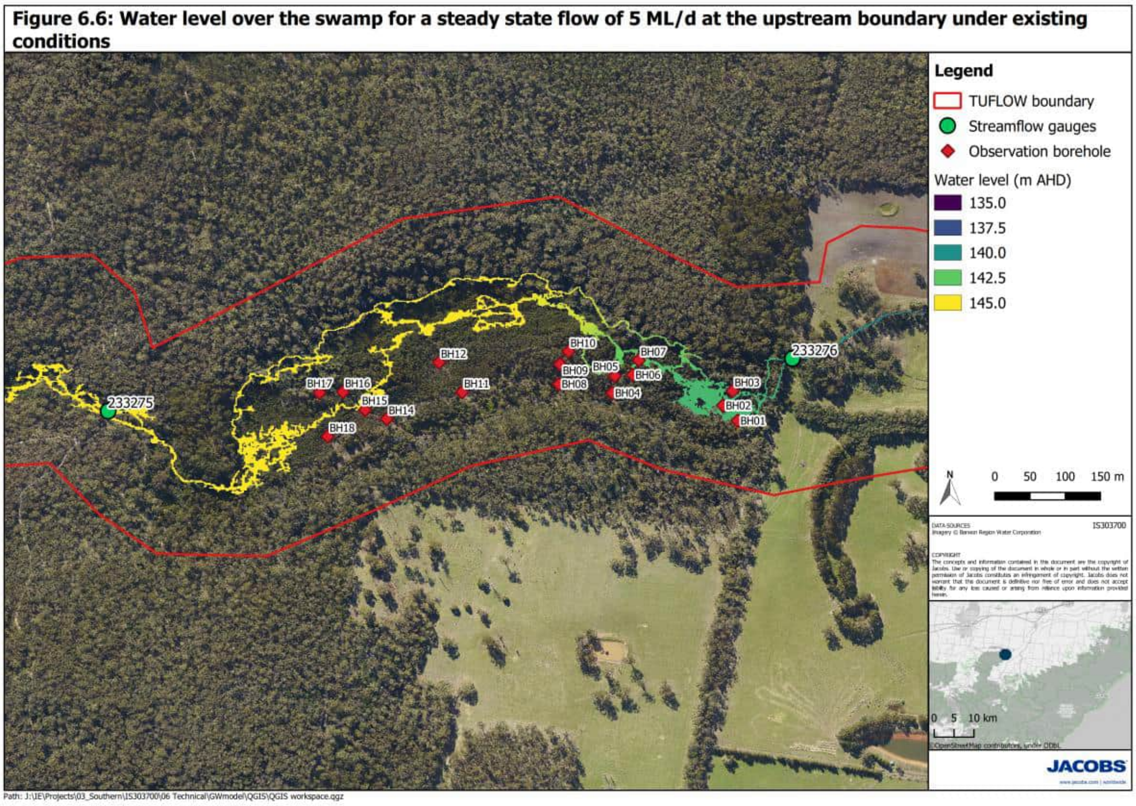

Figure 6-6: Water level over the swamp for a steady state flow of 5 ML/d at the upstream boundary under existing conditions

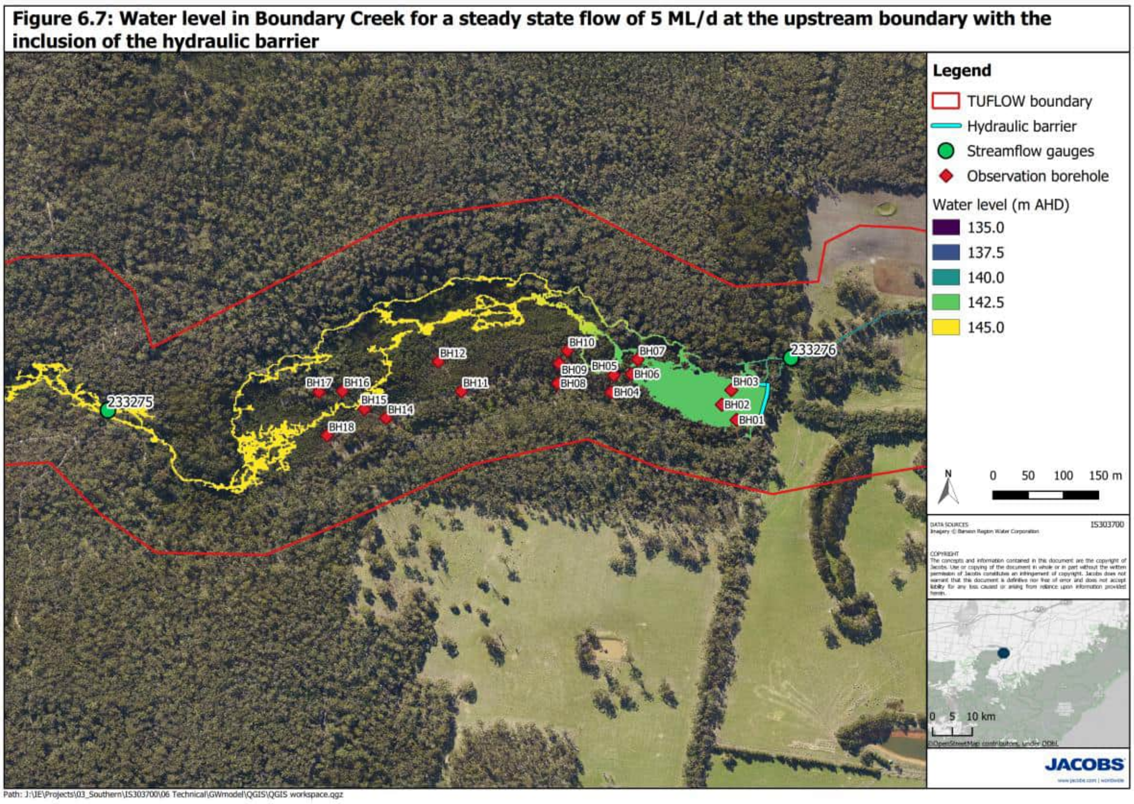

Figure 6-7: Water level in Boundary Creek for a steady state flow of 5 ML/d at the upstream boundary with the inclusion of the hydraulic barrier

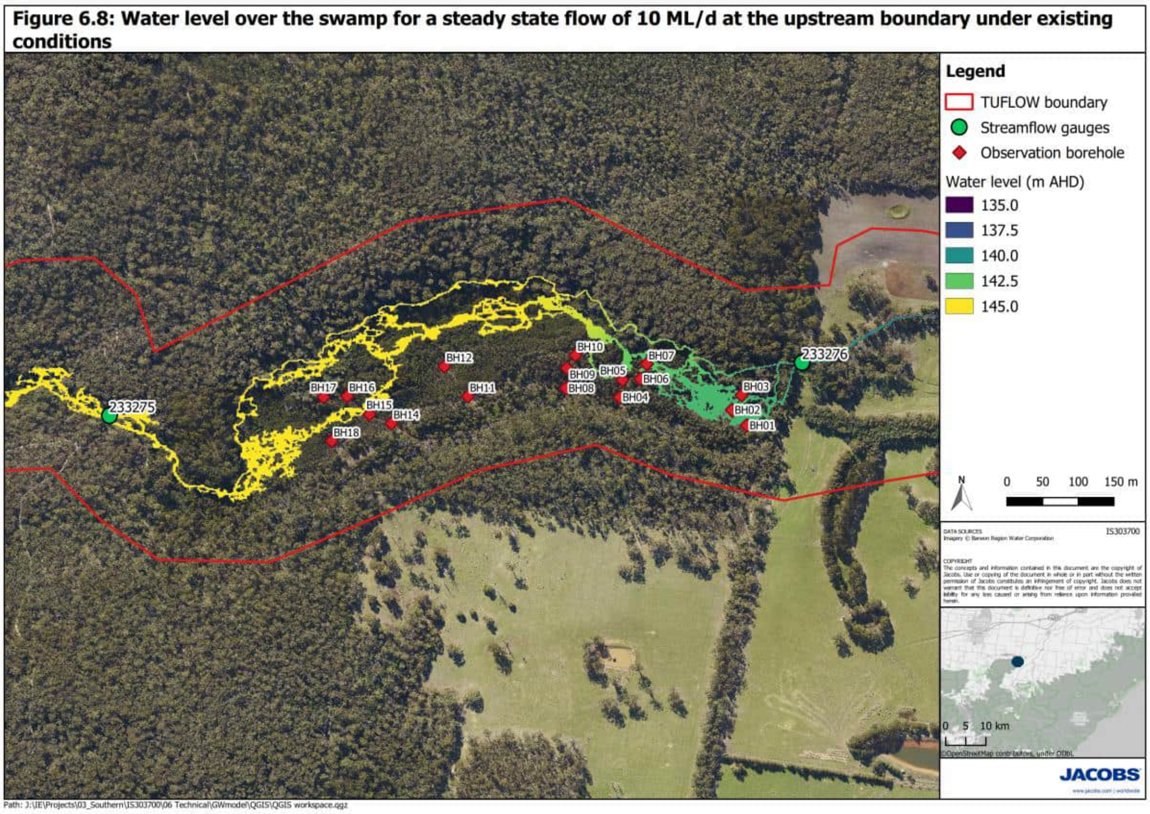

Figure 6-8: Water level over the swamp for a steady state flow of 10 ML/d at the upstream boundary under existing conditions

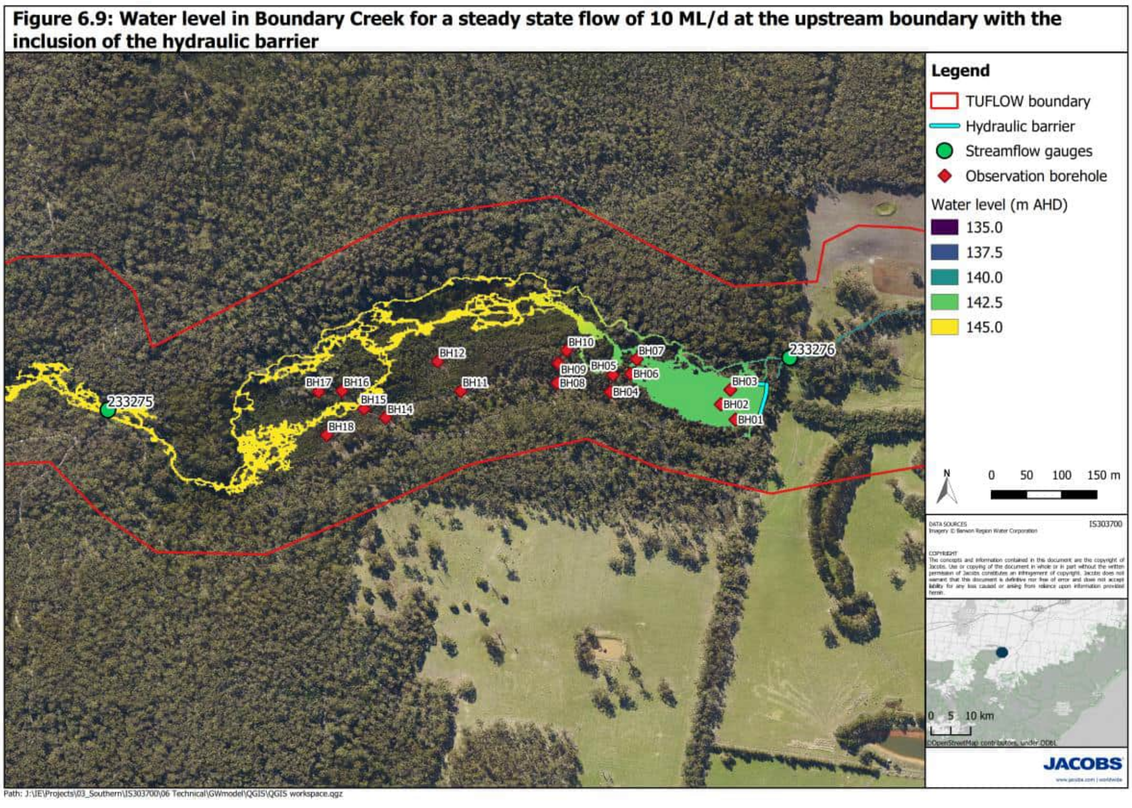

Figure 6-9: Water level in Boundary Creek for a steady state flow of 10 ML/d at the upstream boundary with the inclusion of the hydraulic barrier

Figure 6.10: Water level over the swamp for a steady state flow of 20 ML/d at the upstream boundary under existing conditions

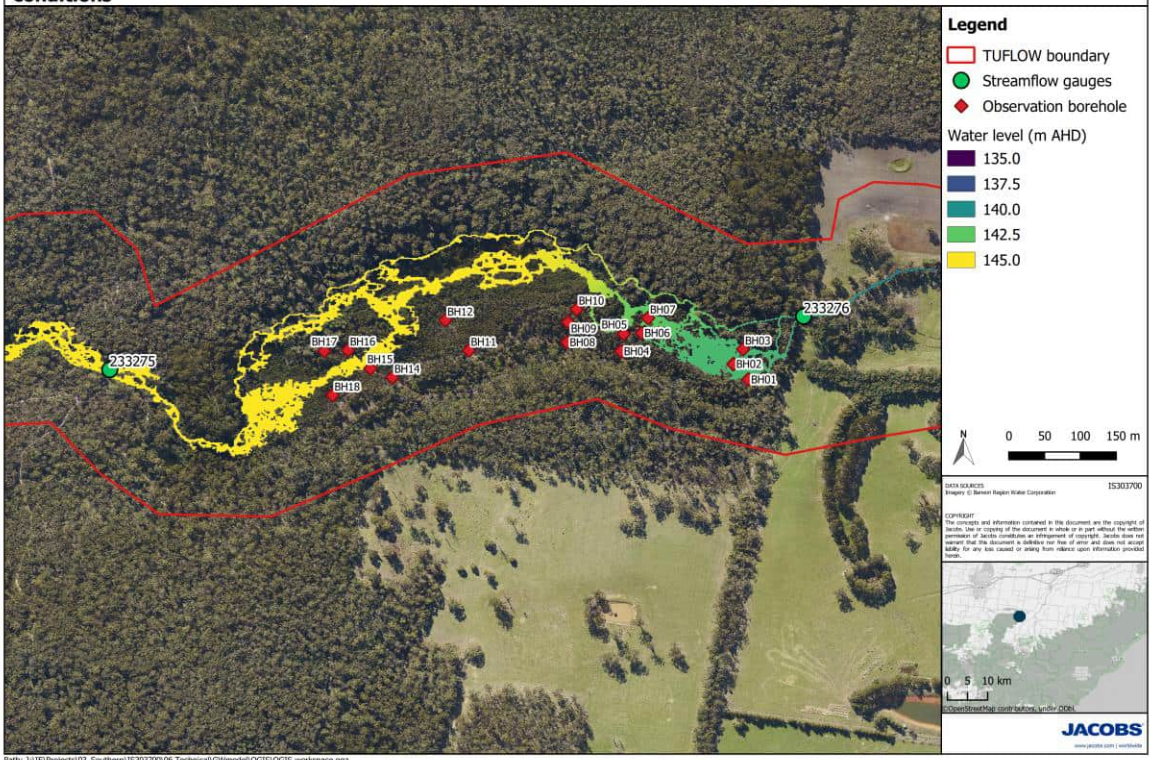

Figure 6-10: Water level over the swamp for a steady state flow of 20 ML/d at the upstream boundary under existing conditions

Figure 6.11: Water level in Boundary Creek for a steady state flow of 20 ML/d at the upstream boundary with the inclusion of the hydraulic barrier

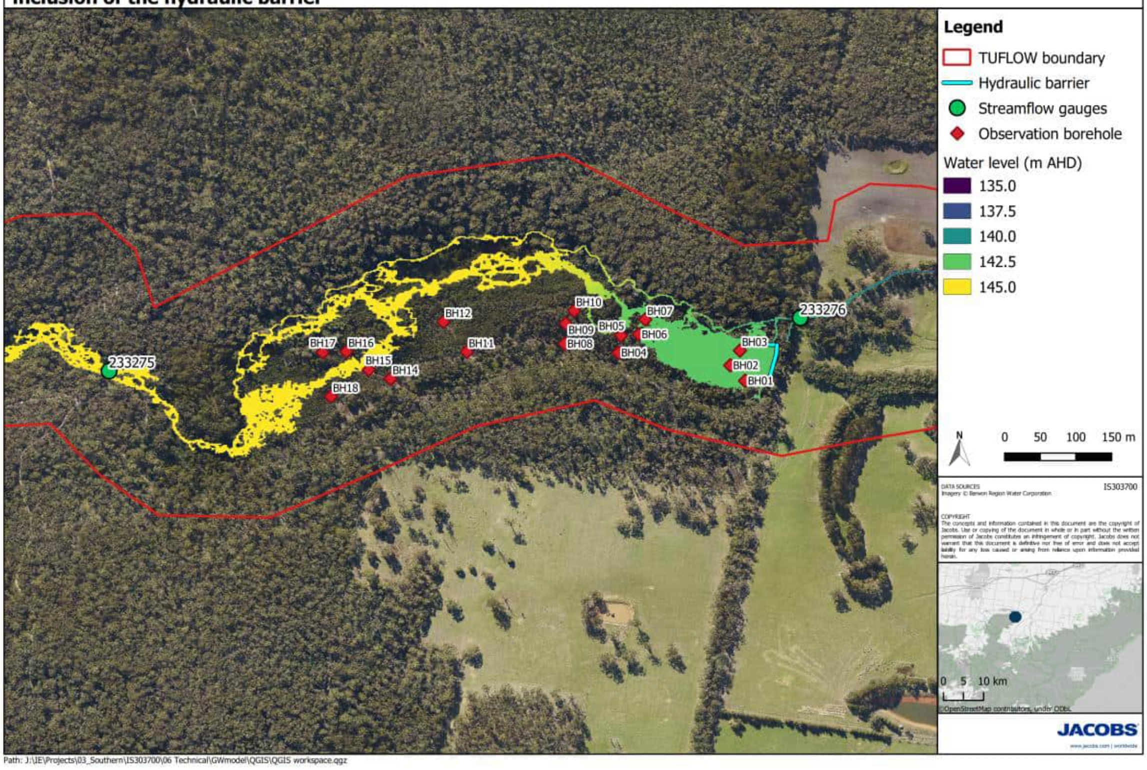

Figure 6-11: Water level in Boundary Creek for a steady state flow of 20 ML/d at the upstream boundary with the inclusion of the hydraulic barrier

7. Groundwater model

7.1 Objectives

A groundwater model has been developed to:

- Assess the potential changes in watertable elevation in the swamp that will arise from future changes in the flow through Boundary Creek including those associated with supplementary flow schemes,
- Estimate the exchange fluxes with Boundary Creek to help calibrate surface water hydraulic models of Boundary Creek,
- Assess the potential changes in groundwater heads in the swamp that may occur as a result of the construction of a hydraulic barrier at the downstream edge of the swamp (see Figure 6-5).

7.2 Confidence level classification

During discussions held as part of the project inception meeting it was agreed that the amount of data available for the development of a groundwater model would likely preclude the development of a high confidence level model. As a result, and in line with the modelling objectives, it was agreed that a Class 2 (on a scale of 1 to 3) Confidence Level Classification (Barnett *et al*, 2012) is an appropriate and realistic target for the model. While a greater level of confidence in the model is desirable and is warranted by the significance of the problem being modelled, the target level of a moderate confidence level model (Class 2) is the best that can be achieved with the available data on which the groundwater system can be conceptualised and the model calibrated.

7.3 Software code

The FEFLOW finite element modelling code has been adopted for this project. The finite element formulation allows for an efficient spatial discretisation that includes a fine mesh of calculation nodes at points of interest and a coarser mesh of nodes in areas where spatial detail is not required. FEFLOW is a widely used modelling code that is able to simulate groundwater flow in the saturated and unsaturated zones around ephemeral stream systems and includes a number of options for representing groundwater interaction with surface water and is therefore considered ideal for this project.

7.4 Model domain and spatial discretisation

The model domain covers an area of about 4 km by 4 km, centred on Boundary Creek and including Big Swamp. The mesh is refined around the creek where node spacing is set at 4 m to match every second calculation node in the surface inundation model. With a node spacing of 2 m, to match the surface inundation model calculation nodes, resulted in unacceptable model run times. Increasing the nodal spacing to 4 m has no measurable impact on the accuracy of the data transfer between the models. Element size (nodal spacing) increases to about 60 m away from the creek and swamp. The model domain and calculation mesh are shown in Figure 7-1.

7.5 Model layers and aquifer units

The model layer structure is based on the hydrostratigraphy included in the existing regional scale numerical model and is summarised in Table 7-1. The ground surface is derived from a high resolution Digital Elevation Model (DEM) as used for flood hydraulic modelling. The top model layer is one metre thick and is included to provide representation of the creek bed across the full extent of inundation under flooding. The hydraulic conductivity of the creek bed sediments can be used to regulate the surface water exchange fluxes if necessary.

Where present, the alluvial sediments are represented by layers of 1 and 2 m thickness (Layers 1 and 2 are 1 m thick and layers 3 to 6 are 2 m thick) that provide the fine vertical resolution required to model the unsaturated zone that forms near ground surface. These thin layers (Layers 1 to 6) are draped across the full model domain and where the alluvial sediments are absent they represent the upper 10 m of the outcropping geological unit as shown in Figure 7-1. Deeper model layers are designed to provide equitable subdivision of the thicker regional hydrogeological units as represented in the regional groundwater model i.e., the Lower Tertiary Aquifer, the Mid-Tertiary Aquitard (Gellibrand Marl) and the Basement. The base of the model has been set at the base of the Lower Tertiary Aquifer or at 0 mAHD where the Lower Tertiary Aquifer plunges below this elevation.

The model layer structure can be seen in Figure 7-2 and Figure 7-3 and is summarised in Table 7-1.

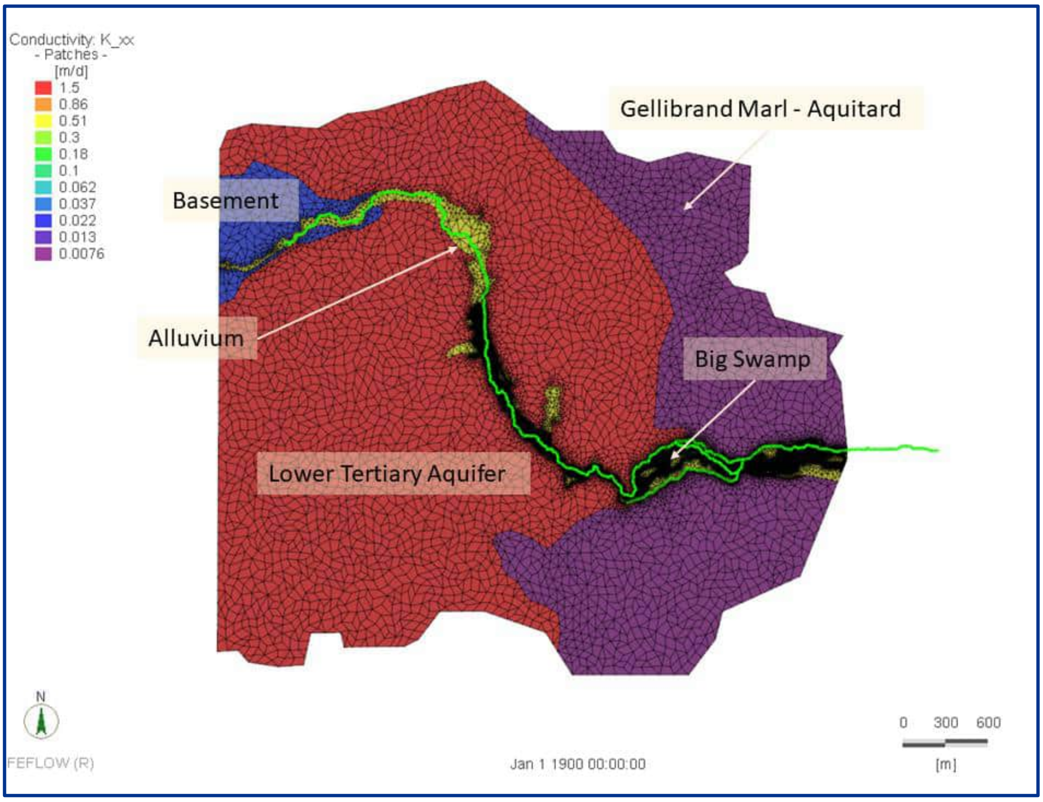

Figure 7-1 Model domain, calculation mesh and hydraulic conductivity of outcropping units

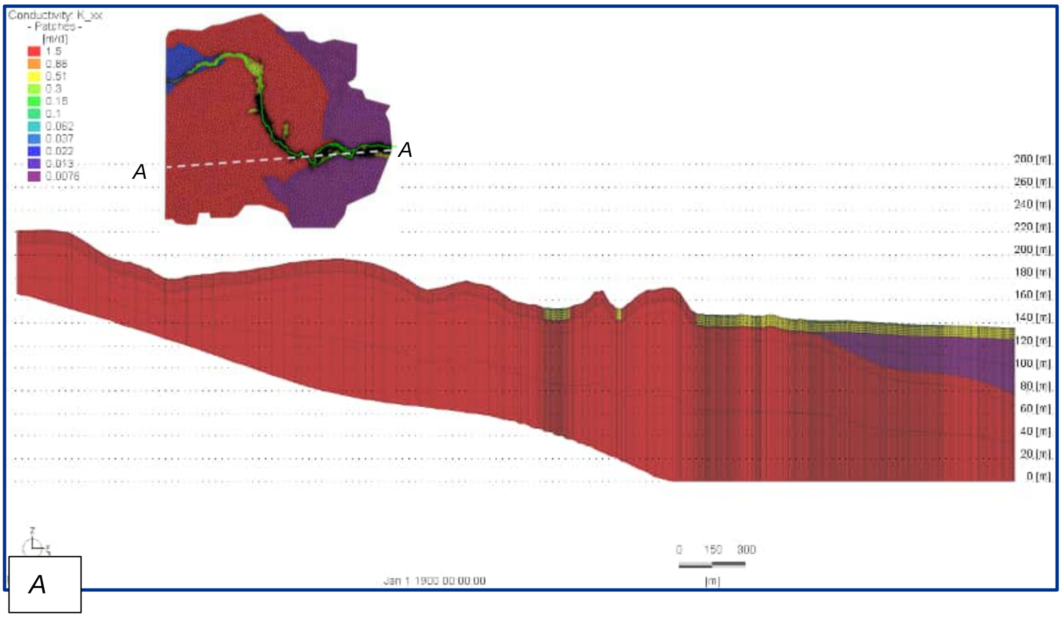

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Figure 7-2 East – West Cross Section of the model showing hydraulic conductivity and model layers

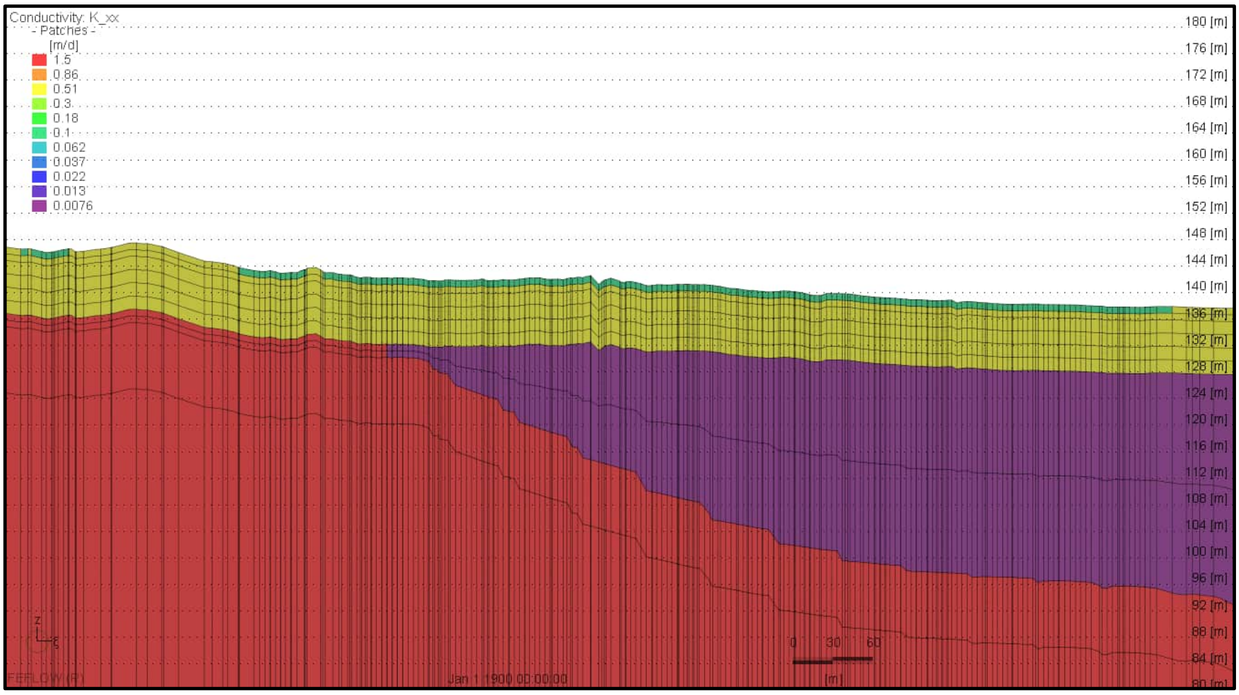


Figure 7-3 Magnified view of East – West Cross Section showing detailed layer structure.

Table 7-1: Model layer structure

Layer	Units*	Thickness
1, 2	River bed and alluvium#	1 m thick layers. River bed sediments in Layer 1 only
3 - 6	Alluvium#	2 m thick layers aimed at providing fine vertical resolution in Alluvial sediments.
7, 8	Mid-Tertiary Aquitard	Layers of equal thickness that subdivide the Marl
9	Lower Tertiary Aquifer	10 m thick layer at top of LTA
10, 11	Lower Tertiary Aquifer	Layers of equal thickness that subdivide the lower part of the LTA

** Basement is present in all layers within the area where it outcrops.*

 # Where alluvium is not present these layers represent the upper 10 m of the outcropping unit

7.6 Hydrogeological properties

The hydrogeological properties assigned to the model were adjusted during model calibration. Initial estimates and ranges for each parameter are presented in Table 7.2. The PARNMME column in the table is the parameter naming convention used in the PEST automated calibration. Parameter ranges and initial estimates were obtained from the existing regional scale groundwater model and from the conceptual understanding of the alluvium within the swamp.

Table 7.2: Initial estimates of aquifer parameters

Description	Units	PARNME	Lower Bound	Upper bound	Initial Value
Alluvium Horizontal Hydraulic Conductivity	m/d	kxy_1	4.00E-02	2.00E+00	4.00E-01
MTA Horizontal Hydraulic Conductivity	m/d	kxy_2	8.64E-04	8.64E-02	8.64E-03

Description	Units	PARNME	Lower Bound	Upper bound	Initial Value
LTA Horizontal Hydraulic Conductivity	m/d	kxy_3	1.00E-02	1.50E+01	1.00E+00
Bedrock Horizontal Hydraulic Conductivity	m/d	kxy_4	1.00E-03	1.00E-01	2.00E-02
Alluvium Vertical Hydraulic Conductivity	m/d	kv_1	4.00E-03	2.00E-01	4.00E-02
MTA Vertical Hydraulic Conductivity	m/d	kv_2	8.64E-06	8.64E-04	8.64E-05
LTA Vertical Hydraulic Conductivity	m/d	kv_3	1.00E-03	1.50E+00	1.00E-01
Bedrock Vertical Hydraulic Conductivity	m/d	kv_4	2.00E-04	2.00E-02	2.00E-03
River Bed Hydraulic Conductivity	m/d	k_5	4.00E-03	2.00E-01	4.00E-02
Alluvium porosity		po_1	0.05	0.25	0.10
MTA porosity		po_2	0.01	0.2	0.05
LTA porosity		po_3	0.01	0.3	0.05
Bedrock porosity		po_4	0.01	0.1	0.05

7.7 Boundary conditions

The Feflow Type 3 Transfer Boundary Condition was assigned along the model edges in Layers 9, 10 and 11 that represent the Lower Tertiary Aquifer. The heads assigned to the boundary were obtained from the regional groundwater model from a time in mid 2018. In this manner the groundwater model heads are tuned to match those of the regional model in the Lower Tertiary Aquifer.

7.8 Rainfall recharge

Rainfall recharge was applied to the top layer across the whole model domain through the Feflow *"In/outflow on top/bottom"* material property. Recharge rates are applied in zones that correspond to the outcropping geological unit. Initial estimates and ranges assigned to PEST are defined in Table 7.3.

Table 7.3: Initial estimates and range of recharge assessed during calibration.

Description	Units	PARNME	Lower Bound	Upper bound	Initial Value
Alluvium Recharge	m/a	rc_1	1.00E-02	1.00E-01	5.00E-02
MTA Recharge	m/a	rc_2	1.00E-03	5.00E-02	1.00E-02
LTA Recharge	m/a	rc_3	1.00E-02	0.1	5.00E-02
Bedrock Recharge	m/a	rc_4	1.00E-03	5.00E-02	1.00E-02

7.9 Boundary Creek interactions

The Feflow Type 1 (Constant Head) Boundary Condition was used to simulate groundwater interaction with Boundary Creek and McDonalds Dam. The boundary condition implementation requires the definition of heads (either constant or variable with time) at each node within the river and dam. As noted, the model is being run in conjunction with a surface water hydraulic model that predicts the wetted area (flow channels) and river stage for Boundary Creek under any given flow condition. The approach adopted for this investigation is to run the hydraulic model to generate appropriate predictions of wetted area and river stage (water level) across Boundary Creek and the swamp and transfer this information to the groundwater model to inform the boundary condition used to simulate the interactions between groundwater and surface water (refer to Section 5.3).

To facilitate the exchange of data from the inundation model, the groundwater model mesh was constructed with calculation nodes on a 4 m square grid throughout the maximum wetted area for the Creek and Swamp as estimated by the inundation model. Each of the Feflow river exchange nodes aligns with a calculation node used in the inundation model thereby facilitating the direct transfer of data between the two models. The arrangement of Feflow calculation nodes in part of the swamp is presented in Figure 7-4.

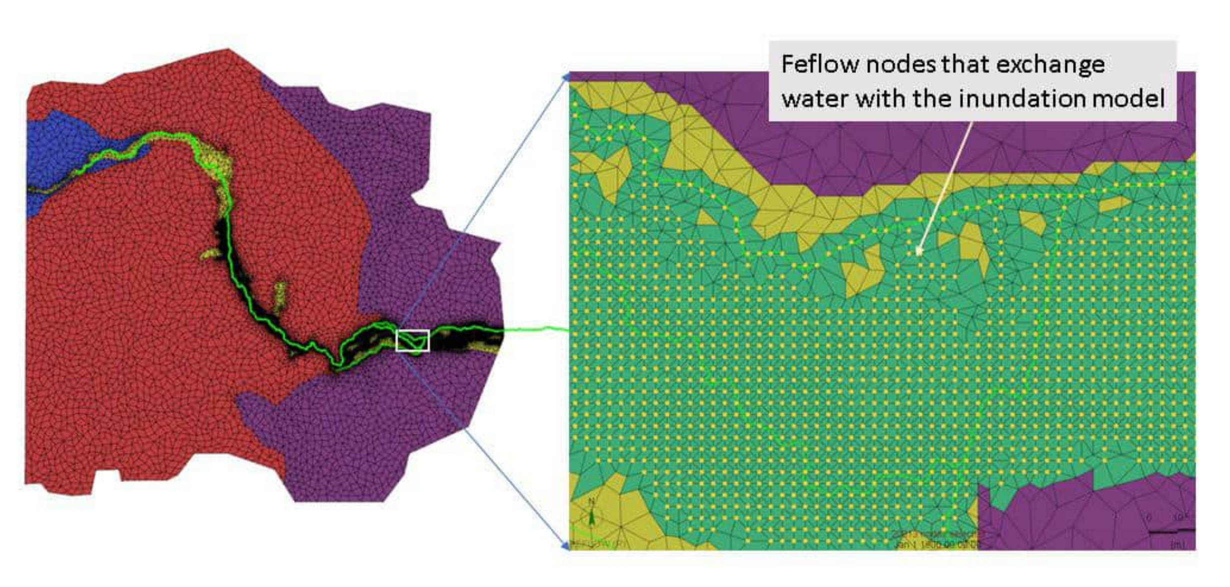


Figure 7-4: Feflow nodes used to simulation interaction with surface waters.

7.10 Calibration

7.10.1 Calibration procedure

The model calibration is hampered by a lack of local scale groundwater head data that are suitable for defining steady state heads throughout the swamp. Although there are 17 recently installed shallow wells in the swamp, data from these wells is limited to the period June to September of 2019 and do not provide a useful definition of steady state groundwater conditions. The locations of the Big Swamp observation bores are shown in Figure 7-5 and the recorded groundwater heads in all these bores are presented in Figure 7-6.

Furthermore, the explicit representation of surface water groundwater interaction over a period that would be meaningful for calibration of the groundwater model is prohibitive in terms of data transfer and computational effort. A fully transient surface water model requires short time steps (in the order of one second) and produces a unique time series of wetting and stage elevation for each of the exchange nodes in the groundwater model (about 21,000 nodes in total). The complexity of constructing a fully transient model for both the inundation and groundwater model and the high level of computational effort required to create individual time series inputs for all exchange nodes precludes the development of such a model within the available time for the project.

An alternative, less rigorous, quasi transient calibration approach was adopted. The model was formulated to simulate a 10 year period (2010 to 2019) with a synthetic sequence of river flows assumed to occur as a repeating annual sequence as shown in Figure 7-7. The flow sequence reflects observations and anecdotal evidence of creek flows over the period of calibration. It assumes no river flow through summer months, a steady flow of 2ML/day through autumn and spring and a high flow of 10 ML for winter. The groundwater model utilises steady state inundation model results (wetted area and stage at all exchange nodes see for instance Figure 6-4

Figure 6-4) for each of the nominated flows. The resultant simulation is aimed at producing groundwater heads that are similar to those observed in the monitoring bore network between June and September 2019 and at reproducing streamflow losses in the order of 1.5 ML/day during periods when the river is assumed to be flowing at 2 ML/d immediately downstream of the Dam.

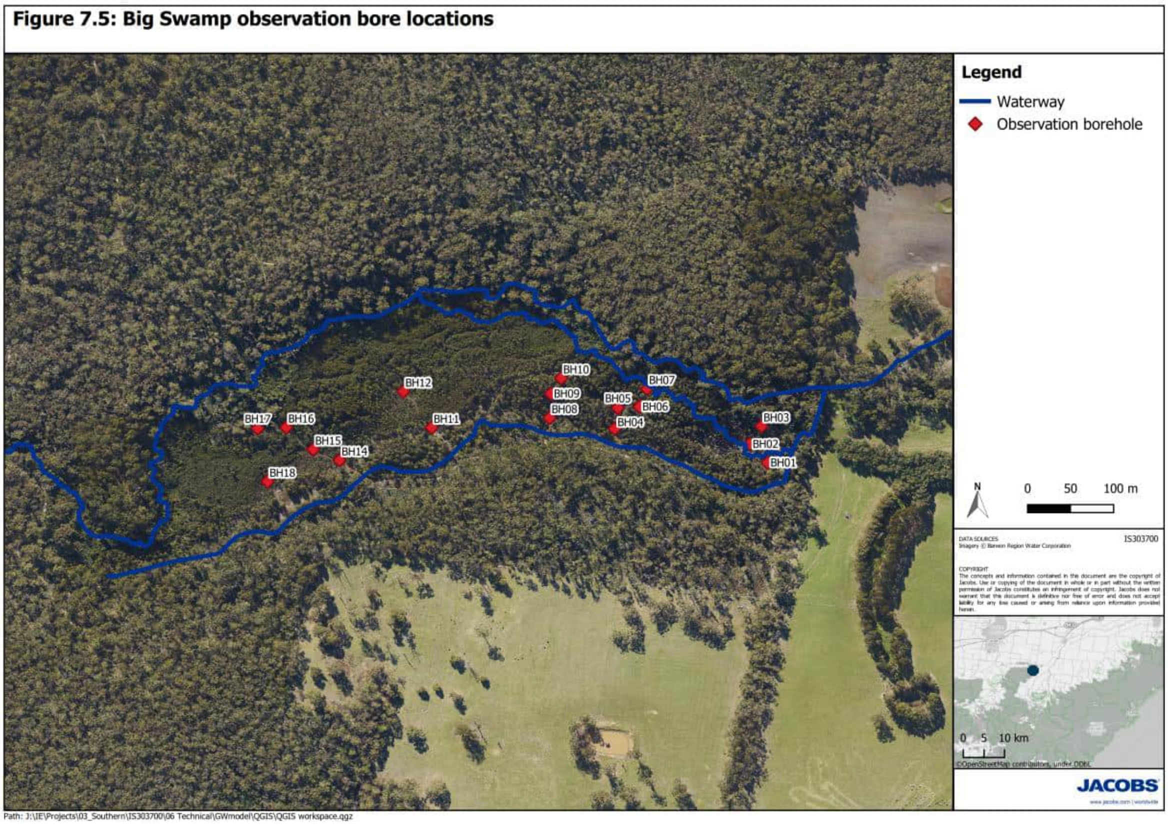


Figure 7-5: Big Swamp observation bore locations

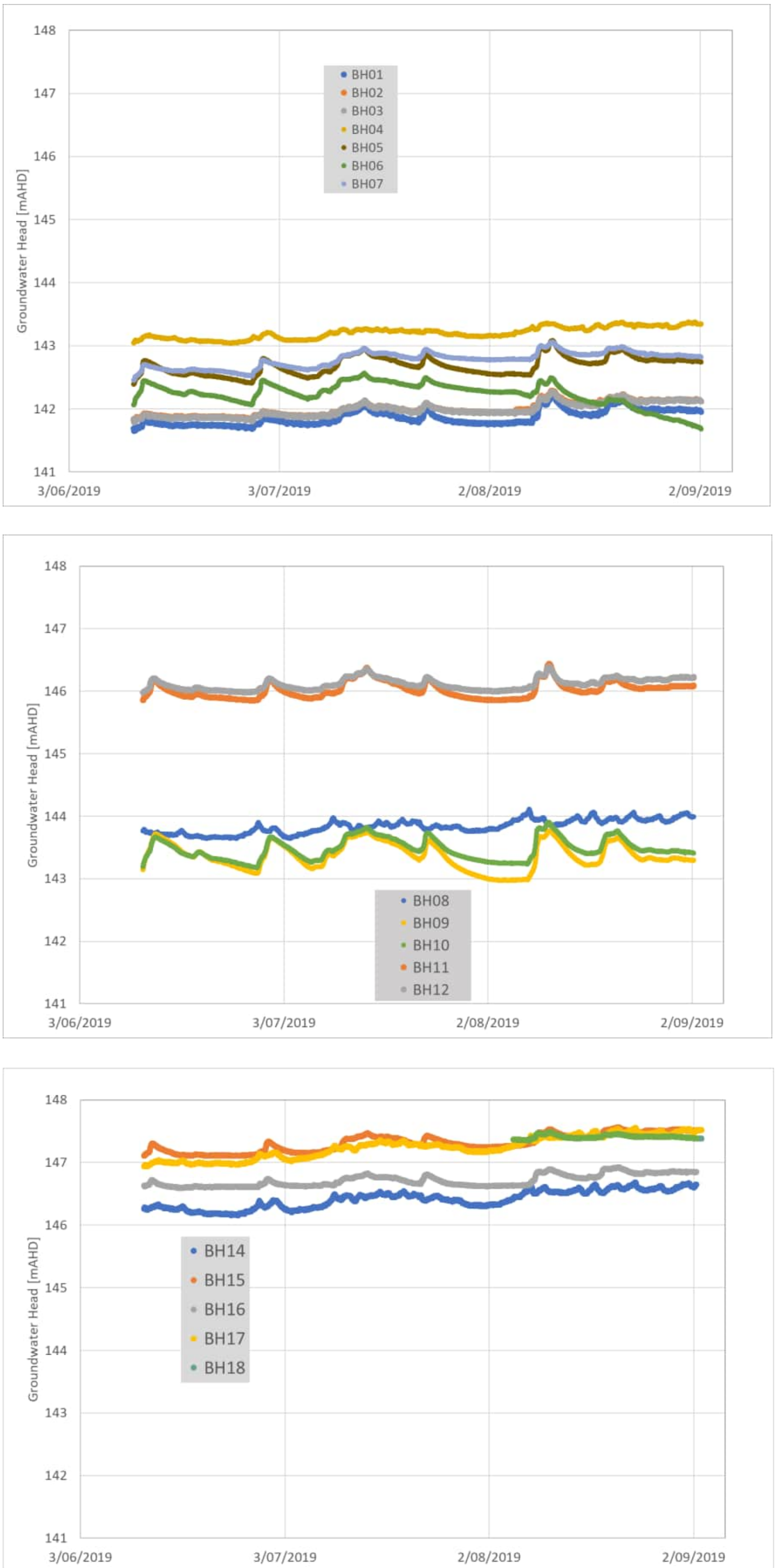


Figure 7-6: Measured hydrographs in Big Swamp observation bores.

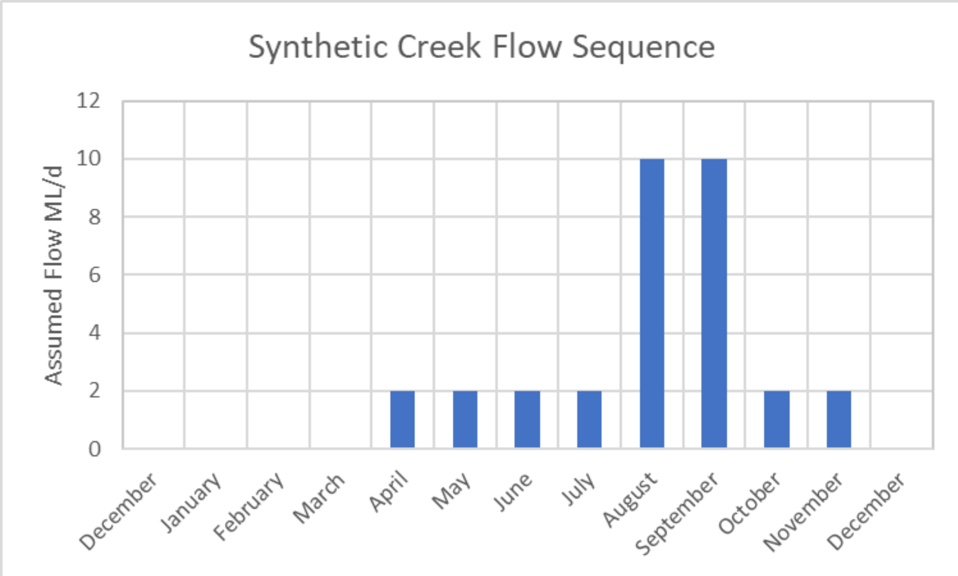


Figure 7-7: River flow sequence assumed for each year of the transient calibration model.

7.10.2 Calibration results

The calibration result is illustrated in Figure 7-8 as a comparison between the modelled and measured watertable surfaces (potentiometric surfaces) for September 2019.

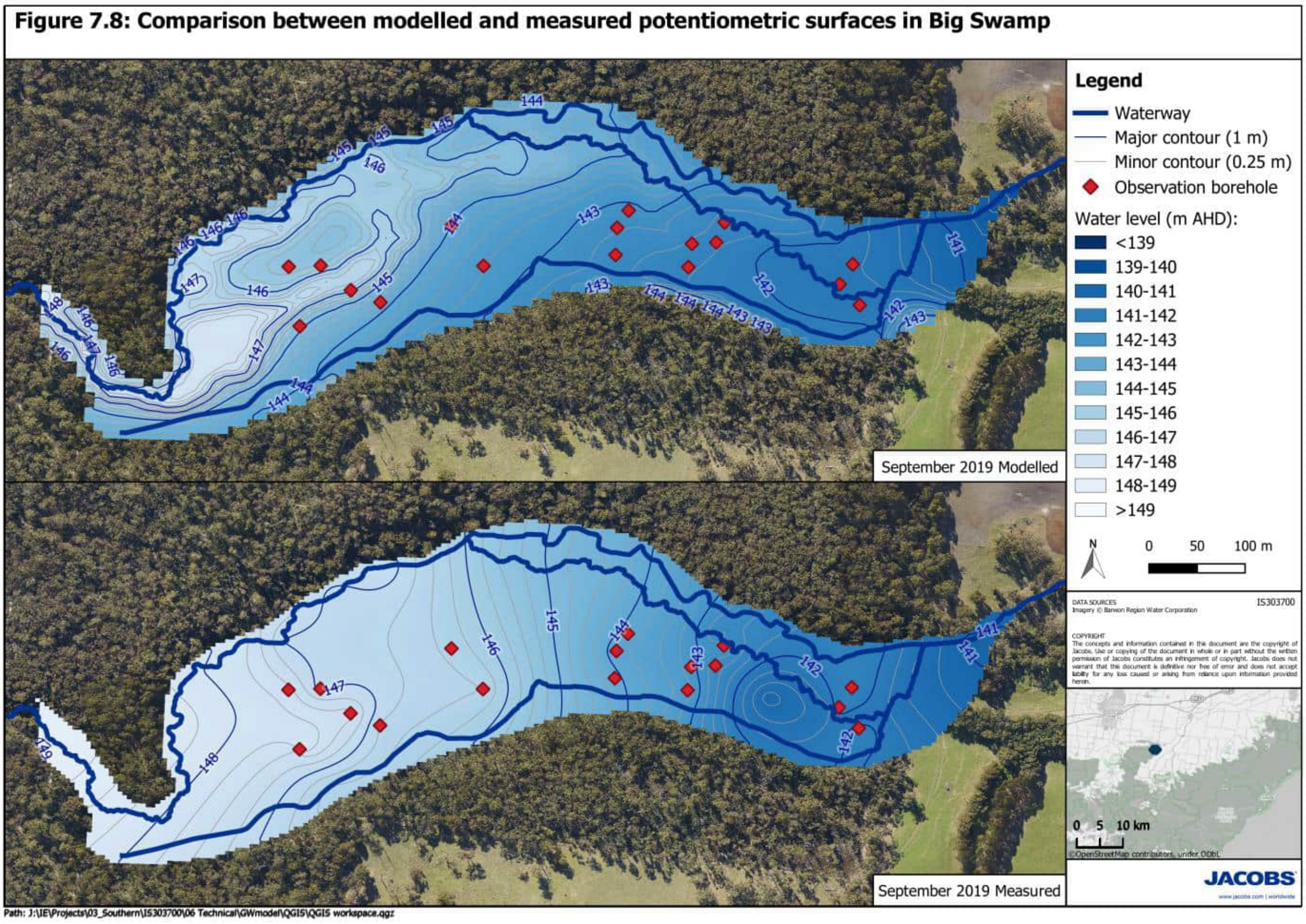


Figure 7-8: Comparison between modelled and measured potentiometric surfaces in Big Swamp.

Figure 7-9 shows a comparison between measured and predicted hydrographs in a selection of the Big Swamp monitoring bores in the period April to September 2019. The result suggests that the modelled heads are reasonably close to the observed levels at the downstream end of the swamp (for example, BH01) and that predicted heads are generally lower than measured throughout the central and upstream parts of the swamp.

The level of agreement between the modelled and observed heads is reasonable given that the calibration model is not based on a measured record of flow in the creek, rather it is based on synthetic flow data.

The modelled losses of water from Boundary Creek vary seasonally with the assumed flows in the creek. For periods when the creek flow is assumed to be 2 ML/d, the model predicts a loss of about 0.5 ML/d through Big Swamp and a loss of about 1.1 ML/d through the Damplands. The total loss of 1.6 ML/d is close to the calibration target of about 1.5 ML/d for a release of 2 ML/d.

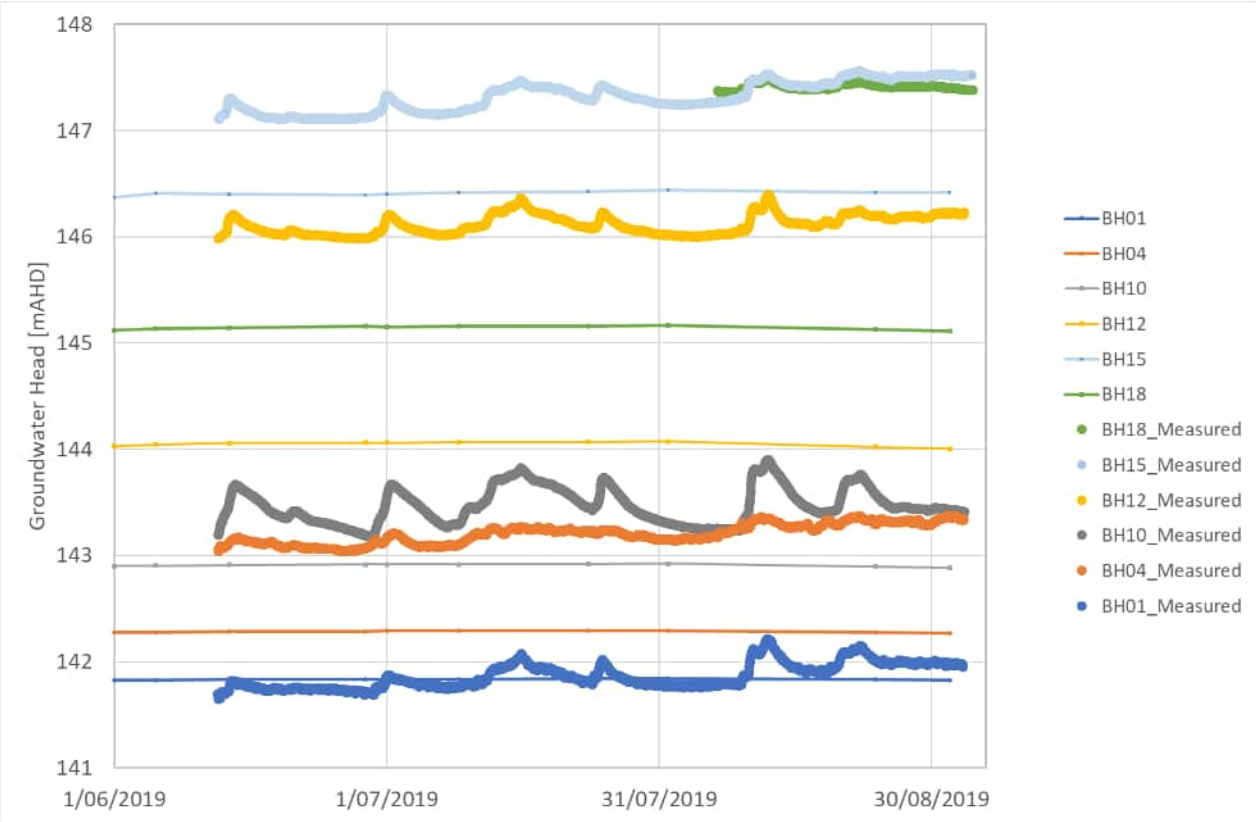


Figure 7-9: Predicted and measured groundwater levels in the Big Swamp monitoring bores.

8. Groundwater model predictive scenarios

8.1 Procedure

Six predictive scenarios have been formulated and run to assess various future flow regimes in Boundary Creek. These scenarios were designed to replicate conditions under low and high flow over short periods of time (6 months) and a longer term scenario with typical average flows. All scenarios were run with and without a hydraulic barrier at the eastern end of the swamp to determine the influence of the barrier on inundation areas and groundwater levels.

Scenario 1 to 4 are short term (150 days) simulations that assume a dry period in which the creek flow is entirely supported by supplementary flow released immediately downstream of the dam. The scenarios include an upper and lower estimate of the supplementary flow that may be required and hence provide limits within which results can be interpolated for intermediate rates of supplementary flow. The scenarios assume worst case climatic conditions in which Boundary Creek and Big Swamp do not receive any natural runoff, overland flow or baseflow.

Scenarios 1 and 3 assume that current flow conditions in the Creek and swamp while Scenarios 2 and 4 assume that a levee is constructed across the outflow channels at the downstream end of the swamp to a level of 142.5 mAHD (see Section 6.1) at the downstream limit of the swamp. These scenarios provide an indication as to changes in groundwater conditions that may occur as a result of introducing a hydraulic barrier at the downstream edge of the swamp.

Scenarios 5 and 6 are longer period simulations with an assumed seasonal fluctuation in creek flow based on the analysis presented in Section 5.3 with and without the hydraulic barrier. The head dependent boundary conditions that define the river stage and wetted area of Boundary Creek have been obtained from the hydraulic modelling scenarios including the intermediate scenarios described in Section 6.

The scenarios are defined as:

- **Scenario 1** assumes a constant release of 2 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with no hydraulic barrier.
- **Scenario 2** assumes a constant release of 2 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with a hydraulic barrier with surface water levels from Figure 6-5.
- **Scenario 3** assumes a constant release of 20 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with no hydraulic barrier.
- **Scenario 4** assumes a constant release of 20 ML/d from McDonald’s Dam with no additional contribution to streamflow from natural sources with a hydraulic barrier with surface water levels from Figure 6-11.
- **Scenario 5** is a ten year simulation that assumes an annual cycle of flows as illustrated in Figure 8-1 with no hydraulic barrier.
- **Scenario 6** is a ten year simulation that assumes an annual cycle of flows as illustrated in Figure 8-1 with a hydraulic barrier.

The flow sequence is an estimate of what could potentially be achieved with a supplementary flow of 2 ML/d providing continuous flow through summer and autumn with much higher flows occurring in wet winter months due to the flow regime (see for instance Figure 5-4).

Initial conditions for all scenarios were obtained from the calibration model at September 2019. In this case the simulations assume that flow supplementation starts in late winter when the groundwater levels in the swamp are relatively high.

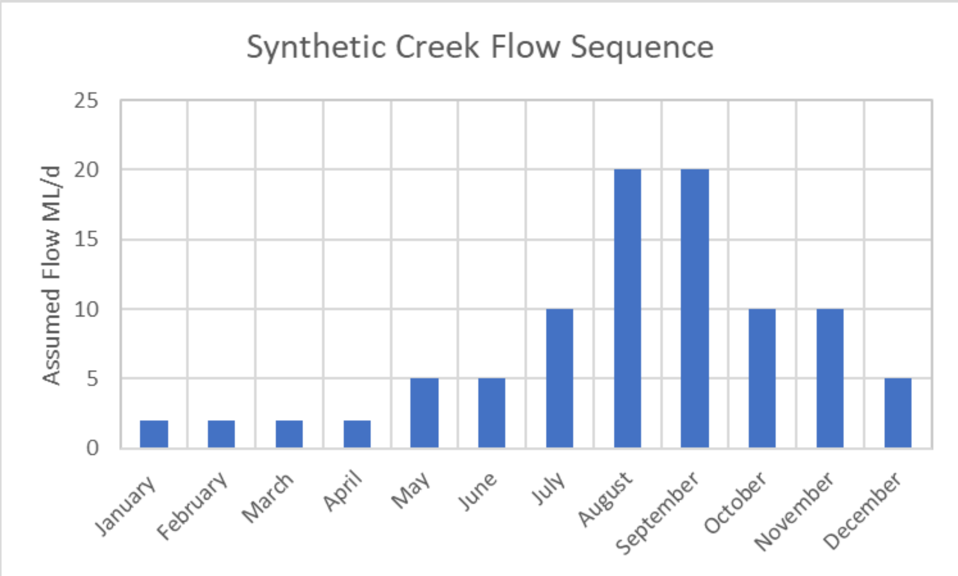
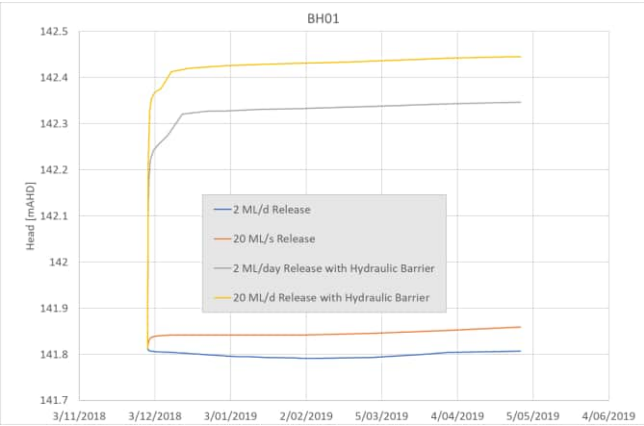


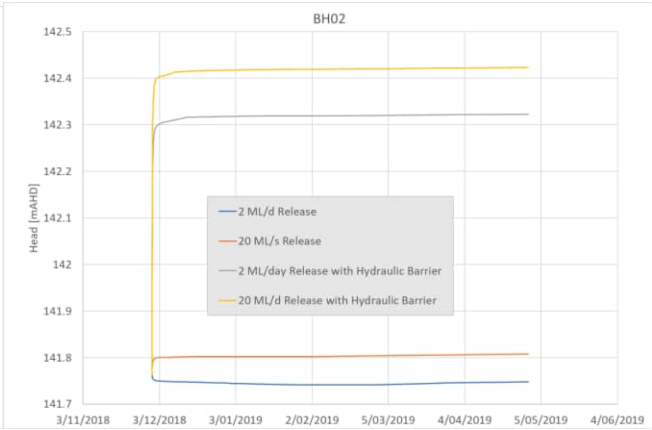
Figure 8-1: Assumed annual cycle of flows assumed in Boundary Creek immediately downstream of McDonald's Dam for Scenarios 5 and 6.

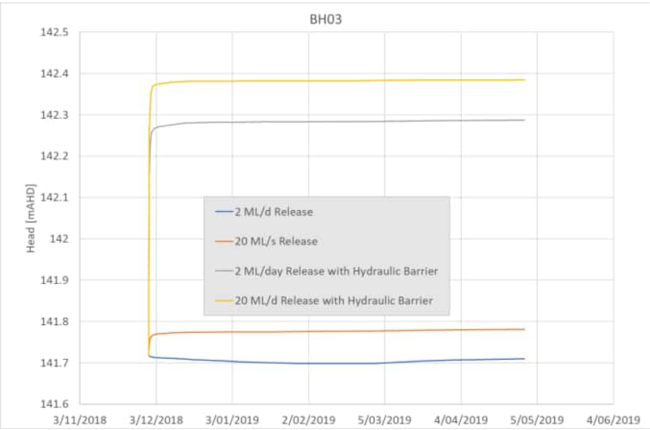
8.2 Results

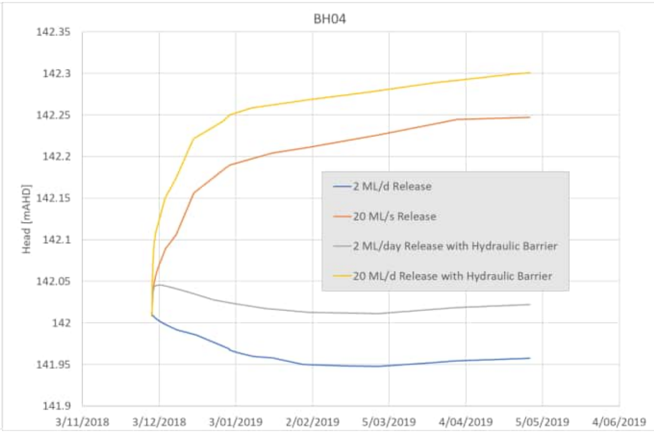
8.2.1 Changes in Groundwater Head

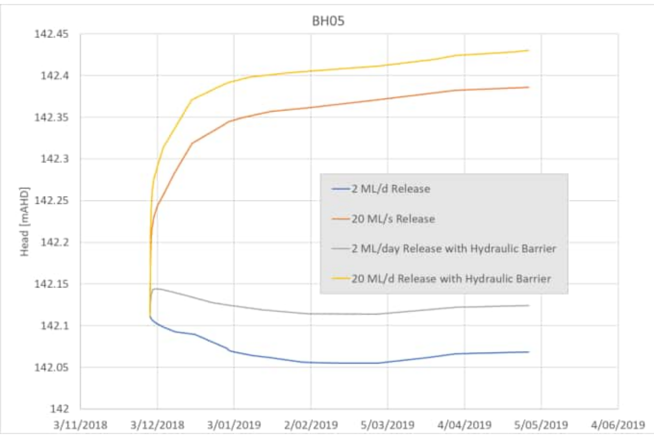
The scenarios predict changes in groundwater level in response to the applied boundary conditions in the creek and swamp. The predicted head responses in each of the swamp monitoring wells in all Scenarios 1 to 4 are presented in Figure 8-2.

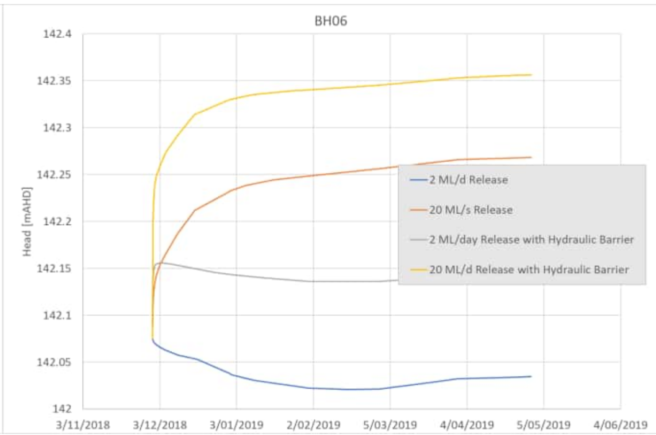

BH01
Head [mAHD]
142.5
142.4
142.3
142.2
142.1
142
141.9
141.8
141.7
3/11/2018
3/12/2018
3/01/2019
2/02/2019
5/03/2019
4/04/2019
5/05/2019
4/06/2019
2 ML/d Release
20 ML/s Release
2 ML/day Release with Hydraulic Barrier
20 ML/d Release with Hydraulic Barrier

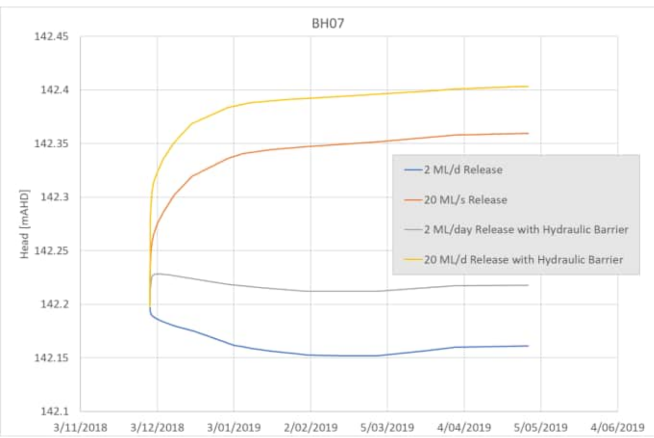

BH02
Head [mAHD]
142.5
142.4
142.3
142.2
142.1
142
141.9
141.8
141.7
3/11/2018
3/12/2018
3/01/2019
2/02/2019
5/03/2019
4/04/2019
5/05/2019
4/06/2019
2 ML/d Release
20 ML/s Release
2 ML/day Release with Hydraulic Barrier
20 ML/d Release with Hydraulic Barrier

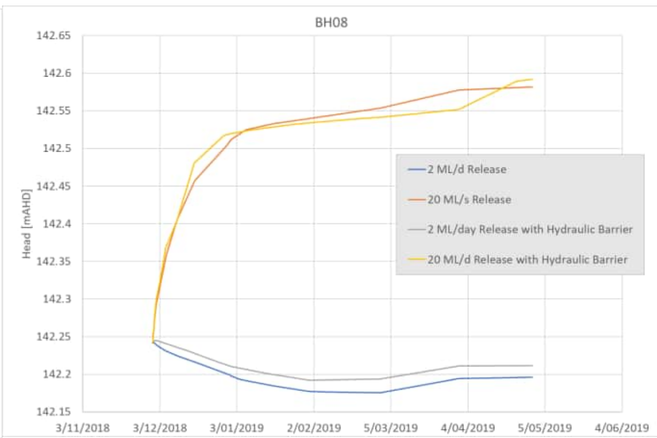

BH03
Head [mAHD]
142.5
142.4
142.3
142.2
142.1
142
141.9
141.8
141.7
141.6
3/11/2018
3/12/2018
3/01/2019
2/02/2019
5/03/2019
4/04/2019
5/05/2019
4/06/2019
2 ML/d Release
20 ML/s Release
2 ML/day Release with Hydraulic Barrier
20 ML/d Release with Hydraulic Barrier


BH04
Head [mAHD]
142.35
142.3
142.25
142.2
142.15
142.1
142.05
142
141.95
141.9
3/11/2018
3/12/2018
3/01/2019
2/02/2019
5/03/2019
4/04/2019
5/05/2019
4/06/2019
2 ML/d Release
20 ML/s Release
2 ML/day Release with Hydraulic Barrier
20 ML/d Release with Hydraulic Barrier


BH05
Head [mAHD]
142.45
142.4
142.35
142.3
142.25
142.2
142.15
142.1
142.05
142
3/11/2018
3/12/2018
3/01/2019
2/02/2019
5/03/2019
4/04/2019
5/05/2019
4/06/2019
2 ML/d Release
20 ML/s Release
2 ML/day Release with Hydraulic Barrier
20 ML/d Release with Hydraulic Barrier


BH06
Head [mAHD]
142.4
142.35
142.3
142.25
142.2
142.15
142.1
142.05
142
3/11/2018
3/12/2018
3/01/2019
2/02/2019
5/03/2019
4/04/2019
5/05/2019
4/06/2019
2 ML/d Release
20 ML/s Release
2 ML/day Release with Hydraulic Barrier
20 ML/d Release with Hydraulic Barrier


BH07
Head [mAHD]
142.45
142.4
142.35
142.3
142.25
142.2
142.15
142.1
3/11/2018
3/12/2018
3/01/2019
2/02/2019
5/03/2019
4/04/2019
5/05/2019
4/06/2019
2 ML/d Release
20 ML/s Release
2 ML/day Release with Hydraulic Barrier
20 ML/d Release with Hydraulic Barrier


BH08
Head [mAHD]
142.65
142.6
142.55
142.5
142.45
142.4
142.35
142.3
142.25
142.2
142.15
3/11/2018
3/12/2018
3/01/2019
2/02/2019
5/03/2019
4/04/2019
5/05/2019
4/06/2019
2 ML/d Release
20 ML/s Release
2 ML/day Release with Hydraulic Barrier
20 ML/d Release with Hydraulic Barrier

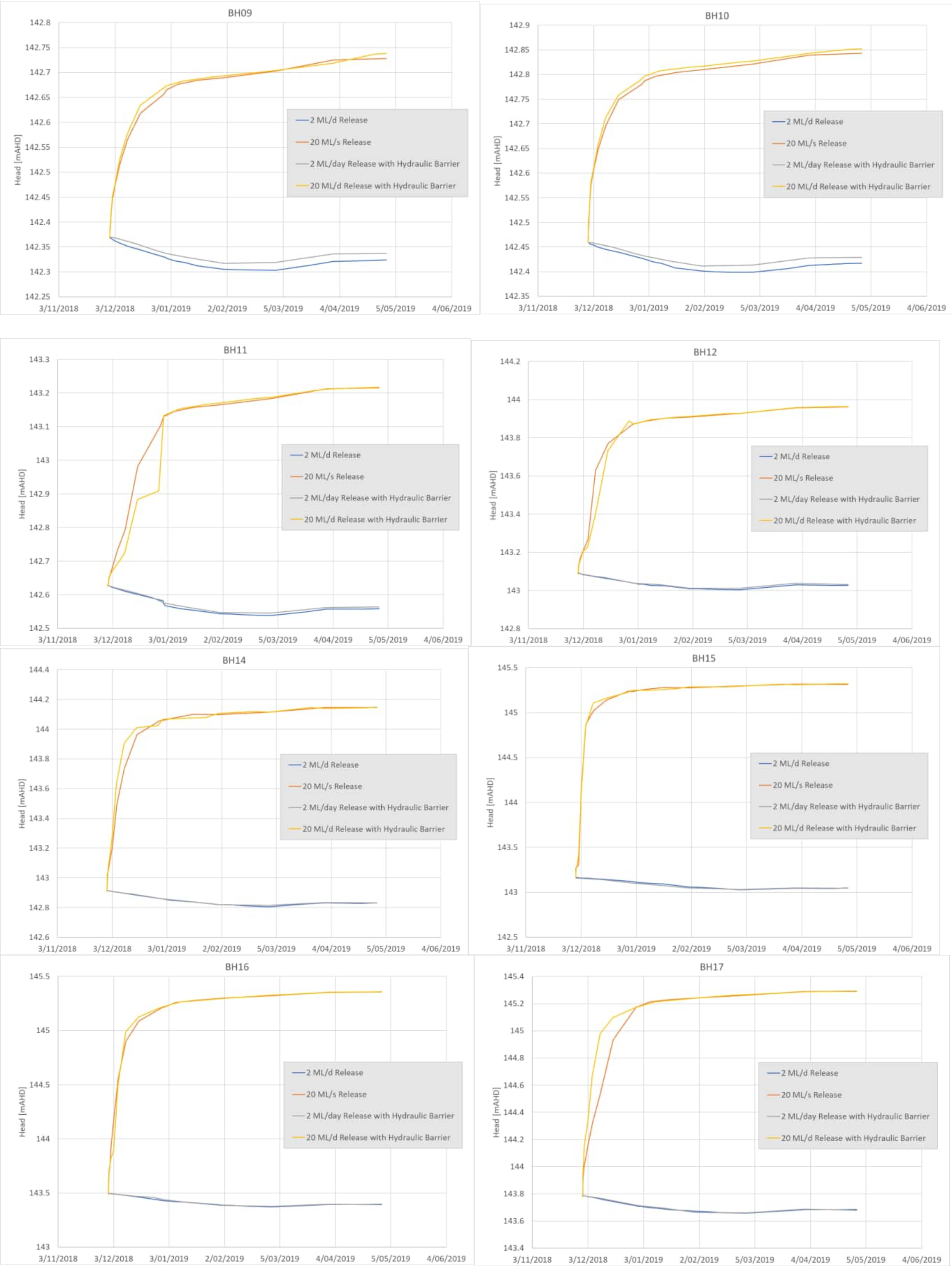
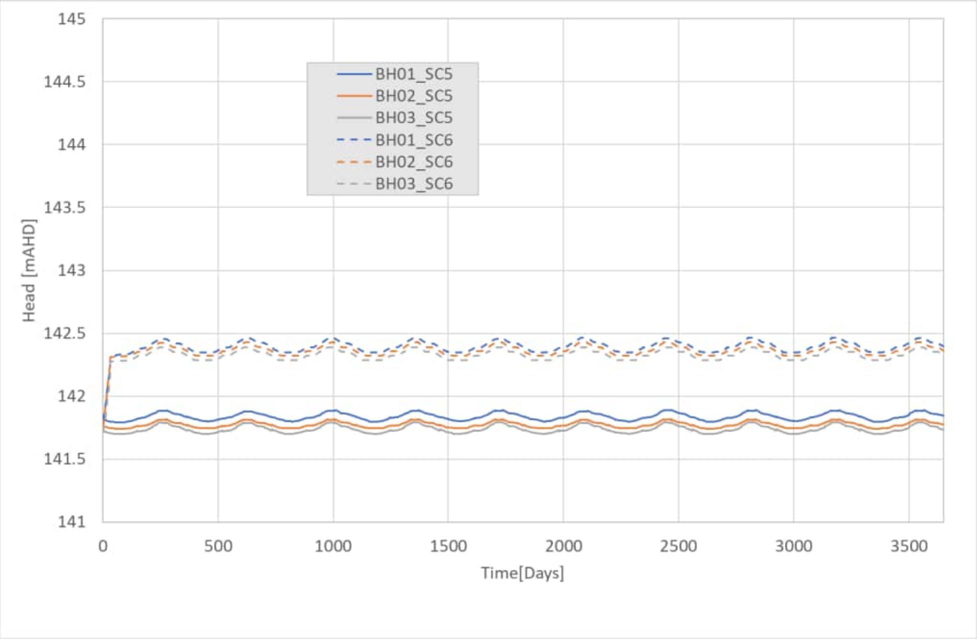
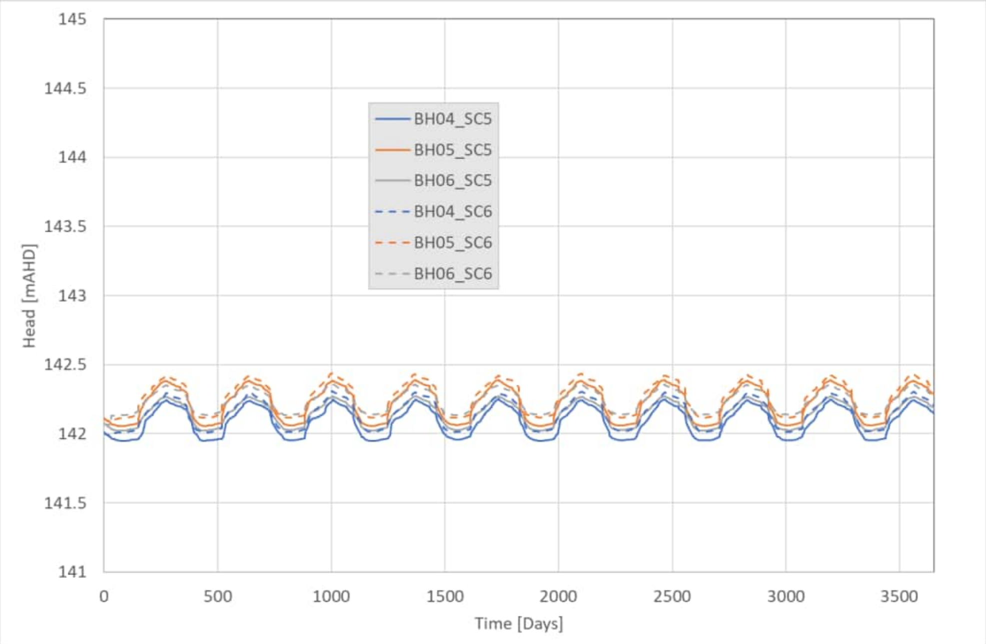


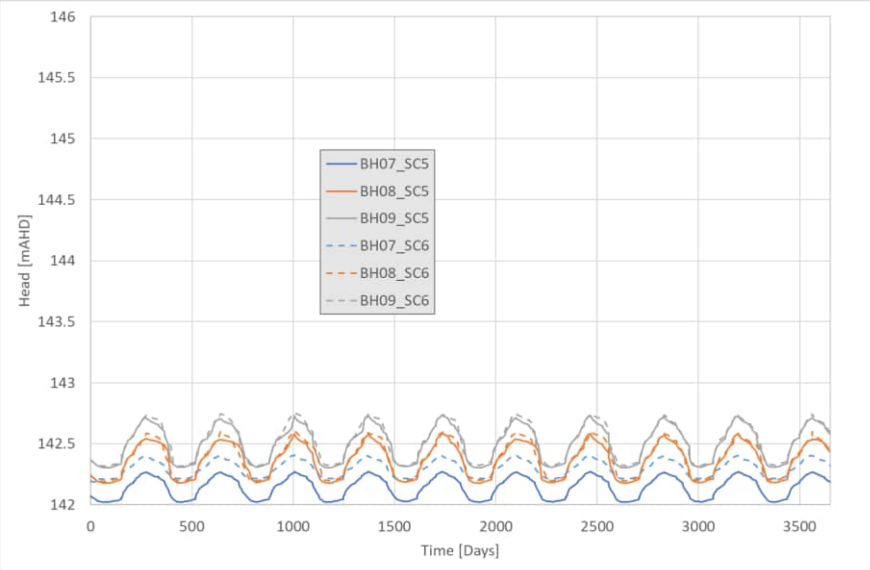
Figure 8-2: Predicted heads at all monitoring bore locations for Scenarios 1 to 4.

The predicted groundwater head responses at the groundwater monitoring bores in the swamp for Scenarios 5 and 6 are presented in Figure 8-3 The results indicate that long term trends in groundwater heads are not expected suggesting that the groundwater system equilibrates quite rapidly with changing flows in the creek. The predicted groundwater heads fluctuate seasonally around a long term average condition. The predicted impacts of the hydraulic barrier are constrained to the downstream part of the swamp and the increases in groundwater head caused by the barrier are not predicted to be propagated upstream of monitoring bores BH7, 8 and 9.

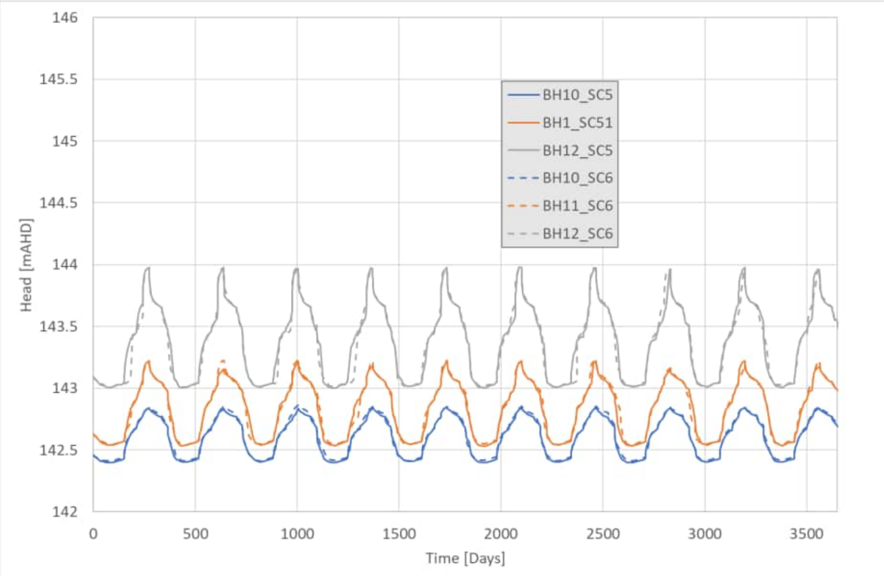
It is also of interest to note that the seasonal fluctuations in groundwater heads are predicted to be far more pronounced in areas of higher elevation in the upper parts of the Swamp, most likely due to available storage where the unsaturated zone is thicker.



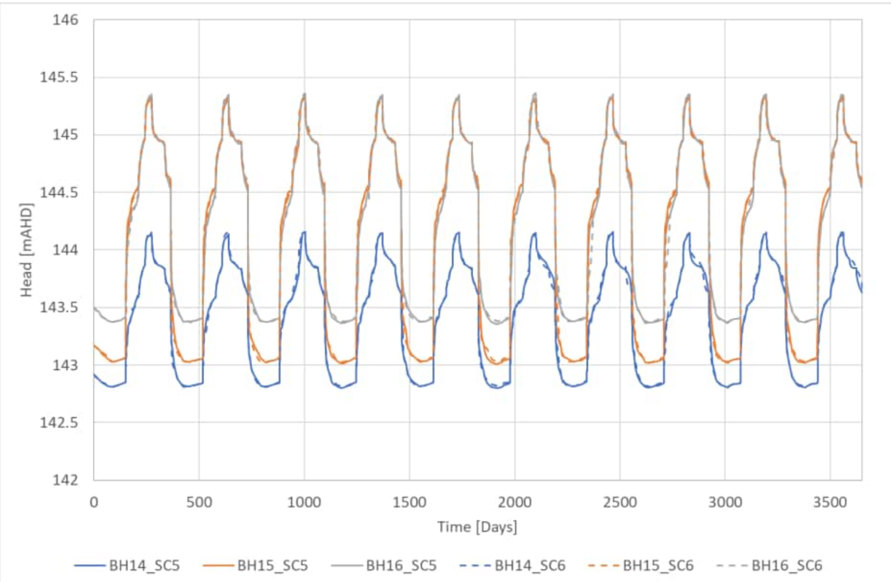




146
145.5
145
144.5
144
143.5
143
142.5
142
Head [mAHD]
0
500
1000
1500
2000
2500
3000
3500
Time [Days]
BH07_SC5
BH08_SC5
BH09_SC5
BH07_SC6
BH08_SC6
BH09_SC6



146
145.5
145
144.5
144
143.5
143
142.5
142
Head [mAHD]
0
500
1000
1500
2000
2500
3000
3500
Time [Days]
BH10_SC5
BH1_SC51
BH12_SC5
BH10_SC6
BH11_SC6
BH12_SC6



146
145.5
145
144.5
144
143.5
143
142.5
142
Head [mAHD]
0
500
1000
1500
2000
2500
3000
3500
Time [Days]
BH14_SC5
BH15_SC5
BH16_SC5
BH14_SC6
BH15_SC6
BH16_SC6

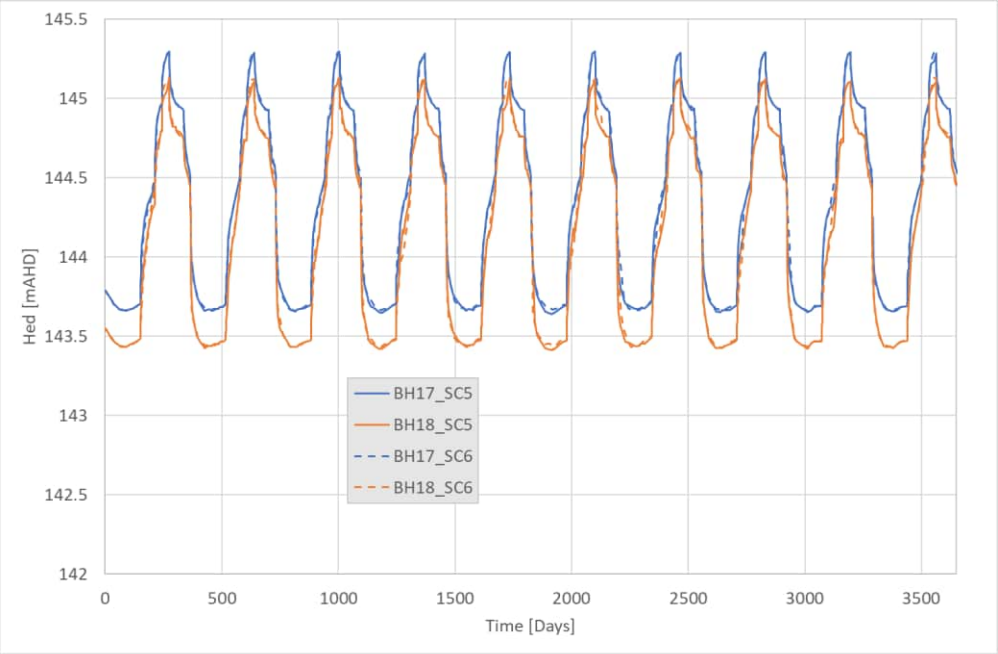


Figure 8-3: Predicted head responses in swamp monitoring bores for Scenarios 5 and 6.

Contour maps of the predicted change in head across the swamp for Scenarios 1 to 4 after 150 days of constant flow releases are presented in Figure 8-4 to Figure 8-7 respectively. In these figures the green shades represent areas where the watertable is predicted to fall with respect to the starting conditions in September 2019. The orange shading represents areas where the watertable is predicted to rise. When the flow release from the dam is set at 2 ML/day (Scenarios 1 and 2), the model predicts that heads will generally fall across the swamp. Scenario 2 (Figure 8-5) indicates that for a constant release of 2 ML/day, the construction of a hydraulic barrier at the downstream edge of the swamp is predicted to generate mounding in heads immediately upstream of the barrier.

When the flow release is assumed to increase to 20 ML/day, the model results suggest that the watertable is expected to rise over most of the swamp.

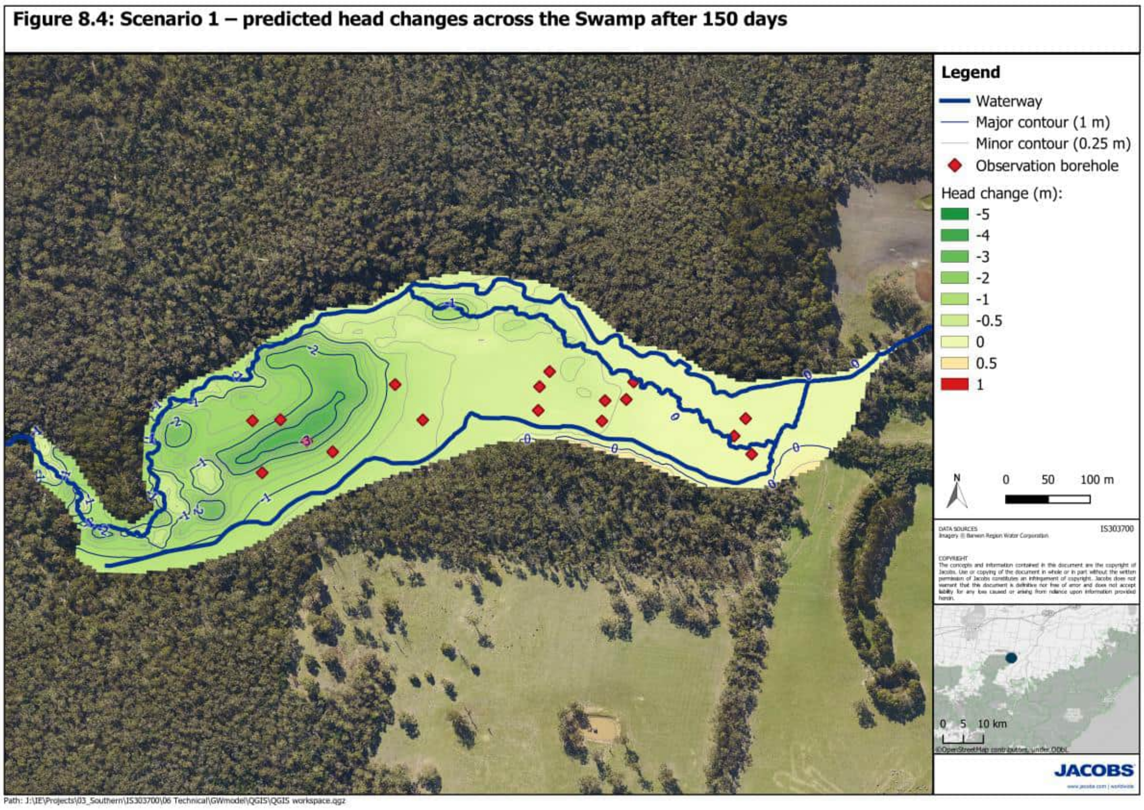


Figure 8-4: Scenario 1 – predicted head changes across the Swamp after 150 days

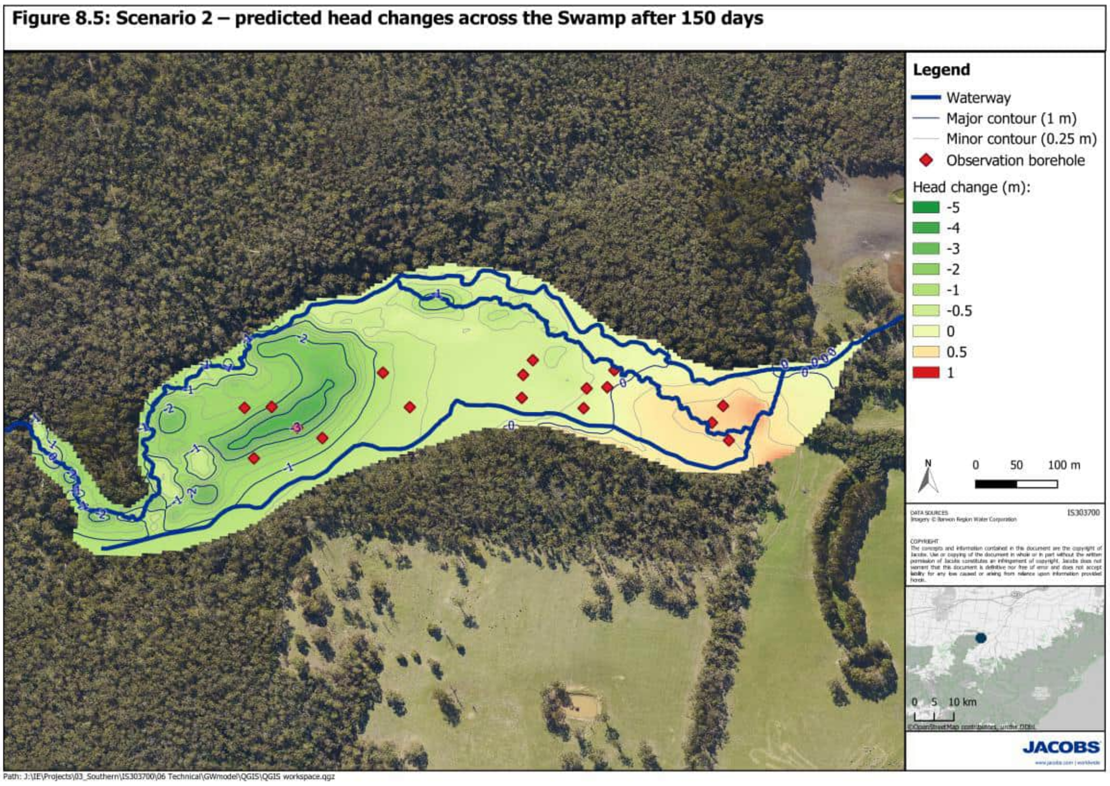


Figure 8-5: Scenario 2 – predicted head changes across the Swamp after 150 days

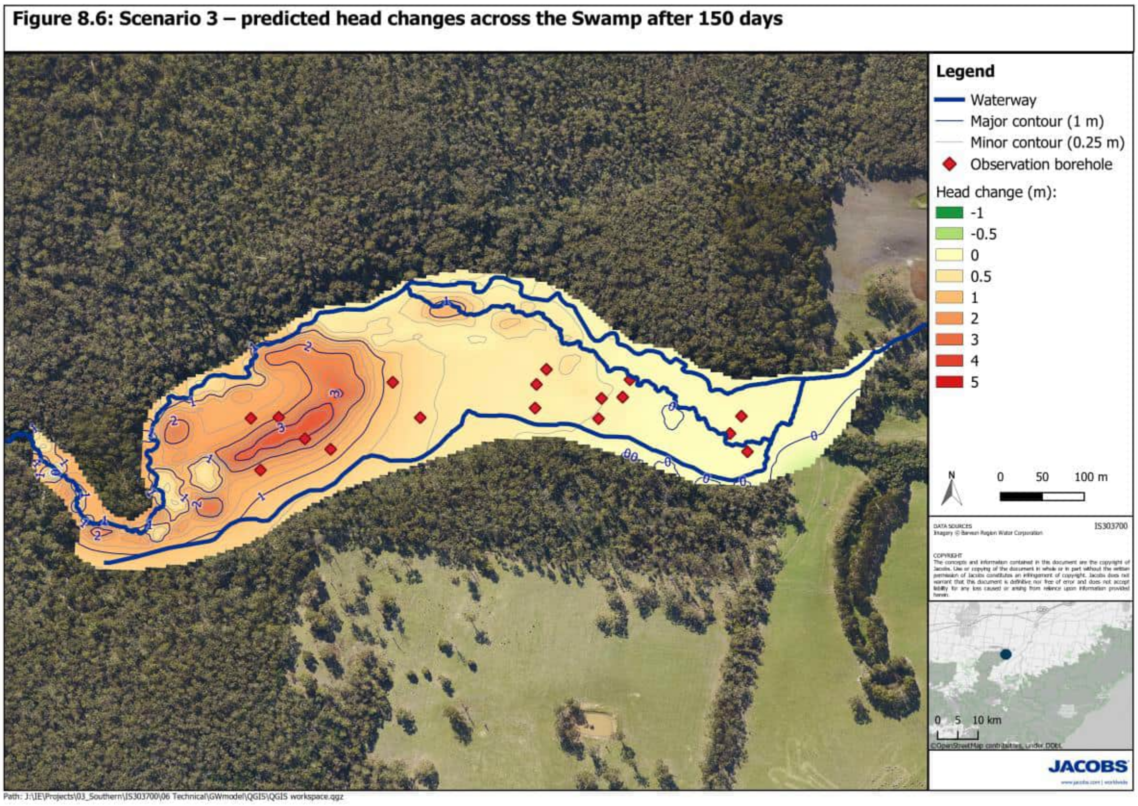


Figure 8-6: Scenario 3 – predicted head changes across the Swamp after 150 days

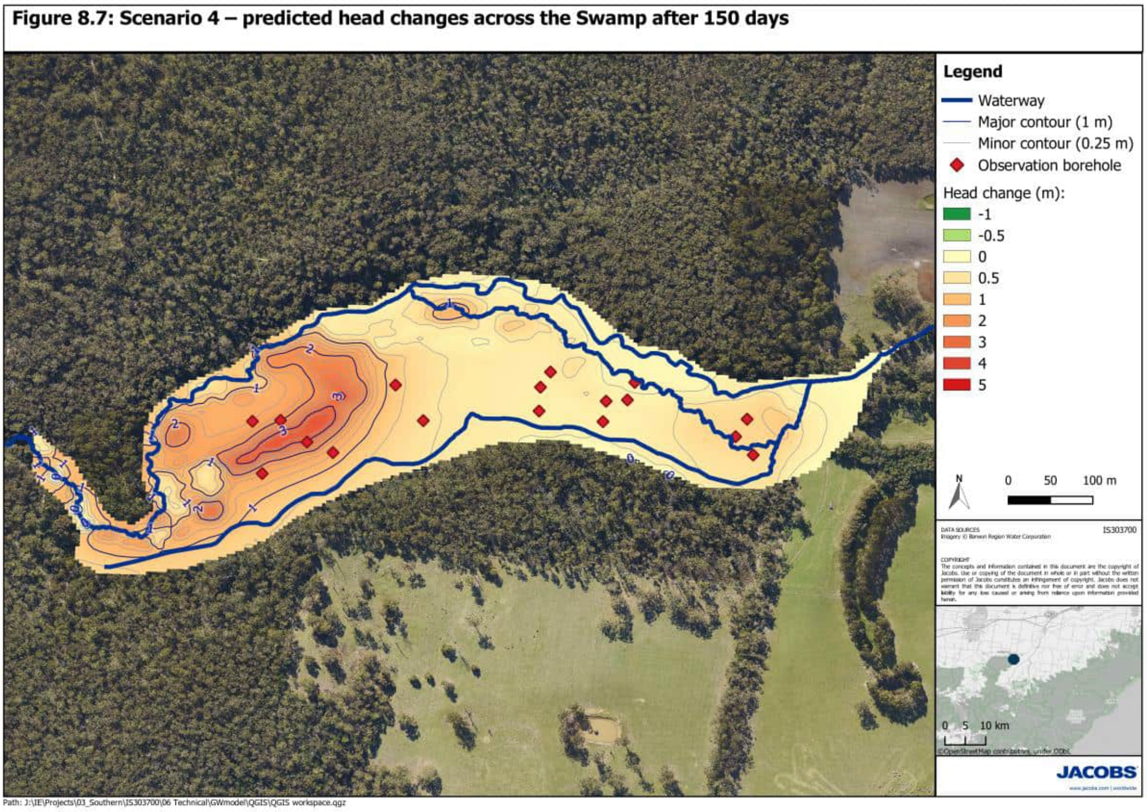


Figure 8-7: Scenario 4 – predicted head changes across the Swamp after 150 days

8.2.2 Depth to Watertable

The predicted depth to watertable contours predicted after 150 days of flow release are plotted in Figure 8-8 to Figure 8-11 for Scenarios 1 to 4 respectively. Areas of water ponding at the surface are shown in purple in these figures.

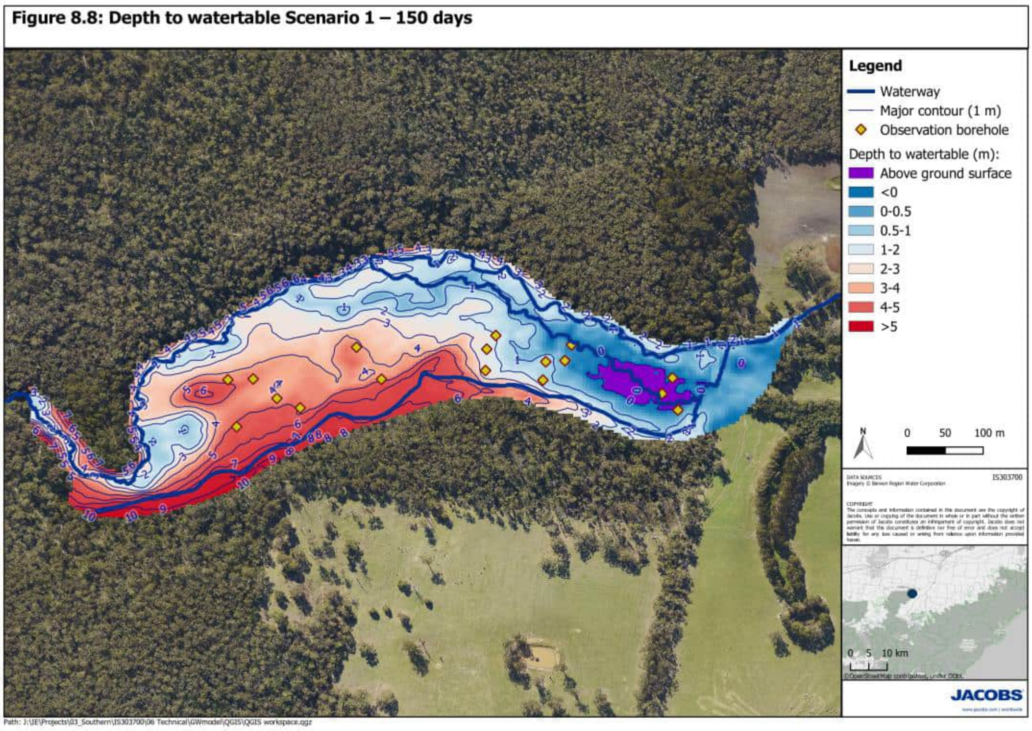


Figure 8-8: Depth to watertable Scenario 1 – 150 days

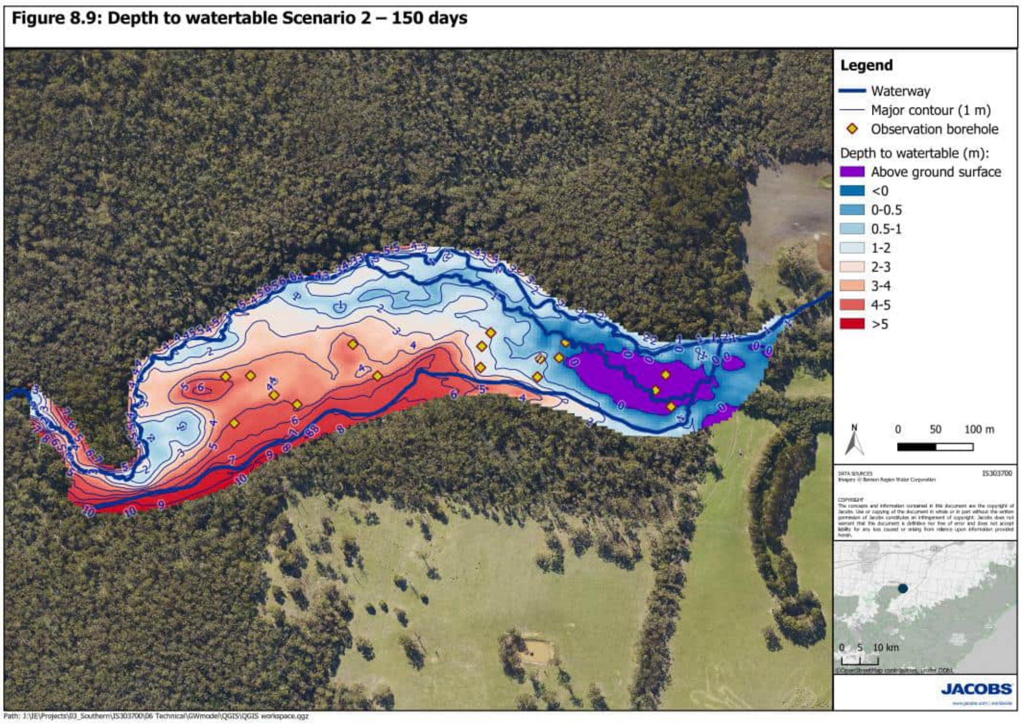


Figure 8-9: Depth to watertable Scenario 2 – 150 days

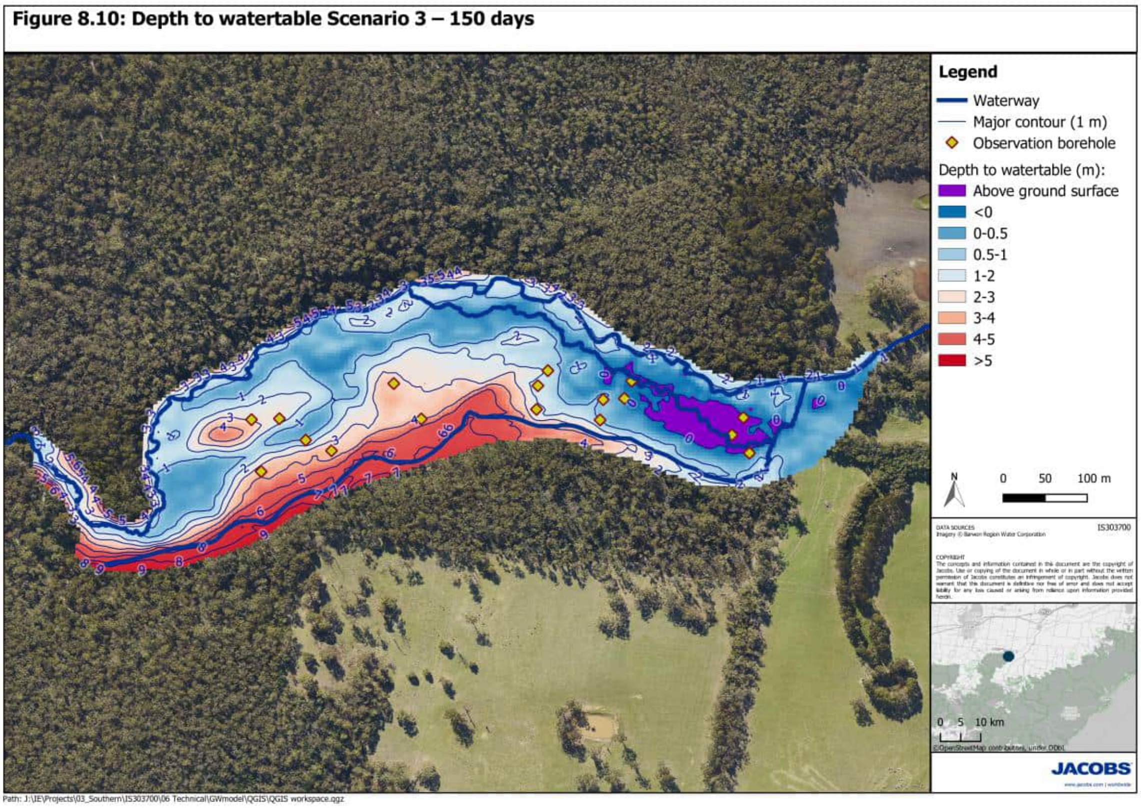


Figure 8-10: Depth to watertable Scenario 3 – 150 days

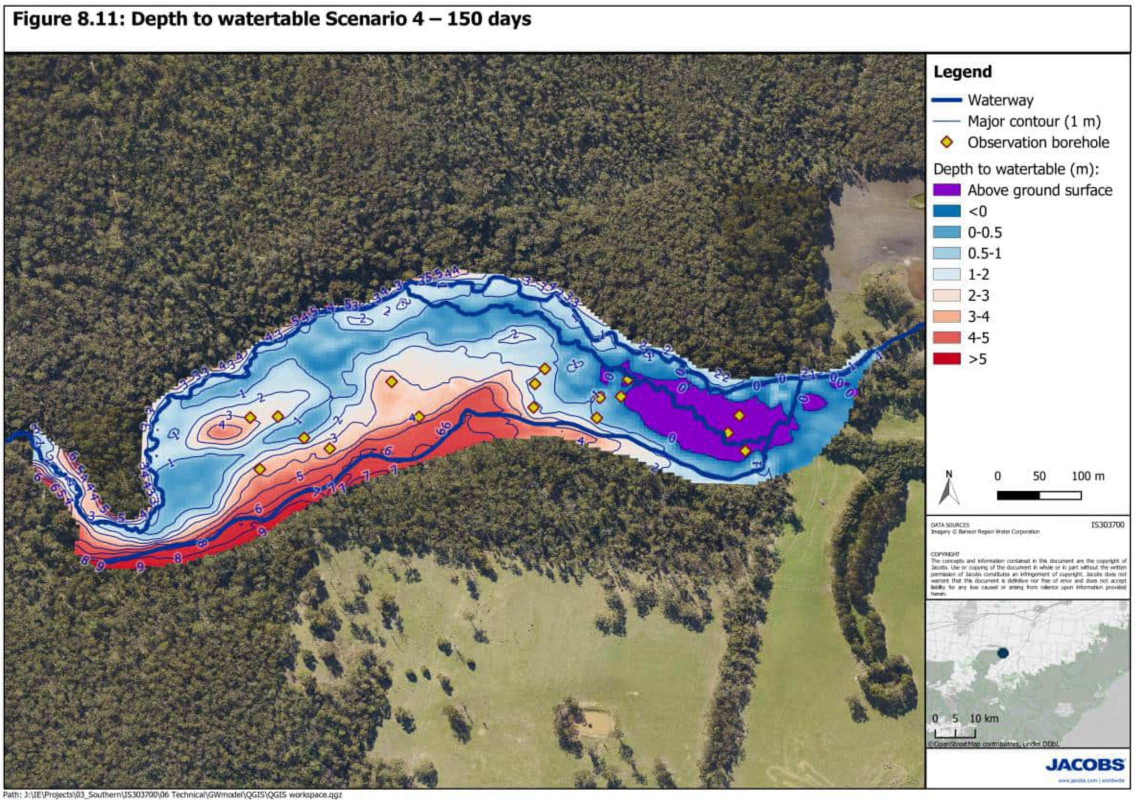


Figure 8-11: Depth to watertable Scenario 4 – 150 days

Predicted depth to watertable plots for Scenario 6 in June (low levels) and September (high levels) are presented in Figure 8-12 and Figure 8-13.

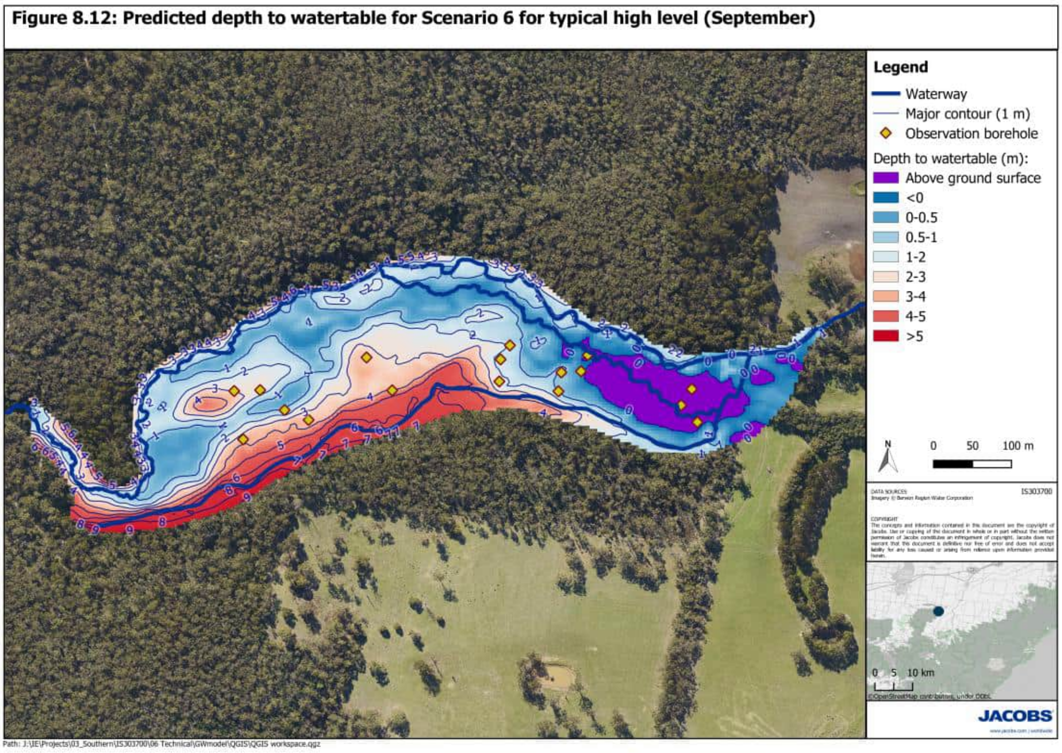


Figure 8-12: Predicted depth to watertable for Scenario 6 for typical high level (September).

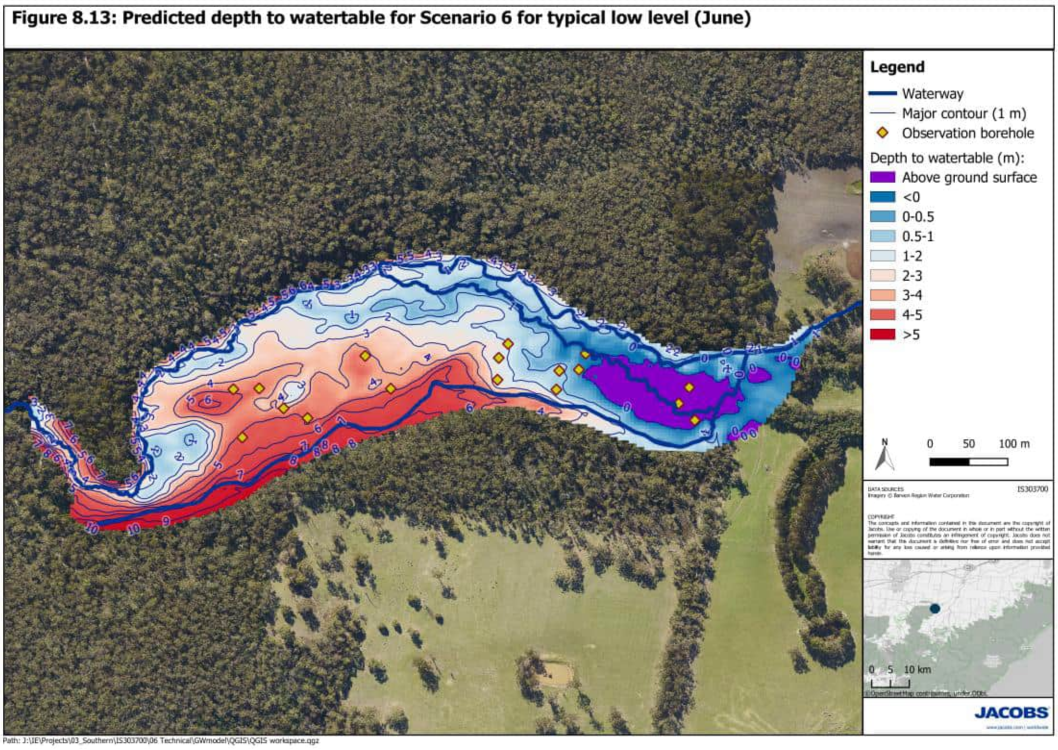


Figure 8-13:Predicted depth to watertable for Scenario 6 for typical low levels (June).

8.2.3 Surface water groundwater interaction.

Predicted groundwater exchange fluxes with Boundary Creek for Scenarios 1 to 4 are presented in Figure 8-14. The exchange fluxes are relatively constant and show very little seasonal variability. In Figure 8-14, positive fluxes represent groundwater discharge to the creek while negative fluxes correspond to predicted seepage from the creek to groundwater. The results suggest that Boundary Creek is losing to groundwater throughout the swamp and damplands and is gaining from groundwater in the region downstream of the swamp.

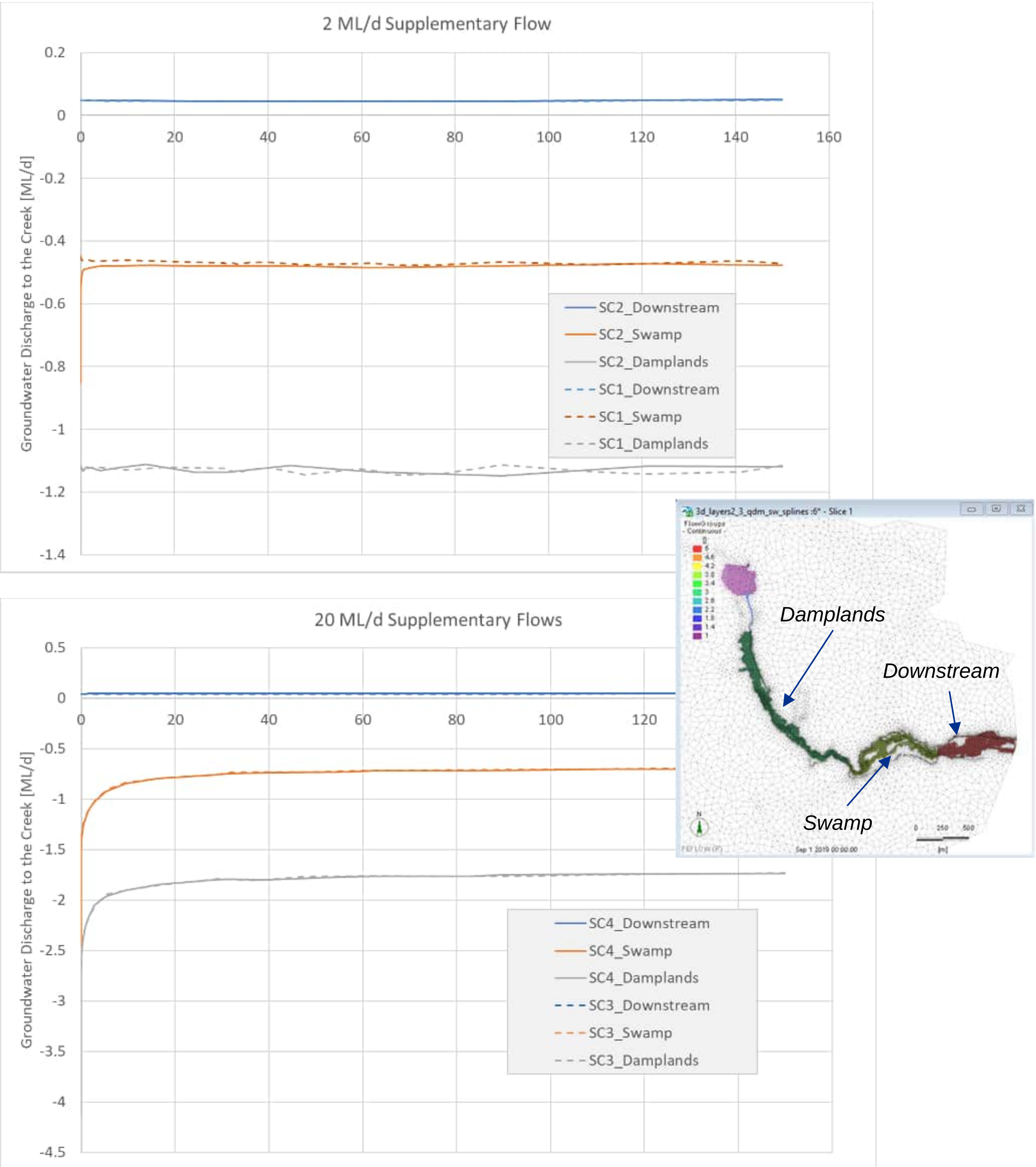


Figure 8-14: Predicted exchange fluxes for Scenarios 1 to 4.

Scenarios 5 and 6 include a level of dynamic behaviour through the assumed seasonal variation in creek flow conditions. These scenarios provide a more realistic simulation of the transient exchange fluxes between groundwater and the creek compared to the other scenarios that include constant head boundary conditions for Boundary Creek. Predicted groundwater fluxes to and from Boundary Creek in Big Swamp are shown in Figure 8-15. Note that the fluxes are predicted for the swamp only and represent about a third of the overall exchange fluxes throughout the model domain.

Figure 8-15 indicates the predicted interaction between Boundary Creek and groundwater is dominated by seepage out of the creek. The predicted losses from Boundary Creek are about ten times greater than the predicted groundwater discharge into the creek.

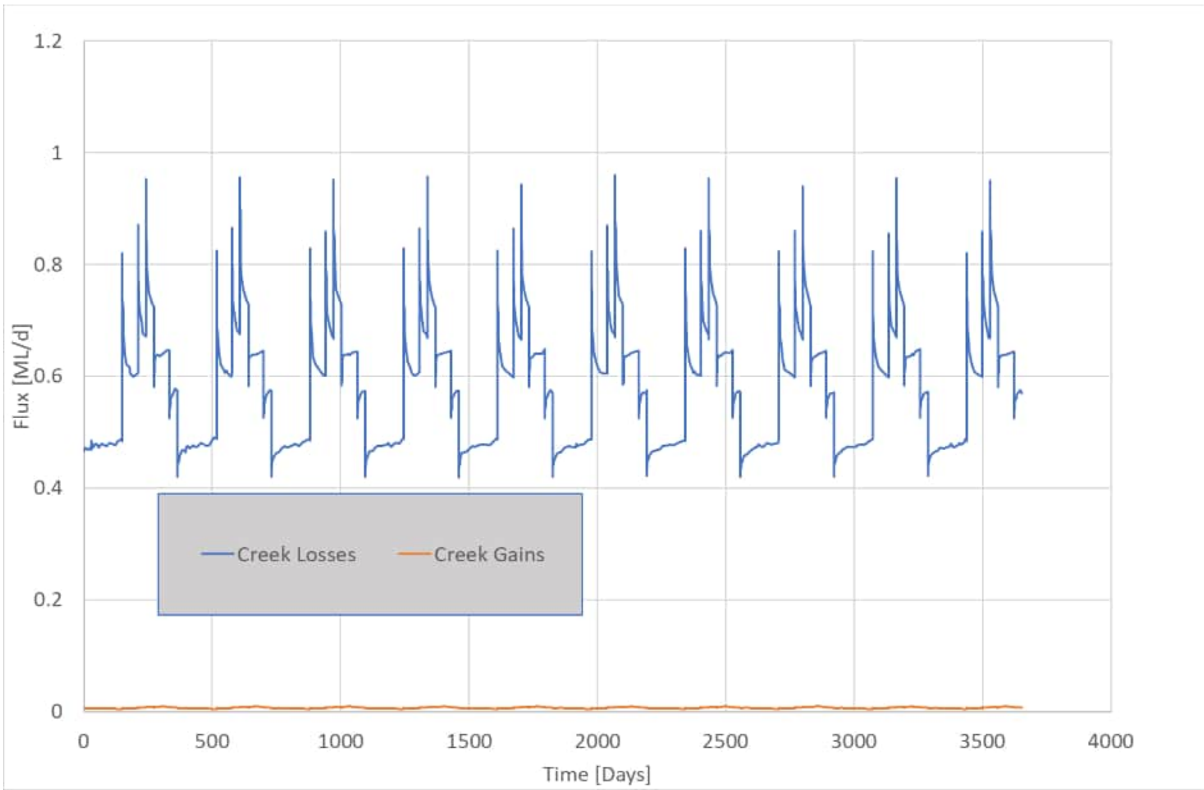


Figure 8-15: Predicted groundwater surface water exchange fluxes in Big Swamp (Scenario 5).

9. Discussion

The exchange of data between the surface water inundation model and the groundwater model provide a significant challenge for transient models. The surface water model requires a time step of about one second and produces very large data sets when the model runs for a period that is meaningful for groundwater model calibration and prediction. Typically, hydraulic models are run for individual flooding events and are not required to solve for extended periods of time. The issue can be partially solved by taking instantaneous results or averaging surface water model results over a period that is appropriate for a groundwater model stress period (days or weeks). However, the surface water model will take an excessively long time and produce extremely large output files if it is run through a transient period that would be appropriate for groundwater model calibration or prediction.

These problems have hindered the development of a fully coupled model and have led to simplifications in order to generate appropriate inputs for a groundwater model. The calibration process for the groundwater model has been simplified by applying a repeating annual flow sequence that assumes a progression of steady state surface water stage and inundation areas obtained from the hydraulic model. Predictions are similarly limited to short term simulations that assume steady state surface water flow conditions (Scenarios 1 to 4) or to a synthetic annual sequence of steady state surface water flow conditions.

Despite these simplifications, the groundwater model provides a reasonably good approximation to groundwater heads measured throughout the swamp over the period June to September 2019. The validity of the model is further reinforced by the predicted creek losses matching the conceptual or indicated losses in recent years.

Additional confidence in the groundwater model can be expected in future as additional flow and groundwater head observations are collected and through improved integration with the surface water model. In this regard the selective accumulation, averaging and saving of surface water data may generate an appropriate set of river stage and inundation areas that would be suitable for transient groundwater model runs, albeit of a restricted time period. While it may never be possible to fully couple a long-term predictive model, results obtained to date suggest that the groundwater system equilibrates quite rapidly to changes in surface flows and hence long-term predictions may not be required.

The predictive model results indicate the following:

1. The groundwater heads through the swamp are expected to fluctuate seasonally as surface water flows respond to local rainfall. The magnitude of the seasonal head fluctuations is expected to be much greater in the upper reaches of the swamp than the lower reaches.

2. If a hydraulic barrier were to be constructed at the outlet from the swamp, it would likely increase groundwater levels and lead to perennial inundation of the lower parts of the swamp. The effects of a hydraulic barrier are not predicted to propagate to the central and upstream part of the swamp.

3. The combination of providing a continuous release of water from the dam and the installation of hydraulic barriers can be expected to increase groundwater levels throughout the swamp and to maintain flow in Boundary Creek, however this would need to be confirmed with further modelling to assess appropriate heights and locations of additional barriers.

The combined groundwater surface water model results have demonstrated that:

1. Increasing supplementary flow leads to increasing inundation extent over dry conditions but less than what is typically experienced at end of winter and early spring. A supplementary flow of 20 ML/d more than doubles the area inundated by a supplementary flow of 2 ML/d.
2. The hydraulic barrier at the downstream end of the swamp increases the area of inundation immediately upstream and this inundated area is largely independent of supplementary flow i.e. there is only minor differences in the area of this pool in the four supplementary flow rates modelled. In this regard, the area of inundation is controlled by the height and location of the barrier.

3. A supplementary flow of 2 ML/d does not maintain groundwater levels at typical winter levels throughout the swamp whereas a supplementary flow 20 ML/d raises groundwater levels to varying degrees throughout the swamp.
4. The incorporation of a hydraulic barrier is effective in raising groundwater levels in the vicinity of the increased area of surface water inundation. This result can be seen in Figure 8.2 where predicted groundwater levels at BH01, BH02 and BH03 (all located within the inundated area) increase significantly for both 2 ML/d and 20 ML/d.
5. Long term trends in groundwater heads are not expected as the groundwater system equilibrates quite rapidly with changing flows in the creek.

The modelling results indicate that a supplementary flow of 2 ML/d with no other interventions is not effective in increasing the inundated area or raising groundwater levels above those typically experienced at the end of winter (nominally September) in recent years. However, the hydraulic modelling suggests that this level of flow release will ensure flows through the swamp through all seasons and hence represents an improvement in historic groundwater levels throughout the swamp. While this scenario is conservative, in that no additional flows to the system were modelled, it is not unrealistic over the summer where extended periods of low flow are normally experienced. Increasing the supplementary flow to 20 ML/d is effective in increasing both the area inundated and groundwater levels; however, the flow rates represent the average August and September flows and continuous delivery of this flow is not feasible.

The scenarios incorporating a single hydraulic barrier have demonstrated the benefit is limited to the area immediately upstream of the barrier. The surface water results of a barrier with different supplementary flows found that there were diminishing returns with higher flows.

Model results indicated that the benefit of the hydraulic barrier is localised and it is recommended that multiple sites throughout the swamp be identified where benefits may be realised from the increased inundation from a barrier. Suitable location of additional barriers may be determined from the topographic (LiDAR) data and results of modelling to determine potential impacts. In addition, the results from parallel studies including the vegetation study and the geochemical study may help locate the barriers in areas that have the highest likelihood of providing benefit to the swamp. Further, the results of the hydraulic model for a number of flow rates demonstrated that there are diminishing returns with increasing supplementary flows. Hence, a modest supplementary flow with multiple hydraulic barriers may provide the greatest benefit and limit the export of acid water. It is recommended the initial concept developed here is examined in the future with multiple barriers.

The groundwater model includes significant levels of uncertainty that arise from our inability to accurately map and characterise local scale heterogeneities that are important in controlling groundwater behaviour in the local scale. In this regard it is no different from all other groundwater models and simply reflects the fact that the model behaviour is controlled by underground features that cannot be seen, measured or even inferred from the surface. Dealing with model uncertainty is an active area of research and numerical methods are now available to help illustrate the likely error bars associated with any particular prediction. We recommend that quantitative uncertainty analysis be included in future modelling investigation of Boundary Creek and Big Swamp. Understanding the potential errors included in predictions will help clarify the level risk of associated with the use of model results that are not necessarily precise.

10. References

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Appendix A. Rainfall-runoff modelling details

In order to understand the hydrological characteristics of the catchment a rainfall-runoff model was developed. In addition to characterising the catchment in terms of hydrology, the model was used to:

- The streamflow in Boundary Creek downstream of McDonalds Dam (at streamflow gauge 233229) and at Yeodene (at streamflow gauge 233228) to infill missing gauged data;
- Catchment runoff for the intermediate catchment between McDonalds dam and Yeodene; and
- These outputs were subsequently used to inform the loss analysis and infill streamflow series inputs used as part of the hydraulic model.

A continuous daily GR4J rainfall-runoff model was created to produce an estimate of the surface runoff in response to input climate conditions (represented by a timeseries of both rainfall and potential evapotranspiration). The transformation of climate inputs into runoff is controlled by the model structure and parameters.

This section provides background on the continuous rainfall-runoff model, describes the model build and presents the results.

A.1 GR4J

GR4J (Perrin et al., 2003) is a conceptual daily timestep rainfall-runoff model which can be applied in a lumped or semi-distributed fashion. The structure of GR4J is illustrated in Figure 10-1; rainfall can be discharged to two stores (a production store (X1) and a routing store (X3)) or routed overland. Water stored in the routing store is partitioned into a quick and slow flow component which are routed by a unit hydrograph for each partition, the time base of which is controlled by X4. Water can also be exchanged (gained or lost) from a conceptual groundwater store which is represented by X2.

A description of each of the GR4J parameters is provided in Table A.1: GR4J parameters (Perrin et al., 2003), together with typical parameter ranges. Calibration of a rainfall-runoff model involves adjusting the model parameters until the output matches, as closely as possible, the observed stream flows.

Table A.1: GR4J parameters (Perrin et al., 2003)

Parameter	Description	Units	Default	Range
x1	Capacity of the production soil (SMA) store	mm	350	1 - 1500
x2	Water exchange coefficient	mm	0	-10.0 - 5.0
x3	Capacity of the routing store	mm	40	1 - 500
x4	Time parameter for unit hydrographs	days	0.5	0.5 - 4.0

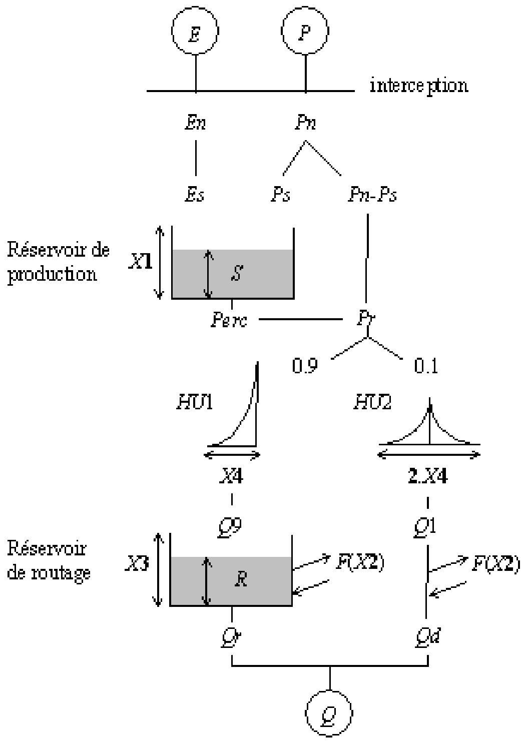

Figure 10-1: GR4J model schematic (Perrin et al, 2003)

A.1.1 Model build and catchment conceptualisation

The daily continuous GR4J rainfall-runoff model was built using the airGR software package available in the R programming language. airGR was developed by the Catchment Hydrology Research Group at Irestea (Coron, 2017) and is freely available online.

The model was conceptualised as two sub-catchments as shown in Figure 10-2 with outlets at:

- The downstream of McDonalds Dam gauge (233229); and
- The Colac-Forest Road by Yeodene gauge (233228).

Each sub-catchment required:

- Catchment area;
- A rainfall timeseries; and
- A PET timeseries.

Additionally, timeseries of observed streamflow, which may include missing data, was required for calibration and validation.

Figure 10-2: GR4J Model conceptualisation

A.1.2 Input climate data

The required climate input data for GR4J is daily rainfall and PET data over the simulation and warm-up period (see Table A.2). Catchment average rainfall and PET data which was derived from gridded SILO data was used (refer to Section 4.1). Daily PET for the missing period (July – September 2019) was infilled using the average daily PET for each month from July 1975 to June 2019. The resulting daily rainfall and PET series are presented in Figure 10-3 and Figure 10-4.

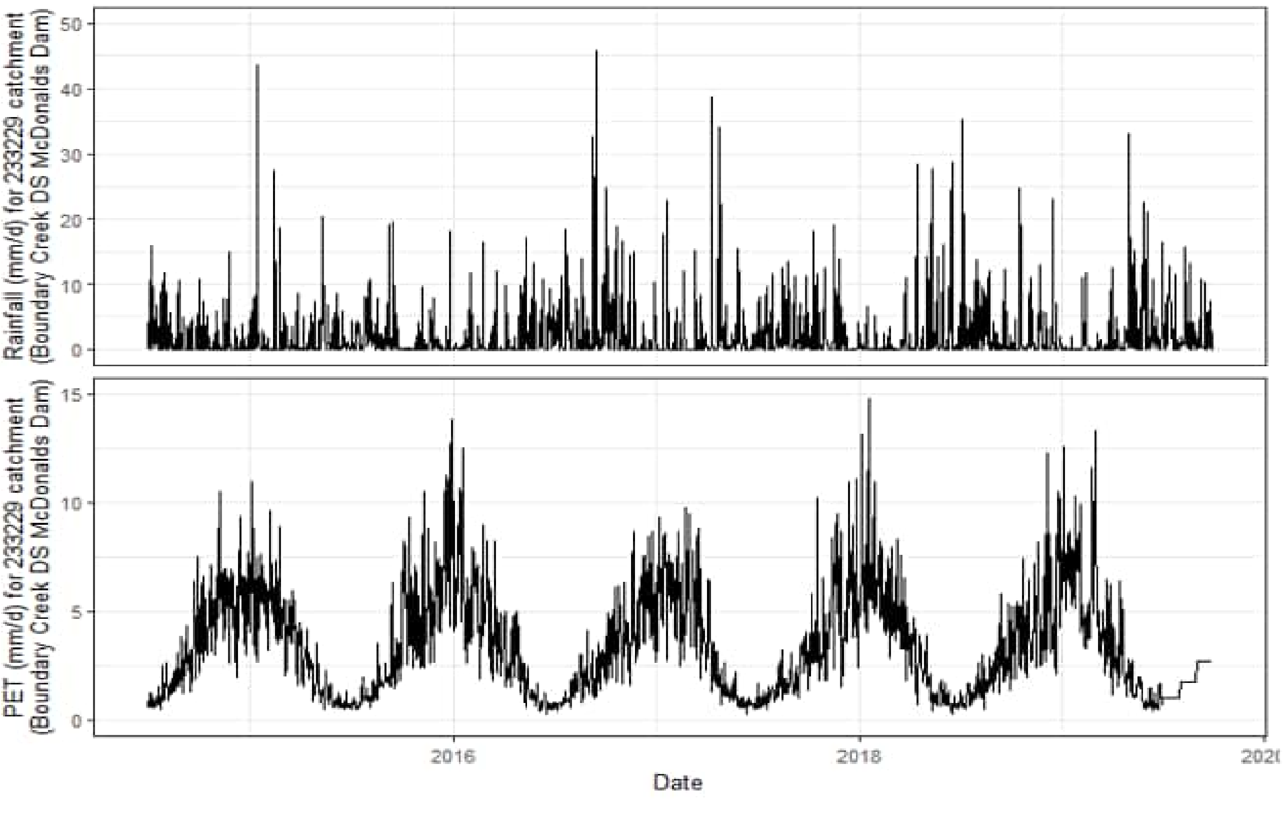

Figure 10-3: Climate inputs into the GR4J model which models the catchment upstream of streamflow gauge 233229

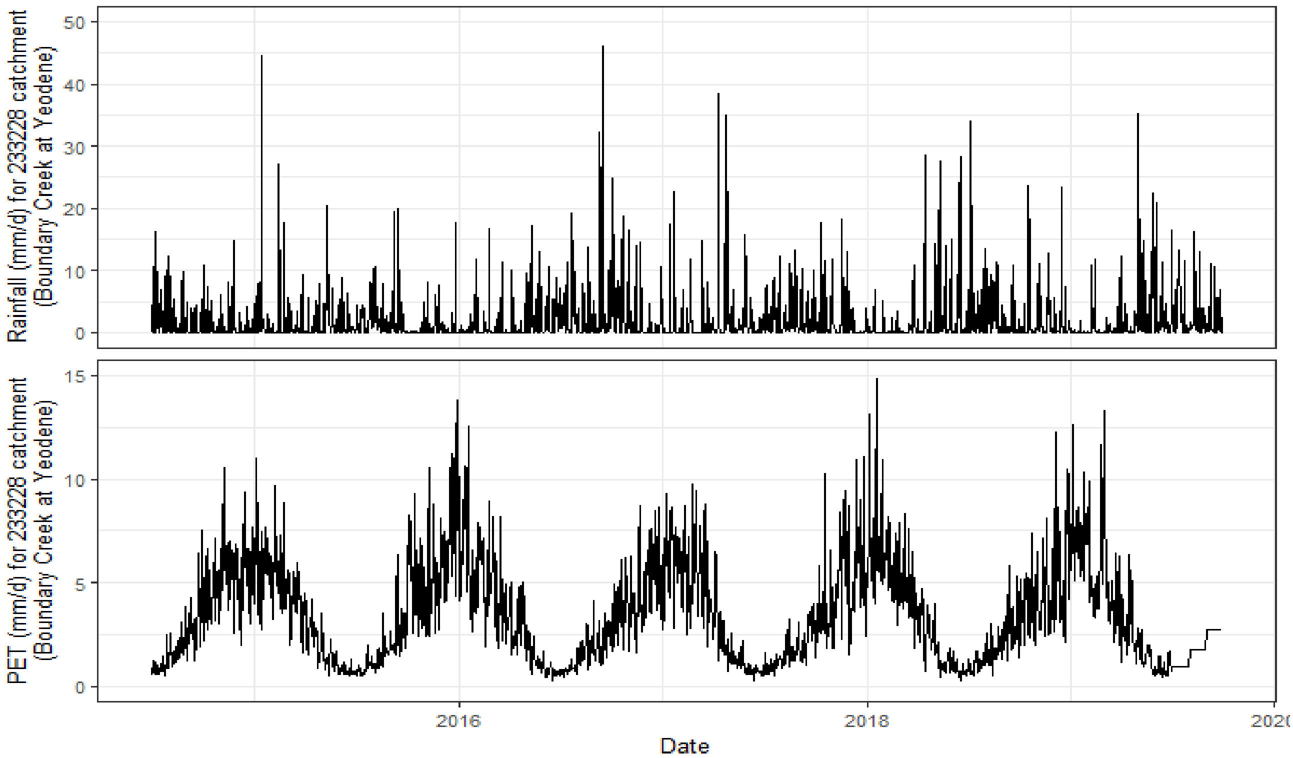

Figure 10-4: Climate inputs into the GR4J model which models the catchment upstream of streamflow gauge 233228

A.1.3 Streamflow data

Daily streamflow series are required for the calibration and verification runs so that the observed data can be compared against the simulated data to assess the goodness of fit. Observed data was sourced from the BoM Water Data Online (2019) as described in Section 4.1.

Due to the limited period of record for the two gauges immediately upstream and downstream of Big Swamp and the missing data over these periods, the streamflow gauges 233229 (Boundary Creek downstream of McDonalds Dam) and 233228 (Boundary Creek at Yeodene) were adopted as the key streamflow locations for this assessment.

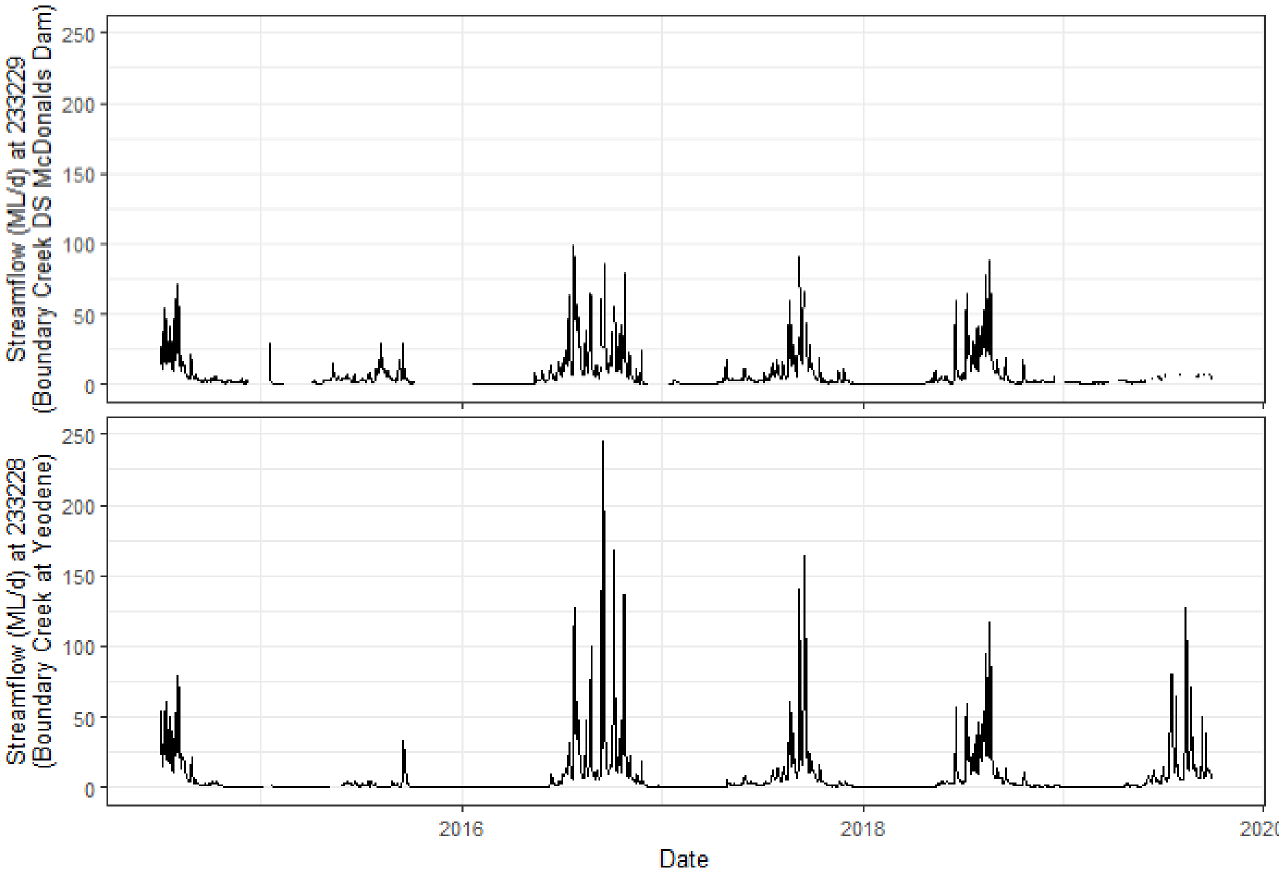

Figure 10-5: Streamflow data at the key streamflow gauges used as inputs into the GR4J model

A.1.4 Calibration / Validation

In undertaking a model calibration, a number of decisions need to be made, such as:

- What calibration method to use – manual or automatic?
- What calibration strategy to use?
- How to measure the fit of the model – what objective functions should be adopted?

These are discussed below.

Calibration method

In general, there are two options for undertaking calibration: manual calibration and automatic calibration. Manual calibration involves manually adjusting model parameters until an acceptable fit had been reached. Automatic calibration on the other hand uses computer algorithms to determine the optimal fit. In automatic calibration a model is run many times and the results compared to observed values. The best fit to the observed values is returned as the optimised parameter set.

Automatic calibration was selected as the calibration method for this assessment. Initially, the PORT optimisation routine (a gradient climbing algorithm) was used to estimate the best-fit parameters, using the parameter bounds and initial parameters as outlined in Table A.1: GR4J parameters (Perrin et al., 2003). The parameters of best fit for the GR4J model were then derived using a Bayesian Markov Chain Monte Carlo (MCMC) framework and specifically the Delayed Rejection Adaptive Metropolis (DRAM) algorithm. Three chains were used with different initial values to assess the convergence of the Markov chains. The number of iterations was fixed at 10,000 with a burning length of 10% (i.e. 1,000).

Calibration strategy

The calibration strategy refers to the way that the optimum parameter set is determined. There are a number of different strategies that can be used to calibrate a model. The most common approach is the *split sample technique* whereby the model is calibrated to a particular period and then validated against another period to assess how well the model performs outside of this period of calibration. Given the short length of available streamflow records a warm-up period of 6 months was used throughout this assessment and excluded from the goodness of fit assessment.

Table A.2: Assessment periods for calibration and validation presents the periods assessment for the split sample calibration.

Table A.2: Assessment periods for calibration and validation

Model period	Calibration	Validation
Warm-up period	01/07/2014 – 31/12/2014	1/07/2017 – 31/12/2017
Simulation period	01/01/2015 – 31/12/2017	1/01/2017 – 31/12/2018

Objective function

The objective function, in this context, aims to reduce the error between the observed and modelled flow series. In this study the daily Kling-Gupta Efficiency (KGE) (Gupta et al., 2009) was used. The KGE is a decomposition of the Nash-Sutcliffe Efficiency (NSE), which comprised different components (correlation, bias and variability) which address some of the limitation of Mean Squared Error (and hence the NSE).

A smaller KGE value is indicative of a poor fit, while a KGE of 1 indicates a perfect fit. Therefore, in order to successfully utilise KGE as the goodness of fit statistic, the automatic calibration attempts to minimise 1 – KGE.

Calibration results

To assess the performance of each GR4J catchment model a number of performance metrics were calculated as listed in Table A.3.

Table A.3: Summary flow metrics for model evaluation

Metric	Description	Range
Mean Error	Mean error between sim and obs.*	-inf to inf
Root Mean Square Error (RMSE)	Root Mean Square Error (RMSE) between sim and obs. RMSE gives the standard deviation of the model prediction error. A smaller value indicates better model performance*	0 to inf

Metric	Description	Range
Percent Bias (PBIAS)	Percent Bias between sim and obs.*	-inf to inf
Nash-Sutcliffe Efficiency (NSE)	The Nash-Sutcliffe efficiency (NSE) is a statistic describes the amount of variance explained by the model (Nash and Sutcliffe, 1970).	-inf to 1
Pearson Correlation coefficient (R)	Is a measure of the linear correlation between two variables obs and sim.	-1 to 1
Coefficient of Determination (R^2)	Describes the proportion of the variance in the sim series that is predictable from the obs series	0 to 1
Kling-Gupta Efficiency (KGE)	Is a goodness-of-fit measure developed by Gupta et al. (2009) to provide a decomposing of the NSE, facilitating the analysis of the relative important of its different components (i.e. correlation, bias and variability)	-inf to 1

A summary of the performance for each catchment is provided in Table A.4 for the goodness-of-fit statistics in Table A.4: Goodness-of-fit statistics. Diagnostic plots for two catchments are provided below to further illustrate the model performance.

Table A.4: Goodness-of-fit statistics

	RMSE	PBIAS	NSE	R	R^2	KGE
CALIBRATION						
233229	0.29	-37.70	0.57	0.79	0.62	0.51
233228	0.28	-1.70	0.66	0.83	0.69	0.83
VALIDATION						
233229	0.25	-15.80	0.75	0.87	0.76	0.74
233228	0.20	28.30	0.67	0.86	0.74	0.67

Calibration results

The MCMC analysis produced a Gelman and Rubin convergence of value of 1 which suggests an acceptable convergence. The posterior density for each parameter is presented in Figure 10-6 and the resulting parameters are presented in Table A.5. As can be observed the posterior density converges for X1 (p1), X2 (p2) and X3 (p3) close to 0 indicating little storage and exchange with groundwater.

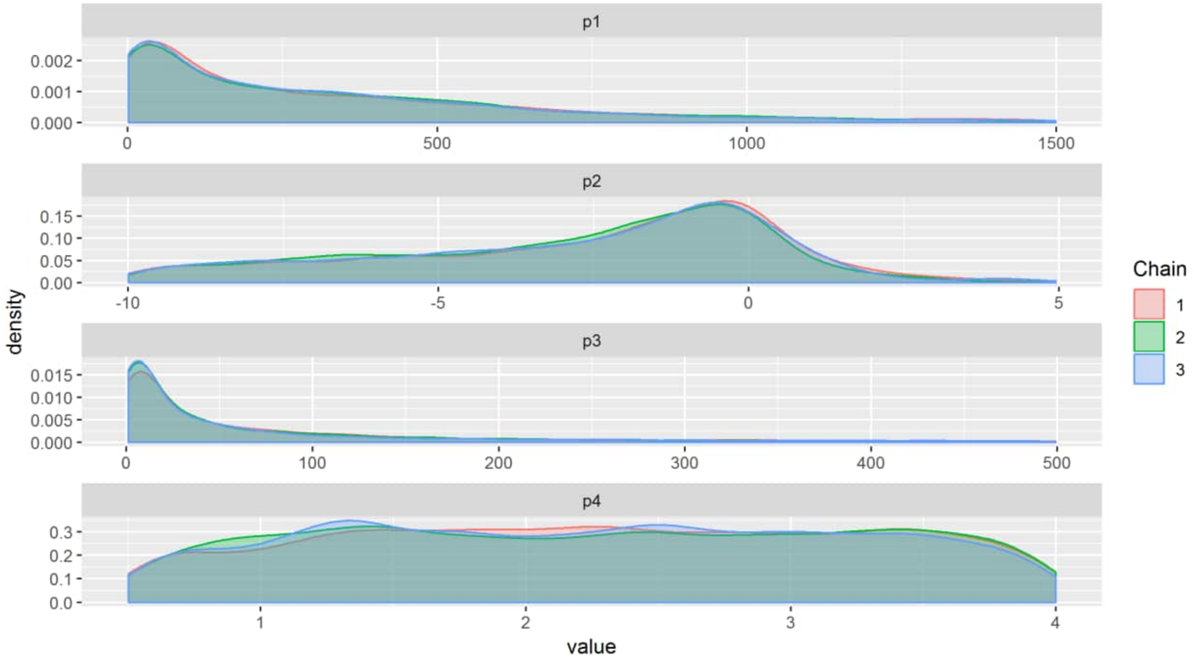

Figure 10-6: Posterior density of the GR4J parameters resulting from the MCMC calibration of the 233228 catchment. Note that p1 (x1) represents the production store capacity coefficient, p2 (x2) represents the intercatchment exchange coefficient, p3 (x3) represents the routing store capacity and p4 (x4) represents the unit hydrograph time constant.

Table A.5: GR4J calibrated parameters

X1	X2	X3	X4
418.69	-0.95	11.56	2.15

The calibration results for the upstream gauge (233229) are displayed in Figure 10-7 with the top two plots showing the observed rainfall and observed and simulated streamflow in mm/day, respectively. It can be seen in this hydrograph that the high flows and low flows occur at the same time for the simulated and observed records. The 30-day rolling mean plot (left bottom plot) indicates that the model is generally able to replicate flows throughout the year although the flows are systematically under predicted in the autumn/winter period (April to August). The flow duration curve (middle bottom plot) indicates that the model preforms better for higher flows. The final diagnostic plot indicates that the daily GR4J model highlights the systematic under prediction with points lying below the 1-1 line (right bottom plot). The goodness of fit statistics conforms these observations of the models calibration, with a KGE of 0.51 and a relatively large PBIAS of - 37%.

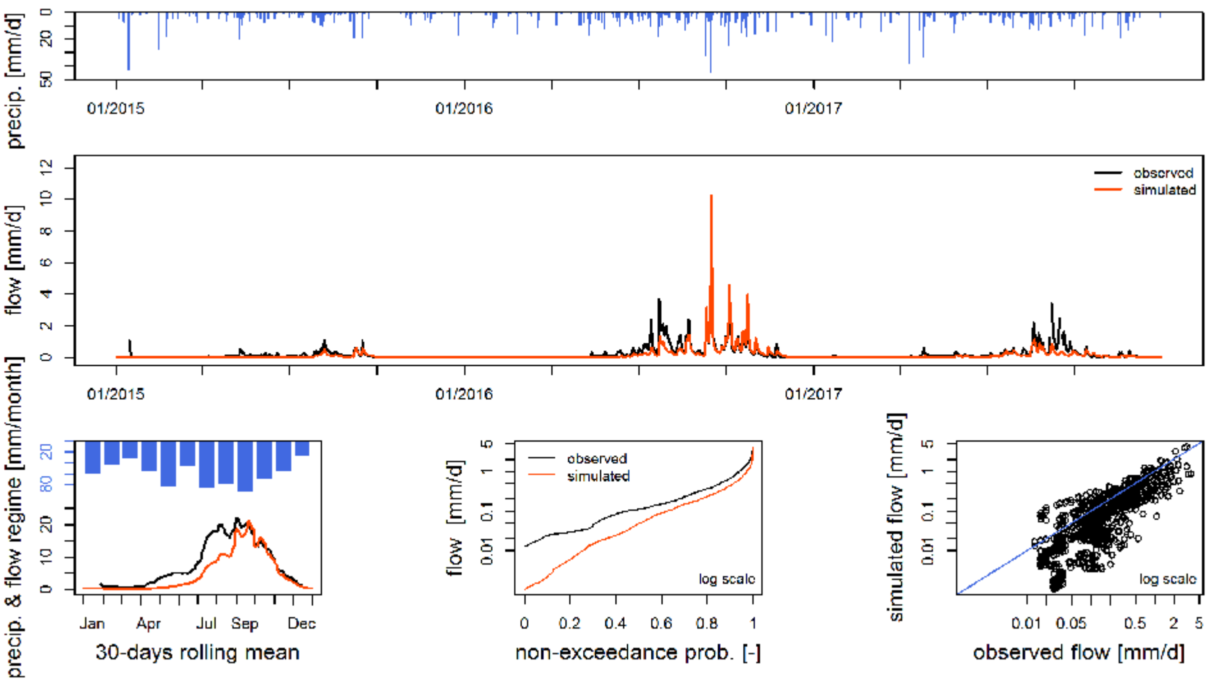

Figure 10-7: 233229 Calibration Diagnostic Plots

The calibration results for the downstream gauge (233228) are displayed in Figure 10-8 with the top two plots showing the observed rainfall and observed and simulated streamflow in mm/day, respectively. It can be seen in this hydrograph that the high flows and low flows occur at the same time for the simulated and observed records. The 30-day rolling mean plot (left bottom plot) indicates that the model is generally able to replicate flows throughout the year, whereas the flow duration curves (middle bottom plot) indicates that the model preforms well across the range of flows. The final diagnostic plot indicates that the daily GR4J model preforms well with points lying relatively close to the 1-1 line (right bottom plot). The goodness of fit statistics provides further evidence of the models ability to predict flows at 233228 over the calibration period, with a KGE of 0.83 and PBIAS within +/- 2%.

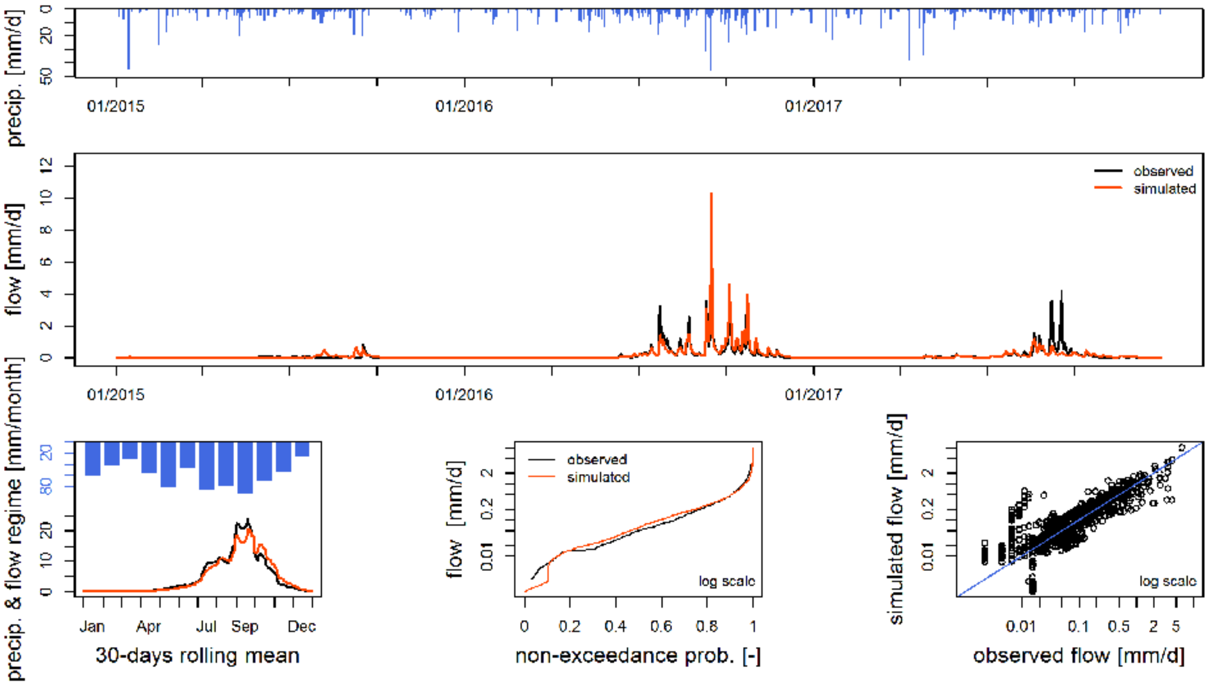

Figure 10-8: 233228 Calibration Diagnostic Plots

Validation results

Figure 10-9 and Figure 10-10 presents the diagnostic plots to assess the goodness of fit between the observed and simulated data over the validation period. In comparison to the calibration period, the model shows a better representation of streamflows at 233229 (the upstream gauge). Figure 10-9 shows that the model is better able to represent the medium and high flows, though the low flows are still underestimated.

The goodness of fit statistics for 233228 (the downstream gauge) over the calibration and validation periods is comparable. The PBIAS and KGE values indicate that the model does not perform as well over the validation period which is usually the case.

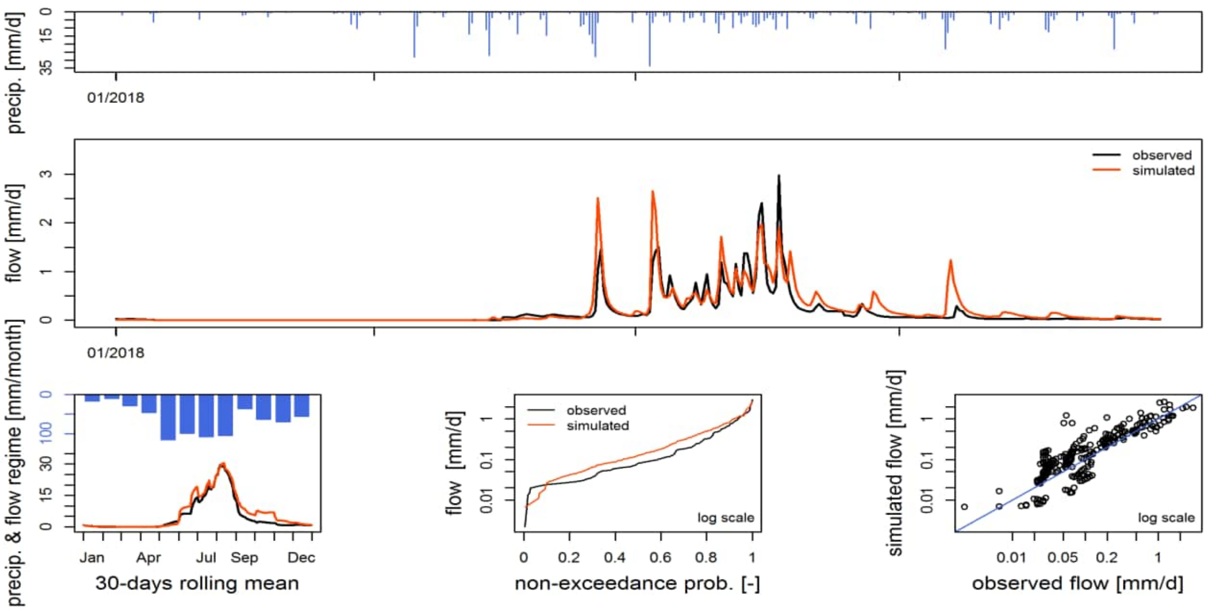

Figure 10-9: 233228 Validation Diagnostic Plots

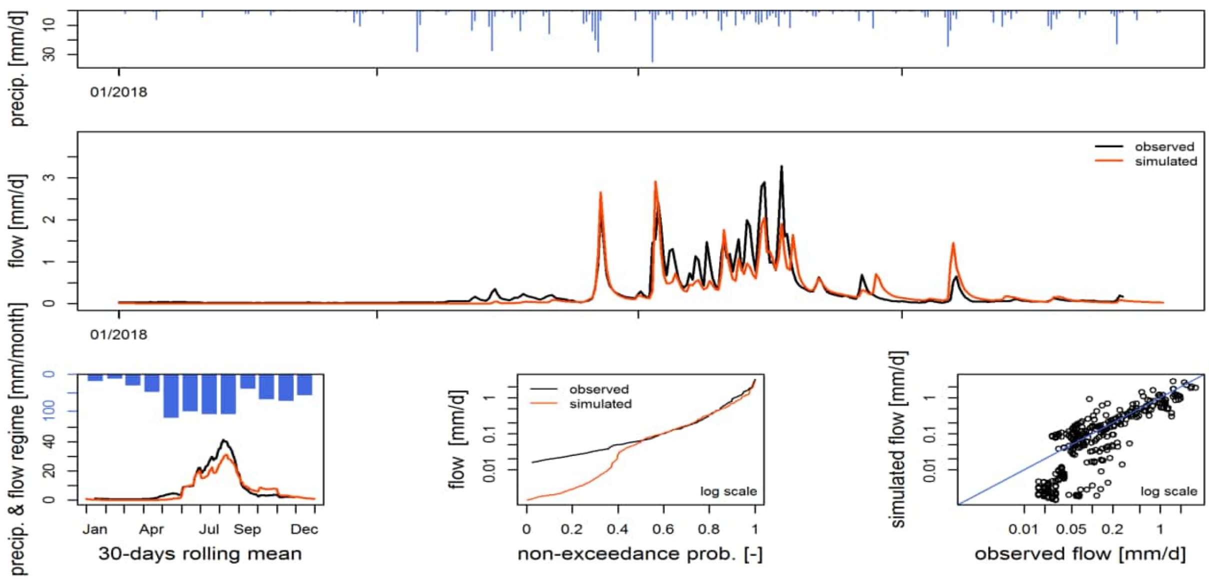

Figure 10-10: 233229 Validation Diagnostic Plots

Simulation results

After calibration and validation, the models were run over the full simulation period from 01/01/2015 – 30/09/2019, not including the 6-month warm-up period.

Figure 10-11 presents a flow duration curve of the timeseries outputs from the sub-catchment:

- Simulated flow at the gauge location 233229: Boundary Creek at Downstream McDonalds Dam
- Simulated flow at the gauge location 233228: Boundary Creek at Yeodene
- Simulated catchment runoff of the downstream gauge (which enters Boundary Creek between the two gauged locations).

A plot of average monthly flow (ML/d) is presented in Figure 10-12.

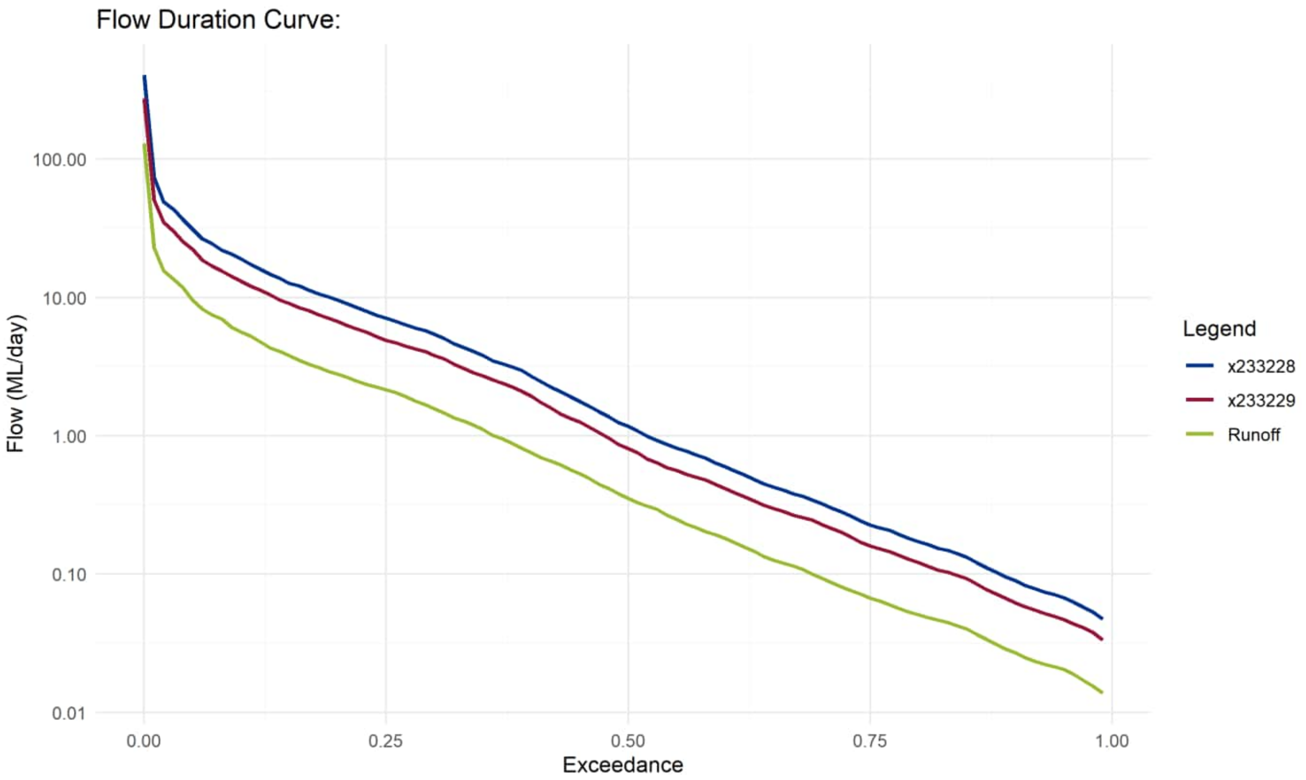

Figure 10-11: Exceedance curve of flow over the full record of simulation (1/01/2015 – 30/09/2019).

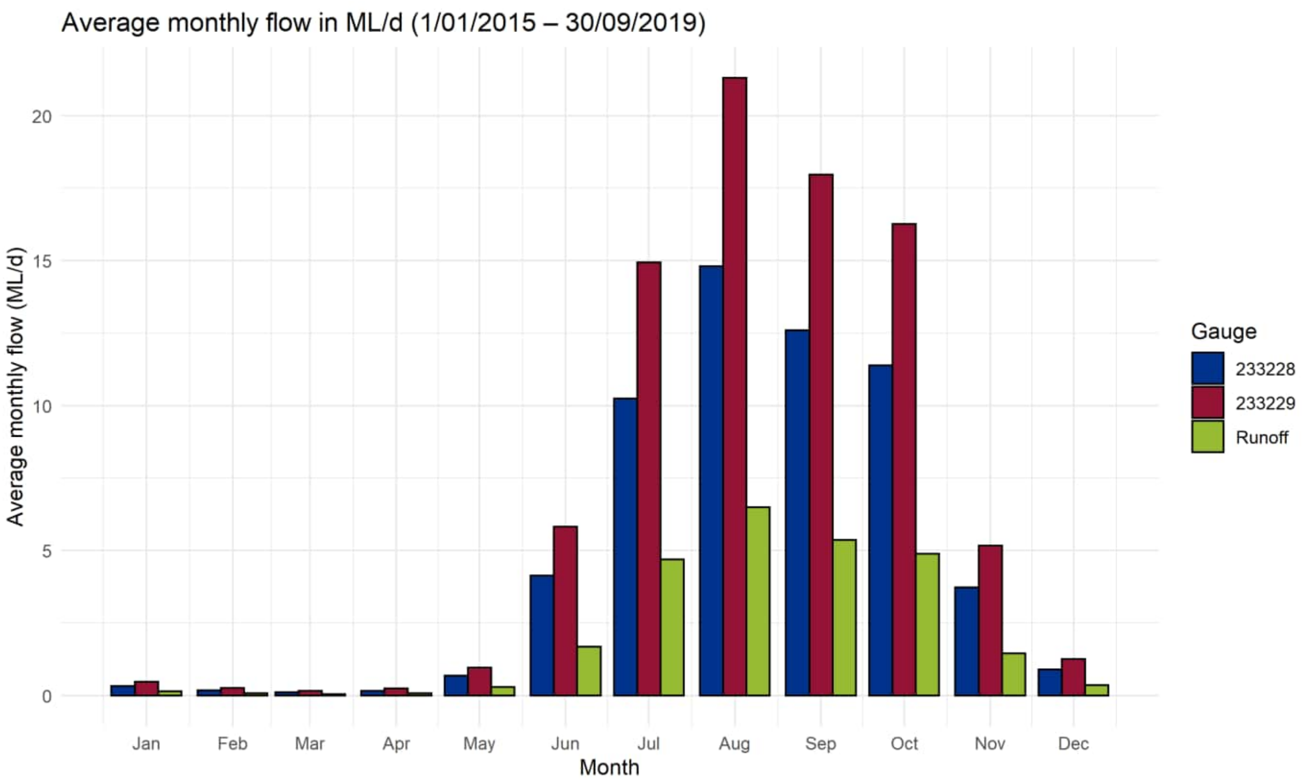

Figure 10-12: Average monthly flow (ML/d) over the full record of simulation (1/01/2015 – 30/09/2019)