GHD

Barwon Water

Big Swamp Integrated Groundwater-Surface Water Modelling for Detailed Design

Technical Modelling Report

April 2021

WATER | ENERGY & RESOURCES | ENVIRONMENT | PROPERTY & BUILDINGS | TRANSPORTATION

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1. Introduction

1.1 Purpose of this report

Big Swamp is a peat swamp located along Boundary Creek, which forms a tributary of Barwon River. The swamp comprises of pyritic sediments that form potential acid sulfate soils where the soils are waterlogged. The reduced flow along Boundary Creek due to a combination of drier climate, groundwater extraction from the Barwon Downs borefield and ineffective regulation of passing flow has led to the lowering of the water table in Big Swamp and activation of acid sulfate soils.

The Remediation and Environmental Protection Plan (REPP) developed for Boundary Creek, Big Swamp and surrounding environment outlines remedial works to stabilise the acidification process and improve the water quality of Big Swamp. These include controlled release of supplementary flow and construction of a series of hydraulic barriers to improve surface water connectivity across the swamp. In order to inform the detailed design of the remediation system, surface water and groundwater modelling is required to quantify the potential effectiveness of different flow regimes and barrier configurations on maintaining the water table in Big Swamp. This report details the findings of integrated surface water – groundwater modelling undertaken to meet this objective.

1.2 Modelling methodology

1.2.1 Modelling objectives

The overarching objective of the modelling is to inform the detailed design of the preferred remediation strategy of the Boundary Creek and Big Swamp system, specifically the hydraulic barrier configurations, supplementary flow regimes and their potential effectiveness in maintaining the water table within the swamp and flow downstream of the swamp.

The achieve this intended model use, the modelling is required to:

- simulate the existing hydrological and hydrogeological processes that are critical to understanding the effectiveness of the remediation strategy, including:
  - the extent, depth and duration of surface water inundation and associated effects on shallow groundwater levels.
  - rainfall recharge and evapotranspiration dynamics and influence of climate on the shallow groundwater system.
  - inter-aquifer connection, such as the rate and direction of leakage to/from the underlying Lower Tertiary Aquifer.
- simulate the interaction between the hydraulic barriers and surface water – groundwater systems, including changed extent, depth and duration of surface water inundation and associated effects on groundwater levels.
- simulate the interaction between Boundary Creek and groundwater, including the effect of supplementary flow regimes on maintaining flow within the swamp and immediately downstream.

The modelling detailed in this report has been commissioned to address specific design related questions such as the number, location and height of barriers that may be required to effectively redistribute surface water flow through a swamp that has a dimension of approximately 250 m by 800 m. The performance of the remediation strategy is also assessed against target groundwater levels set at monitoring bores that are located in close proximity to each other, with spacing as little as 25 m. This means the modelling must be of local scale, with fine grid resolution in critical areas and sufficiently flexible parameterisation to capture subtle spatial variability and associated uncertainty.

1.2.2 Modelling process

The integrated modelling described in this report has been undertaken in accordance with the staged approach of the Australian Groundwater Modelling Guidelines (Barnett et al, 2012). A project inception and model planning meeting was convened at the start of the project to clarify the scope, objectives and expectations of the modelling. This was followed by the conceptualisation, model design and construction, calibration, predictive modelling and uncertainty analysis. The report has been structured to reflect this staged approach, with each chapter aligned with the key stages of the modelling process.

1.3 Scope and limitations

This report: has been prepared by GHD for Barwon Water and *may only be used and relied on by Barwon Water for the purpose agreed between GHD and the Barwon Water as set out in section 1.2 of this report.*

GHD otherwise disclaims responsibility to any person other than Barwon Water arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (in various sections). GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared this report on the basis of information provided by Barwon Water and others who provided information to GHD (including Government authorities)], which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

2. Hydrological and Hydrogeological Conceptualisations

2.1 Purpose of conceptualisation

The general hydrology and hydrogeology of the Boundary Creek catchment and Big Swamp have been documented extensively in prior studies completed by Barwon Water (Jacobs, 2016, 2018a, 2018b, 2019a, 2019b, GHD, 2019). The purpose of hydrological and hydrogeological conceptualisations presented in this section is specific to the needs of the modelling that is the subject of this report and include targeted discussions on:

- Key updates to the existing hydrological and hydrogeological knowledge base, informed by additional data collected and findings from relevant scientific studies that have become available since the earlier studies were completed.
- Features of conceptual model that are of importance to the key model predictions of interest, and hence for strategically informing the design and attributes of the numerical models, including:
  - Hydrostratigraphy of Big Swamp, to inform model structure such as model mesh, layering and material properties.
  - Key hydrogeological processes and their significance, to inform model boundary conditions and sink/source terms. In particular, the elements of the hydrology and hydrogeology have not been sufficiently developed to date given the acid generation-specific objectives of the modelling.
  - Hydrogeological response time, to inform temporal discretisation (stress periods) and flow processes (saturated/unsaturated flow).
  - Inter-aquifer connection and the potential influence of piezometric head changes in the underlying Lower Tertiary Aquifer (LTA).

2.2 Hydrological conceptualisation

The hydrology has been conceptualised in terms of the hydrological processes at a catchment level, and the interactions between catchments, as shown in the following figures.

Catchment interactions

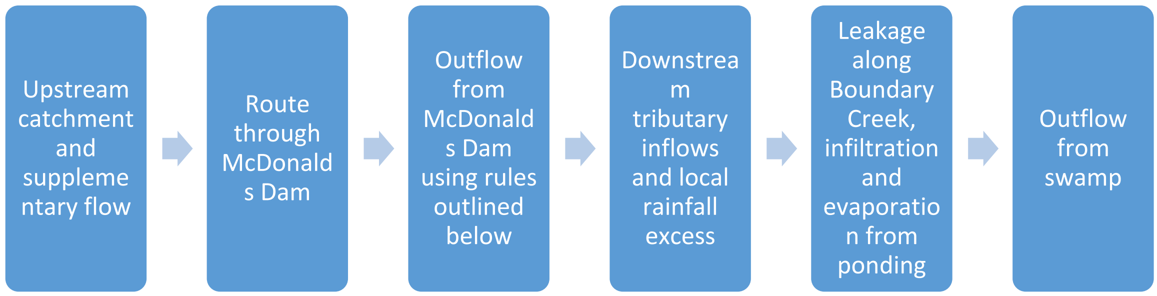


Figure 2-1 Surface water flow conceptualisation

The rules for routing through McDonald's Dam depend on the magnitude of flow, and whether or not it is the harvesting (filling) period for the dam. The decision tree for this is presented in Figure 2-2 below.

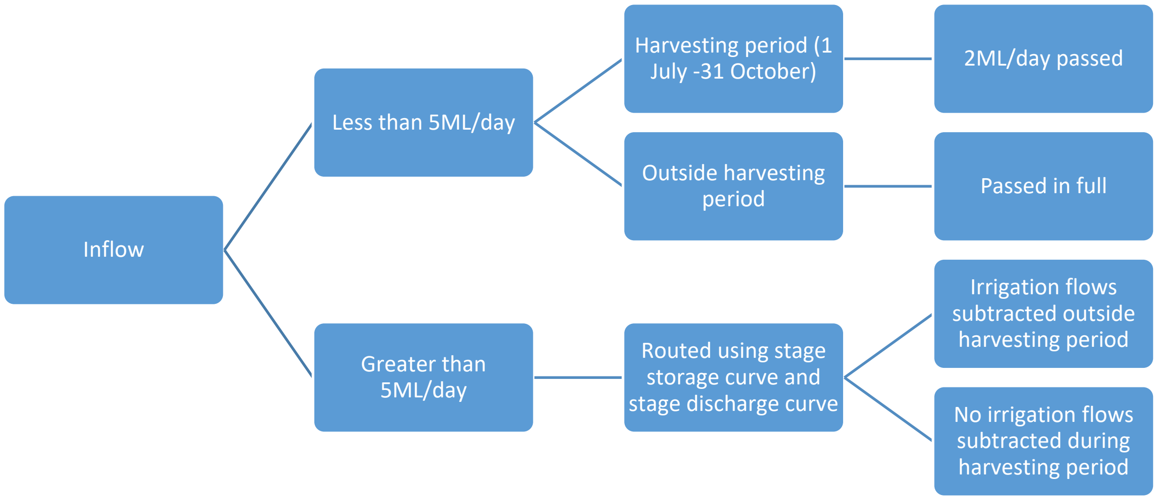


Figure 2-2 Routing rules through McDonald's Dam

Hydrological processes within the catchments in the hydrological model

The mechanisms by which flow is generated in the GR4J hydrological model are illustrated in Figure 2-3 following. The model consists of a production store (soil moisture) and routing store. The routing store determines the groundwater exchange, and therefore the total streamflow from the combined direct and routed flow components.

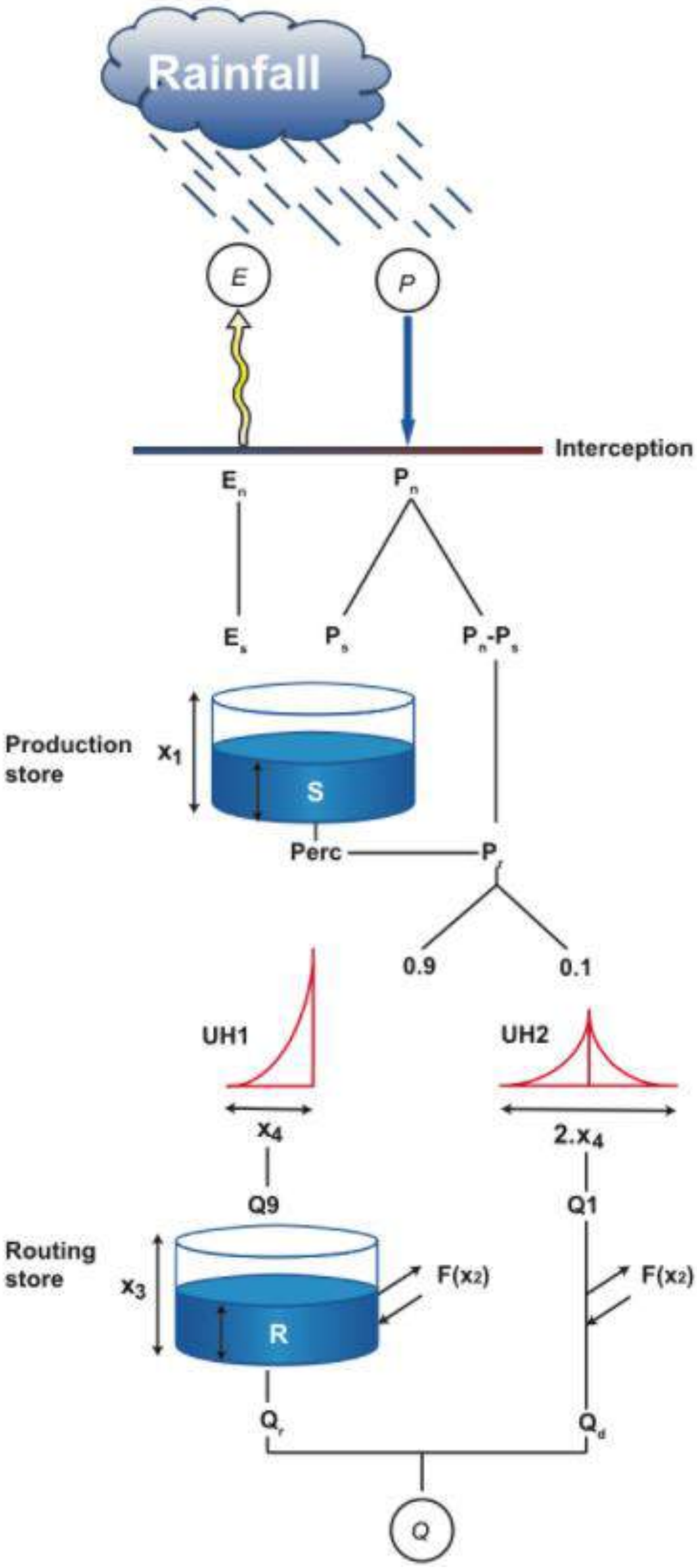


Figure 2-3 GR4J model schematic (from E-Water Source)

Hydrological processes within the hydraulic model domain

The mechanisms by which flow is generated or removed in the hydraulic model domain are illustrated in Figure 2-4.

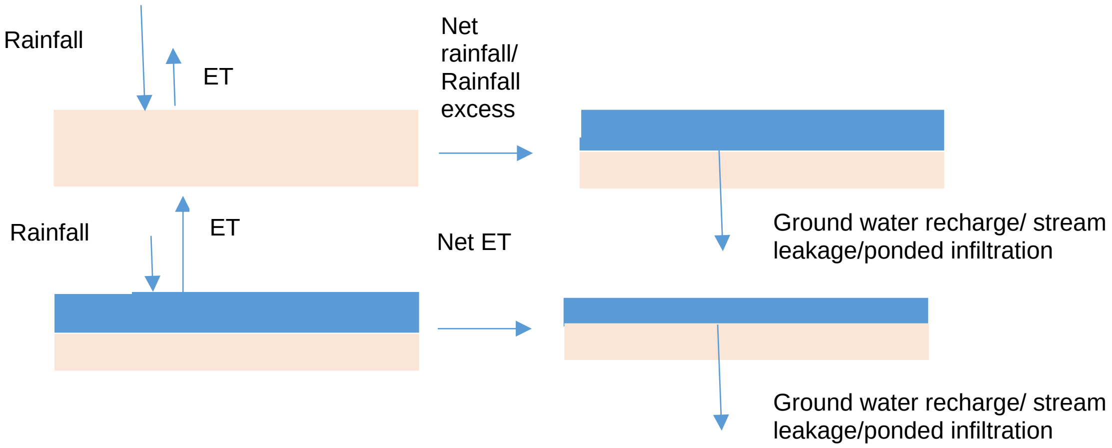


Figure 2-4 Hydrological conceptualisation in the hydraulic model

There are three methods available within TUFLOW to infiltrate water on the 2D surface into the sub-surface. These are Green-Ampt, Horton and Initial Loss/Continuing Loss. The models are used to represent hydrological losses particularly when rainfall is applied directly to the 2D surface and runoff is generated. The infiltration module used, and the parameters selected, are important calibration parameters. The hydraulic conductivity, in conjunction with the initial moisture content, which would be the parameters that are most focused on. The hydraulic conductivity appears to affect the runoff volume throughout the event whereas the initial soil moisture has a limited impact at the beginning of the event before soils become saturated and results converge.

2.3 Hydrogeological conceptualisation

2.3.1 Big Swamp hydrostratigraphy

Aquifer geometry

Big Swamp is located within a narrow alluvial aquifer system, comprising channel-filled sediments associated with Boundary Creek. The width of the alluvial aquifer, as mapped in published geological maps (as sediments of Quaternary age), generally aligns with the topographic valley which is incised into the underlying older strata comprising the Gellibrand Marl (a regional Middle Tertiary Aquitard) and Mepunga/Dilwyn Formation (Lower Tertiary Aquifer). According to published geological maps, the stratigraphic contact between the Gellibrand Marl and Mepunga/Dilwyn Formation occurs approximately in the middle of Big Swamp, traversing in roughly north to south orientation.

Drilling in 2019 confirmed that the alluvial aquifer (hereafter referred to as the Quaternary Aquifer) underlying Big Swamp consists of clay, silt and sand of at least 6 m in thickness. The full thickness of the Quaternary Aquifer (QA) across the swamp is currently not known, although drilling of a nested monitoring site at the downstream end of the swamp indicated predominantly clay formation to a depth of around 26 m. At this location, three nested bores were constructed by Jacobs (2016) at depths of 11.7 m (TB1a), 19 m (TB1b) and 36 m (TB1c). According to Jacobs (2016), bores TB1a and TB1b are constructed in the QA and Middle Tertiary Aquitard (MTD) respectively, although this boundary is not well defined due to similarity in their lithology (potentially demarcated by around 1 m thick coarse sand at 13 m). At depth of 26 m, a coarse sand layer of at least 10 m in thickness was encountered. This defines the top of the Lower Tertiary Aquifer (LTA) within which bore TB1c was constructed.

Drilling records from the state database indicate several bores further upstream of Boundary Creek that were drilled near the creek line to depths ranging from around 15 to 30 m using the mechanical auger drilling method. These bores include 109130, 109143 and 109128 (from upstream to downstream), which are part of the State Observation Bore Network (SOBN) and are indicated to be constructed in the Dilwyn Formation (see Figure 2-12). Lithological logs are not available from these sites, although the information recorded at the time of drilling indicates that these bores were drilled to 17.5 m, 24 m and 30 m. According to Jacobs (2016), bore 109130, furthest upstream, is screened from 8 to 15.5 m, and bore 109143 is screened from 11.5 to 17.5 m. This information suggests that the QA is likely to be <8 m in the upstream reach of Boundary Creek, near McDonalds Dam, and increases in thickness downstream, consistent with the depositional setting of a typical alluvial system.

The FEFLOW groundwater model developed by Jacobs (2019a) assumed a constant nominal thickness of 10 m for the QA along the entire length of the model domain. However, it is more likely that:

- the QA gradually increases in thickness along the length of Boundary Creek and Big Swamp, from less than 8 m adjacent to McDonalds Dam to potentially 14 m in the downstream end of the swamp where the nested monitoring site exists.
- the thickness of QA tapers off towards the edge where it pinches out against the bedrock (LTA/MTD), more consistent with a typical geometry of channel-filled alluvial aquifers.
- the width of the QA at Big Swamp is wide enough to include the nested site TB1, where Jacobs (2016) indicates the QA is at least 12 m in thickness (based on the TB1a bore depth). The QA currently represented in the FEFLOW model does not extend this far.

While a rectangular block of uniform thickness may be considered a reasonable approximation of average geometry, a more realistic representation of the aquifer geometry is considered warranted in this study to better account for the expected changes in aquifer transmissivity and storage along Boundary Creek and towards the edge of the aquifer (see Figure 2-5).

Hydrogeological properties

A key feature of the available data pertaining to aquifer and aquitard hydraulic properties is that they are derived from slug tests, which are generally considered to be of low reliability. Data from other tests such as pumping and packer tests are considered more reliable, but these are not available for this study. The slug test data discussed in this section are therefore useful in broad terms, but their low reliability means wider parameter bounds may be ultimately required during model calibration to adequately replicate the observed hydrogeological response.

The QA comprises predominantly of clay, with minor silts and discrete lenses of sand (which can be up to 3 m along the basal level in some bores). Hydraulic conductivity derived from the analysis of slug tests is variable, ranging from 0.02 to 1.4 m/d with a geometric mean of around 0.2 m/d. There appears to be little relationship between the hydraulic conductivity values derived from slug testing and abundance of sand or clay in a particular bore. This can be seen in Figure 2-6, which summarises the key information from each monitoring bore. For example, low hydraulic conductivity of 0.13 and 0.05 m/d was estimated at BH14 and BH16 respectively despite the presence of 2.5 and 3.2 m of sand and clayey sand respectively. Conversely, the highest hydraulic conductivity of 1.4 m/d was estimated at BH06 comprising predominantly of silty clay.

The implication is that spatial variability in hydraulic conductivity exists within the QA but this cannot be readily associated with a particular lithological material. This means the model should be parameterised to allow spatial variability, albeit without explicit representation of discrete sand and clay lenses as separate model layers which is not feasible based on the lithological data available. As further discussed in Section 2.3.2, the data available from the monitoring bores within Big Swamp capture the net response of the QA at the location of the bores and as such, the groundwater model should be discretised and parameterised at a resolution appropriate for simulating this observed net response (after accounting for the resolution required to satisfy numerical accuracy).

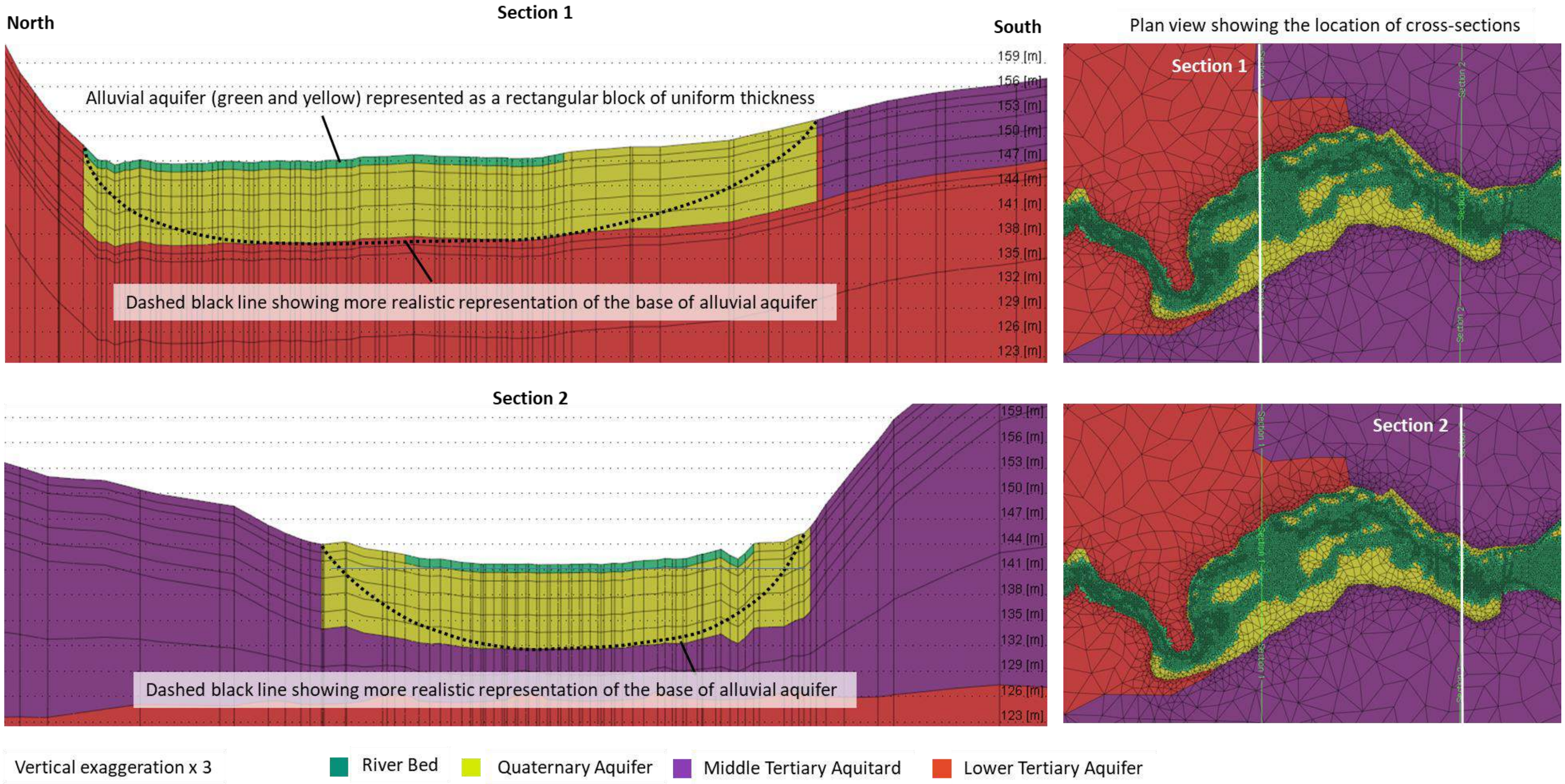
Jacobs (2016) completed slug testing in several bores constructed within the broader Boundary Creek catchment. One of the bores constructed within the QA had a hydraulic conductivity of up to 4.7 m/d (bore Tb2b) and indicates the potential for locally elevated hydraulic conductivity to exist within the QA (e.g. local sand lens). The analysis of data at two bores (A2 and A3) constructed within the MTD downstream of Big Swamp indicates low hydraulic conductivity ranging from 1.8×10^{-5} to 8×10^{-3} m/d. The calibrated hydraulic conductivity of the MTD in the existing FEFLOW model is 7.6×10^{-3} m/d, towards the upper end of this range, although data collected in areas further away from Big Swamp indicates hydraulic conductivity of up to 0.3 m/d (Jacobs, 2016).

For the LTA, slug testing was completed only on bores further to the west of Boundary Creek, with hydraulic conductivity ranging from 9.2×10^{-5} to 0.11 m/d (Jacobs, 2016). Where the bores are shallow and the sand/gravel is abundant, the hydraulic conductivity is generally towards the upper end of this range. The calibrated hydraulic conductivity of the LTA in the existing FEFLOW model is 1.45 m/d, greater than the range reported by Jacobs (2016) from slug testing and is considered to reflect the understanding of hydraulic conductivity from other regional studies. Given the presence of sand at TB1c, high hydraulic conductivity is plausible in the upper part of the LTA in the area of Big Swamp.

Key findings:

- The nominal 10 m thickness assumed in the existing FEFLOW model is considered simplistic and should be modified to account for the thickening of the aquifer along Boundary Creek and Big Swamp, with the aquifer geometry modified from the rectangular block currently assumed to a more realistic channel-filled geometry with some adjustments to its width.
- The QA in the model should be parameterised to allow spatial variability in hydraulic conductivity; however, explicit representation of discrete lenses of clay and sand as separate model layers is not necessary due to the lack of correlation between hydraulic conductivity and sand/clay abundances as well as the discrete nature of lithologic units rendering layer-based representation unsuitable.

Figure 2-5 Big Swamp alluvial aquifer representation in FEFLOW model



Item	BH17
Ground level (mAHD)	148.10
Screen top (mbgl)	1.90
Screen bottom (mbgl)	4.90
Min DTW (mbgl)	0.53
Max DTW (mbgl)	1.94
Average K (m/d)	0.05
Clay thickness (m)	2.00
Silt thickness (m)	0.80
Sand thickness (m)	3.2

Item	BH16
Ground level (mAHD)	147.99
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	1.02
Max DTW (mbgl)	2.29
Average K (m/d)	1.79
Clay thickness (m)	4.10
Silt thickness (m)	0.40
Sand thickness (m)	1.5

Item	BH12
Ground level (mAHD)	147.20
Screen top (mbgl)	1.90
Screen bottom (mbgl)	3.40
Min DTW (mbgl)	0.81
Max DTW (mbgl)	1.60
Average K (m/d)	0.82
Clay thickness (m)	2.20
Silt thickness (m)	NA
Sand thickness (m)	1.2

Item	BH10
Ground level (mAHD)	144.31
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	0.41
Max DTW (mbgl)	1.73
Average K (m/d)	1.26
Clay thickness (m)	4.40
Silt thickness (m)	1.60
Sand thickness (m)	NA

Item	BH05
Ground level (mAHD)	143.08
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	0.00
Max DTW (mbgl)	0.99
Average K (m/d)	0.05
Clay thickness (m)	3.90
Silt thickness (m)	2.10
Sand thickness (m)	NA

Item	BH07
Ground level (mAHD)	142.50
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	-0.56
Max DTW (mbgl)	0.28
Average K (m/d)	0.02
Clay thickness (m)	5.50
Silt thickness (m)	0.50
Sand thickness (m)	NA

Item	BH03
Ground level (mAHD)	141.74
Screen top (mbgl)	2.50
Screen bottom (mbgl)	4.00
Min DTW (mbgl)	-0.53
Max DTW (mbgl)	0.20
Average K (m/d)	0.03
Clay thickness (m)	2.40
Silt thickness (m)	1.60
Sand thickness (m)	NA

Item	BH09
Ground level (mAHD)	144.36
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	0.59
Max DTW (mbgl)	1.46
Average K (m/d)	1.31
Clay thickness (m)	1.80
Silt thickness (m)	4.20
Sand thickness (m)	NA

Item	BH06
Ground level (mAHD)	142.90
Screen top (mbgl)	1.90
Screen bottom (mbgl)	4.90
Min DTW (mbgl)	0.29
Max DTW (mbgl)	1.49
Average K (m/d)	1.44
Clay thickness (m)	4.50
Silt thickness (m)	1.50
Sand thickness (m)	NA

Item	BH18
Ground level (mAHD)	148.72
Screen top (mbgl)	1.50
Screen bottom (mbgl)	3.00
Min DTW (mbgl)	0.52
Max DTW (mbgl)	1.58
Average K (m/d)	NA
Clay thickness (m)	3.00
Silt thickness (m)	0.20
Sand thickness (m)	NA

Item	BH15
Ground level (mAHD)	147.42
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	-0.15
Max DTW (mbgl)	1.24
Average K (m/d)	0.15
Clay thickness (m)	6.00
Silt thickness (m)	NA
Sand thickness (m)	NA

Item	BH14
Ground level (mAHD)	147.67
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	0.82
Max DTW (mbgl)	1.65
Average K (m/d)	0.13
Clay thickness (m)	1.50
Silt thickness (m)	2.00
Sand thickness (m)	2.5

Item	BH11
Ground level (mAHD)	147.09
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	0.65
Max DTW (mbgl)	2.09
Average K (m/d)	0.35
Clay thickness (m)	4.80
Silt thickness (m)	0.30
Sand thickness (m)	0.9

Item	BH08
Ground level (mAHD)	144.62
Screen top (mbgl)	1.90
Screen bottom (mbgl)	4.90
Min DTW (mbgl)	0.51
Max DTW (mbgl)	1.11
Average K (m/d)	0.10
Clay thickness (m)	3.70
Silt thickness (m)	0.30
Sand thickness (m)	2.0

Item	BH04
Ground level (mAHD)	143.37
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	-0.03
Max DTW (mbgl)	0.34
Average K (m/d)	0.09
Clay thickness (m)	0.80
Silt thickness (m)	4.70
Sand thickness (m)	0.5

Item	BH02
Ground level (mAHD)	141.75
Screen top (mbgl)	2.20
Screen bottom (mbgl)	3.70
Min DTW (mbgl)	-0.54
Max DTW (mbgl)	0.26
Average K (m/d)	0.08
Clay thickness (m)	2.50
Silt thickness (m)	1.20
Sand thickness (m)	NA

Item	BH01
Ground level (mAHD)	141.86
Screen top (mbgl)	2.00
Screen bottom (mbgl)	5.00
Min DTW (mbgl)	-0.35
Max DTW (mbgl)	0.40
Average K (m/d)	0.21
Clay thickness (m)	3.80
Silt thickness (m)	2.20
Sand thickness (m)	NA

Legend

Groundwater bore

Paper Size ISO A3

0 20 40 60 80

Metres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 54

N

GHD

Barwon Water
Big Swamp Modelling for Detailed Design

Project No. 12536659
Revision No. B
Date 12/10/2020

Big Swamp Bores: Bore Details

FIGURE 2-6

N:\AU\Melbourne\Projects\31\12536659\GIS\Maps\Deliverables\31_12536659_01_BoreDetails_A3L_RevB.mxd
Print date: 08 Apr 2021 - 18:01

Data source: Barwon Water, Imagery, 2019; Jacobs, Bore Locations, 2019; GHD, bore details, 2020; . Created by: bsmyth (tworth)

2.3.2 Hydrogeological processes and response

The objective of the proposed remediation strategy is to maintain the water table within the Big Swamp QA to the required target levels to prevent activation of acid sulfate soils. In order to simulate the effectiveness of this remediation strategy, the groundwater model must be capable of simulating the processes that control the water table elevation i.e. the inflow and outflow components of the QA water balance that control the volume of shallow groundwater. The critical hydrogeological processes are:

- Recharge processes, such as surface water inundation and rainfall-recharge that maintain the water table; and
- Discharge processes such as evapotranspiration and aquifer through-flow, which influence the rate of drainage of shallow groundwater.

Recharge processes

Figure 2-7 compares the depth to water hydrograph of some of the representative monitoring bores against the stream flow data from upstream gauge 233275A. Also highlighted on the hydrographs are distinct flow events and associated spikes observed in groundwater levels. The hydrographs indicate that:

- the groundwater level in the QA rises rapidly following an increase in stream flow, which is expected given the depth to water table preceding some of the high flow events are less than 1 m. This means the unsaturated zone preceding most flow events is generally small, resulting in minimal "lag" in the water table response. Within the context of modelling, this implies that the simulation of unsaturated flow processes (and corresponding high vertical grid resolution in the top 1 m) is unlikely to be critical for replicating the rapid response/water table fluctuation to stream inundation events. This is also relevant under predictive conditions, given that the remediation strategy is designed to maintain the water table to generally within 1 m of ground surface. This has an important implication for modelling, as the simulation of unsaturated flow processes and corresponding vertical grid resolution can add a significant computational burden and run time.
- While there is short term (high frequency) variability, the onset of rise in groundwater level can be delineated into a total of 21 distinctive flow events for the period of monitoring data. For each flow event, the time it takes for the water table to reach peak elevation ranges from 2 to 8 days with an average of around 4 days. This provides a useful indication of the length and number of stress periods required to adequately simulate the seasonal water table response in the groundwater model i.e. at least 40 stress periods for a monitoring period of 14 months. The implication is that the model would need to be designed to accommodate potentially a large number of stress periods, in order to simulate flow/inundation events under a range of possible future conditions and to enable progressive updates of the model, if required, as additional data become available. A level of simplification, where this is immaterial to the outcome of modelling (for example, neglecting unsaturated flow), would be necessary for the model to simulate the seasonal dynamics over an extended period.
- Due to the rapid water table response, the water table fluctuation method can be applied to derive indicative infiltration (recharge) rates associated with each flow event. Assuming specific yield ranging from 0.05 to 0.1 (based on the porosity used in Jacobs' FEFLOW model), the infiltration rate is estimated to range from 2 to 18 mm/d.

The hydrographs indicate a period of low flow from December 2019 to April 2020, which is accompanied by a gentle decline in the groundwater levels followed by a rise. There are spatial differences in the timing of this groundwater level response, which are further examined in Figure 2-8. The figure shows the stream level at downstream gauge 233276A steadily declines over this period, reaching close to zero in February 2020, while the stream level at the upstream gauge is maintained at around 0.1 m above gauge zero. The same trend is also seen in the flow data, indicating a net loss (stream leakage) along the length of the swamp (note the stream levels are used in this figure instead of flow to more clearly show the peak levels, which are truncated at 12 ML/d for flow). This means Boundary Creek continues to act as a losing stream during drier periods and this is supported by the elevation along the creek line (based on the processed DEM), which is generally above the groundwater elevation in the adjacent bores.

Figure 2-8 shows that the onset of the rising trend in upstream bores BSBH16 and BSBH17 is earlier and more pronounced than the trend seen in downstream bores BSBH07 and BSBH10, potentially reflecting earlier/more stream leakage in the upstream end. This suggests that time-varying stage along Boundary Creek (and appropriate temporal discretisation) would be necessary in the groundwater model to reflect spatial variability in leakage during dry periods and associated response in the QA.

There are also spatial differences in the range of seasonal variations in the groundwater level. Figure 2-9 shows an example of groundwater contours for wet and dry periods and the difference between the two contours. This spatial difference can also be inferred from Figure 2-9, based on the difference between the minimum and maximum depth to water. In general, the range of seasonal variation is greater closer to the alignment of Boundary Creek (northern boundary of the swamp) and decreases further downstream. An area of negative difference is centered on a shallow bore BSBH18 and this is due to anomalously low water levels recorded at this bore up to October 2019.

In addition to surface water inundation, rainfall recharge provides an additional source of inflow into the QA. Figure 2-10 shows that hydrographs generally follow the cumulative departure from mean daily rainfall trend, although this is expected as surface water inundation is also climate (rainfall) driven. For the period from June 2019 to August 2020, the most significant fluctuations generally appear to be caused by surface water inundation; however, it is not apparent from hydrographs alone the extent to which diffuse recharge has contributed to the maintenance of the water table. For example, the extent to which diffuse recharge over preceding months has influenced the water table prior to the onset of surface water inundation events (such as the early onset of the rising trend seen at bore BSBH16 in Figure 2-8). This is important because inflow due to rainfall recharge can accumulate in aquifer storage over time, which could influence how the water table responds to inundation events of different extent and duration under different climatic conditions. From the point of view of modelling, both recharge processes would need to be incorporated as time-varying source term to allow their relative importance to be examined, particularly in the context of the effectiveness of the propose remediation strategy that relies on the maintenance of stream flow.

Discharge processes

Following each inundation event, the groundwater level in Big Swamp declines. The initial decline is typically rapid, reflecting lateral drainage within the QA under high hydraulic gradients. The rate of lateral drainage slows down as the hydraulic gradients reduce across the swamp. During the dry period from December 2019 to March 2020, when stream leakage is limited, the groundwater levels in the monitoring bores are observed to fall to levels below the elevation of Boundary Creek. This means discharge processes continue to lower the water table, most likely as a combination of lateral drainage (aquifer through-flow) and evapotranspiration.

Swamp vegetation depends on groundwater stored in swampland sediments and during the summer months, significant evapotranspiration losses could be expected from the water table aquifer. It is possible that during extended dry periods, the hydraulic gradients would become flatter and evapotranspiration becomes an increasingly important discharge process as vegetation access shallow groundwater to meet its water requirements.

In addition to climate-driven hydrological processes described above, changes in piezometric heads within the underlying LTA influence fluxes into and out of the QA in Big Swamp. This component of the water balance is discussed further in Section 2.3.3.

Data resolution

The hydrographs presented in this section are obtained from bores that have a screen length of 3 m with the gravel pack typically extending 0.5 to 1 m above and below the screen interval. This means the data currently available provide the net response of shallow groundwater within the upper 6 m of the QA and do not provide indications of any subtle vertical differences that may occur within this depth interval (if any). It follows that the model calibrated to these data should be designed to simulate the net response, which would not benefit from high numerical resolution in the vertical direction i.e. multiple model layers of 1 to 2 m in thickness, as assumed in the existing FEFLOW model. An exception would be for simulating the potential effect of hydraulic barriers if they are keyed into the QA, where additional layers would be required to simulate the interference with shallow groundwater.

Key findings:

- Water table responds rapidly to surface water inundation events, with minimal lag (i.e. <4 days) indicating limited unsaturated flow effects due to generally thin unsaturated zone. This provides the opportunity to simplify the groundwater flow problem into saturated flow only, providing considerable numerical efficiency gains.
- Stress periods ranging in duration from 2 to 8 days would be necessary to simulate the seasonal dynamics of shallow groundwater.
- Boundary Creek acts as a losing steam and there are spatial differences in the timing and magnitude of water table response to seasonal flow events. Time-varying stage would be necessary to simulate variable leakage along Boundary Creek during dry periods.
- It is difficult to discern the relative effect of stream inundation and rainfall (diffuse) recharge processes based on the currently available data. The groundwater model would need to simulate both of these processes as time-varying source terms to examine their effect under a range of climate conditions.
- Discharge processes include aquifer through-flow (lateral drainage) and evapotranspiration, which would need to be incorporated into the model.
- Monitoring data provide indications of net groundwater response within the upper 6 m of the QA. This means a high vertical resolution (multiple model layers) is not necessary to simulate this net responds; however, additional model layers would be required to simulate the partial penetration of flow barriers as part of predictive modelling of future remediation strategy.

Figure 2-7 Bore hydrographs and stream flow

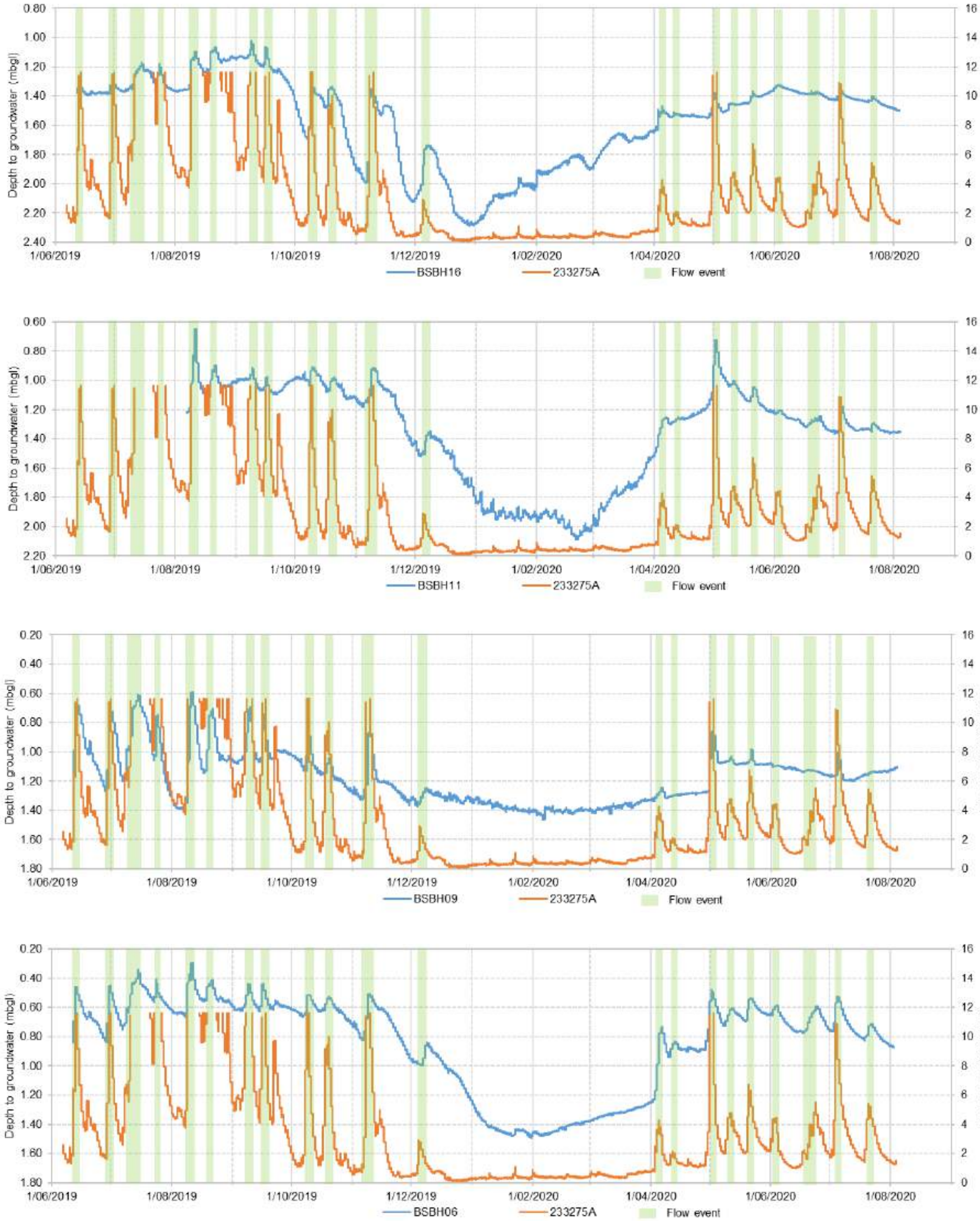
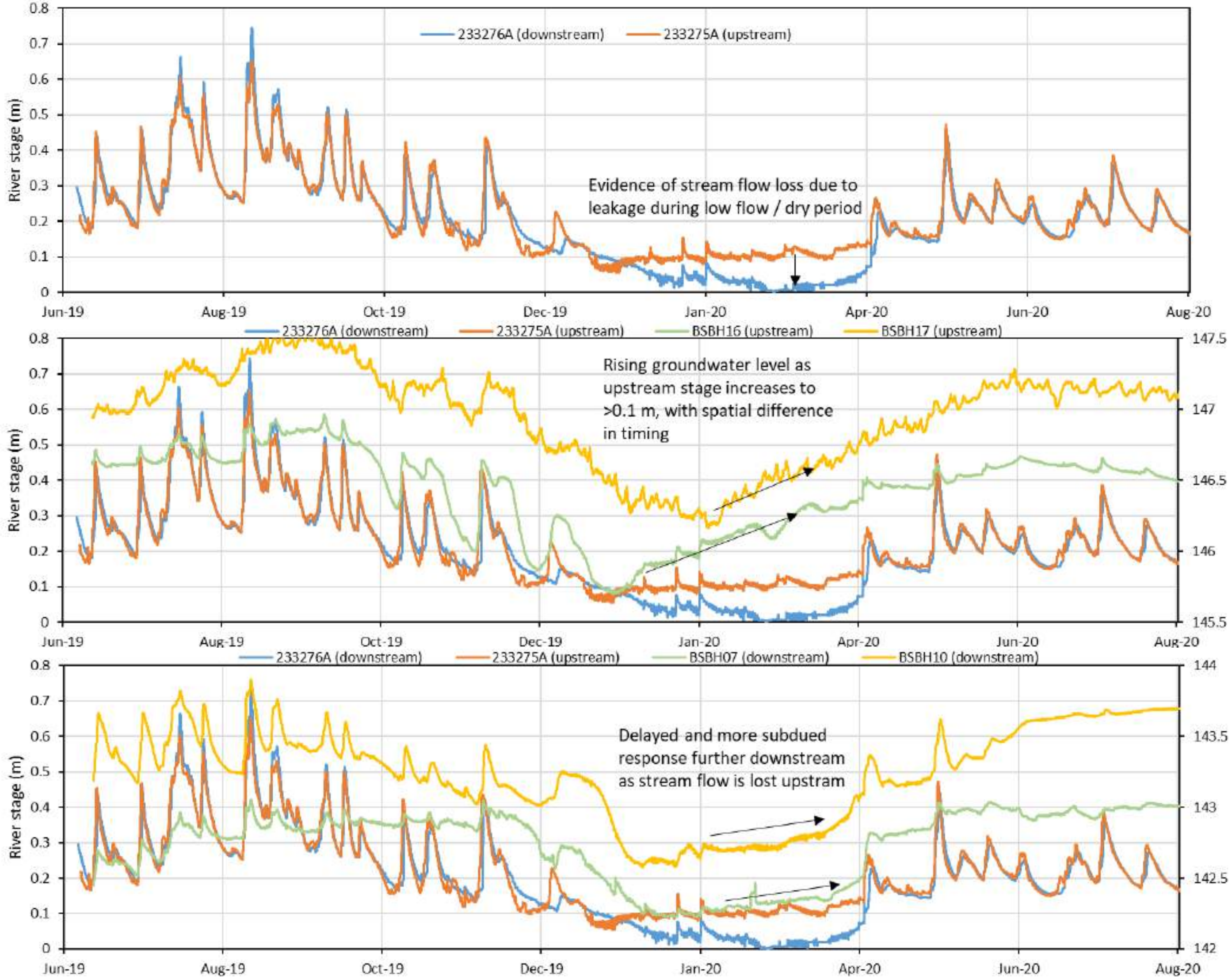
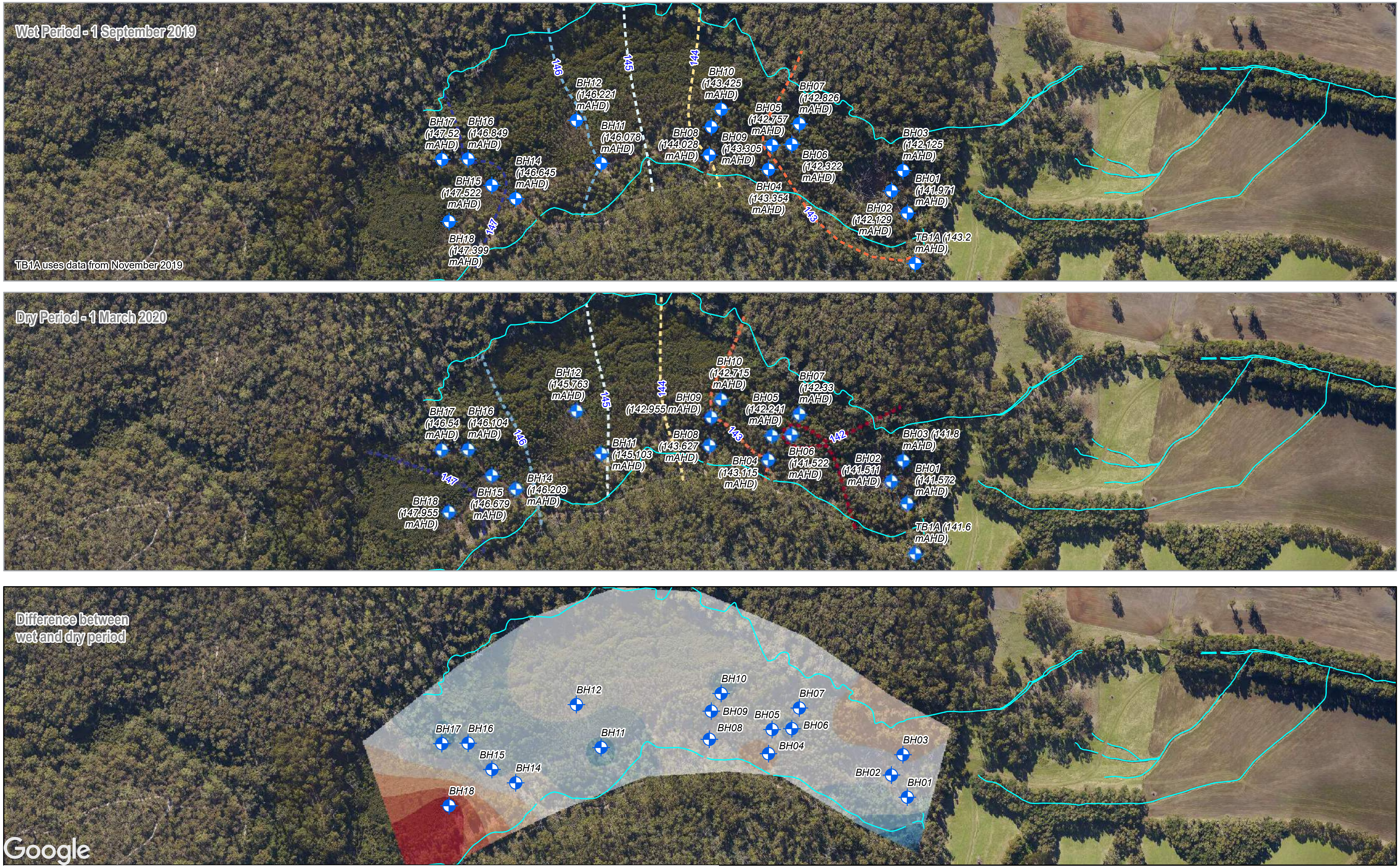


Figure 2-8 Stage hydrographs and upstream and downstream response





Legend

- Watercourse
- Groundwater bore (RWL in mAHD)

Groundwater contour (mAHD)
- 142
- 143
- 144
- 145
- 146
- 147

Difference between wet and dry RWL (m)
- -0.6 - 0.4
- -0.4 - -0.2
- -0.2 - 0
- 0 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1
- 1 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6

Paper Size ISO A3

0 50 100 150 200 Metres

N

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 54

Barwon Water
Big Swamp Modelling for Detailed Design

Wet (Sept 2019) and dry (March 2020) groundwater contours

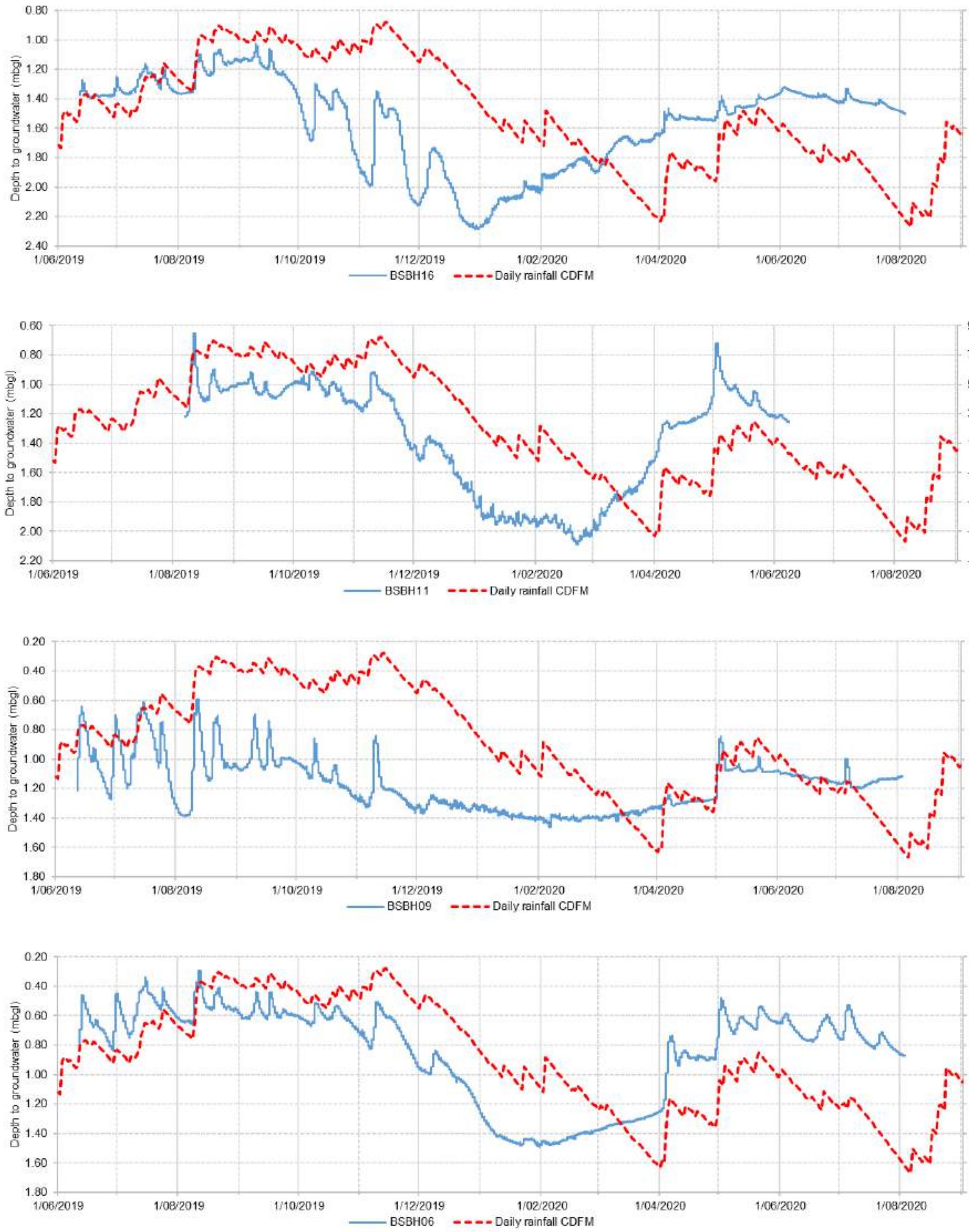
Project No. 12536659
Revision No. C
Date 12/10/2020

FIGURE 2-9

N:\AU\Melbourne\Projects\31\12536659\GIS\Maps\Deliverables\31_12536659_02_Contours_A3L_RevC.mxd
Print date: 08 Apr 2021 - 17:56

Data source: Barwon Water, Imagery, 2019; Jacobs, Bore Locations, 2019; GHD, groundwater contours, 2020; . Created by: bsmyth (tworth)

Figure 2-10 Bore hydrographs and cumulative departure from mean rainfall



2.3.3 Inter-aquifer connection

The LTA (Mepunga/Dilwyn Formation) is a regionally extensive aquifer that outcrops at surface predominantly in an area known as Barongarook High, where the aquifer has its main recharge zone. As discussed in Section 2.3.1, the LTA becomes confined by the MTD approximately in the middle of Big Swamp.

Prior to the commissioning of the Barwon Downs borefield and drier recent climatic condition, groundwater within the QA along Boundary Creek and Big Swamp would have been replenished by a combination of recharge from rainfall and surface water inundation and through-flow and baseflow from the LTA, with the natural water table likely to have fully intersected the QA. At the downstream end of Big Swamp, the upward leakage from the LTA may have been limited by the presence of the MTD, with through-flow from upstream providing an important component of flow into the QA underlying the swamp.

Extraction of groundwater from the Barwon Downs borefield and reduction in recharge due to drier climate have resulted in the lowering of groundwater levels within the LTA, reaching a depth of around 15 m below ground surface in 2010 along the upper reaches of Boundary Creek (based on the groundwater levels in bores 109128 and 109130, upstream of Big Swamp). Assuming a typical thickness of 10 m for the QA along the upstream reaches of Boundary Creek, the water table within the unconfined portion of the LTA potentially became disconnected from the base of QA. Following the cessation of pumping, the groundwater levels have gradually recovered to around 8 m below ground level, albeit still lower than the near surface levels measured in 1997 (however, the 1990s were a very wet climatic period compared to the subsequent 20 years of the 2000s). This means there currently remains a net downward hydraulic gradient from the QA to the LTA along Boundary Creek, and potentially in the upstream end of Big Swamp, which limits the contribution of aquifer through-flow into the QA underlying Big Swamp.

There is limited data on the groundwater level in the LTA at Big Swamp. Figure 2-11 presents the hydrographs of the nested monitoring site TB1 in the downstream end of Big Swamp. The groundwater level in the confined LTA is consistently above the groundwater level in the QA and MTD, indicating an upward vertical hydraulic gradient. However, the declining trend observed in the QA and MTD during the dry period indicates that upward vertical leakage from the LTA is likely to be limited by the low hydraulic conductivity of the MTD and is insufficient to maintain the water table in the QA, which is more strongly influenced by the surface water inundation events and subsequent discharge processes. The hydrographs also show that the vertical hydraulic gradient between the QA and MTD is seasonally variable. The artesian condition within the LTA is supported by bore 109112, located further downstream of Big Swamp, which currently has an artesian groundwater level of around 5 – 7 m above ground i.e. a greater artesian head where the LTA is deeper and confined by thicker MTD (the depth of bore 109112 is 292 m).

There are currently no bores monitoring the groundwater level in the LTA at the upstream end of Big Swamp. As discussed in Section 2.3.2, the bores in the upstream end of Big Swamp show a net declining trend during the dry period and this suggests that the groundwater level in the LTA is either close to or below the minimum groundwater level in the QA (or leakage from the LTA is insufficient to offset discharge via though-flow and evapotranspiration).

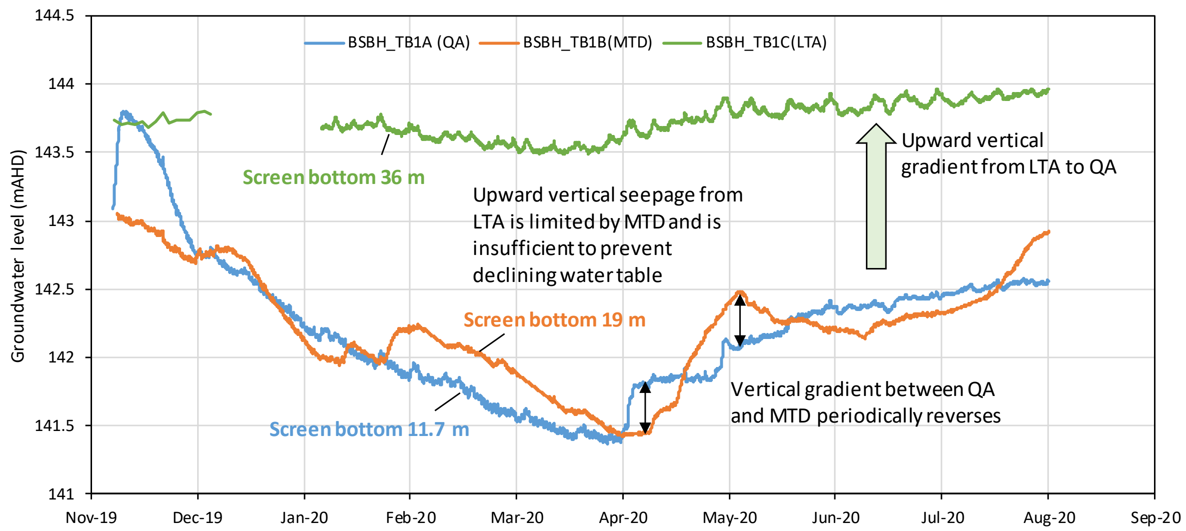
Figure 2-12 presents the location of bores in the LTA and interpreted contours of groundwater level in the LTA (Mepunga/Dilwyn Formation) for 2010 and 2020. Also included in the figure are hydrographs of key bores constructed in the LTA near Boundary Creek and Big Swamp. The interpreted groundwater contours and flow directions are broadly consistent with those derived from previous studies, which generally follow the topographic gradient along Boundary Creek. The horizontal hydraulic gradient between upstream bores 109130 and 109128 varied from around 0.0021 to 0.0051 since 1988, with an average of around 0.0037. The upper end of the range corresponds to periods of higher groundwater levels, such as the current condition and around 1996 prior to the Millennium Drought. The horizontal hydraulic gradient between bore 109128 and TB1C, located at the downstream end of Big Swamp, is around 0.0035 based on the recent data. The contours and hydraulic gradients suggest that the current groundwater level in the LTA could be around 146 mAHD in the upstream end of Big Swamp, similar to or slightly lower than the minimum groundwater level measured in the QA bores nearby. Given the direct connection between the LTA and QA at the upstream end of Big Swamp, the QA is likely to be losing to the underlying LTA following each inundation event i.e. downward leakage represents a component of discharge from Big Swamp after each inundation event. During extended dry periods, the groundwater level in the QA could potentially fall until it either equilibrates with the groundwater level in the surrounding LTA or induce an upward leakage from the LTA into the QA.

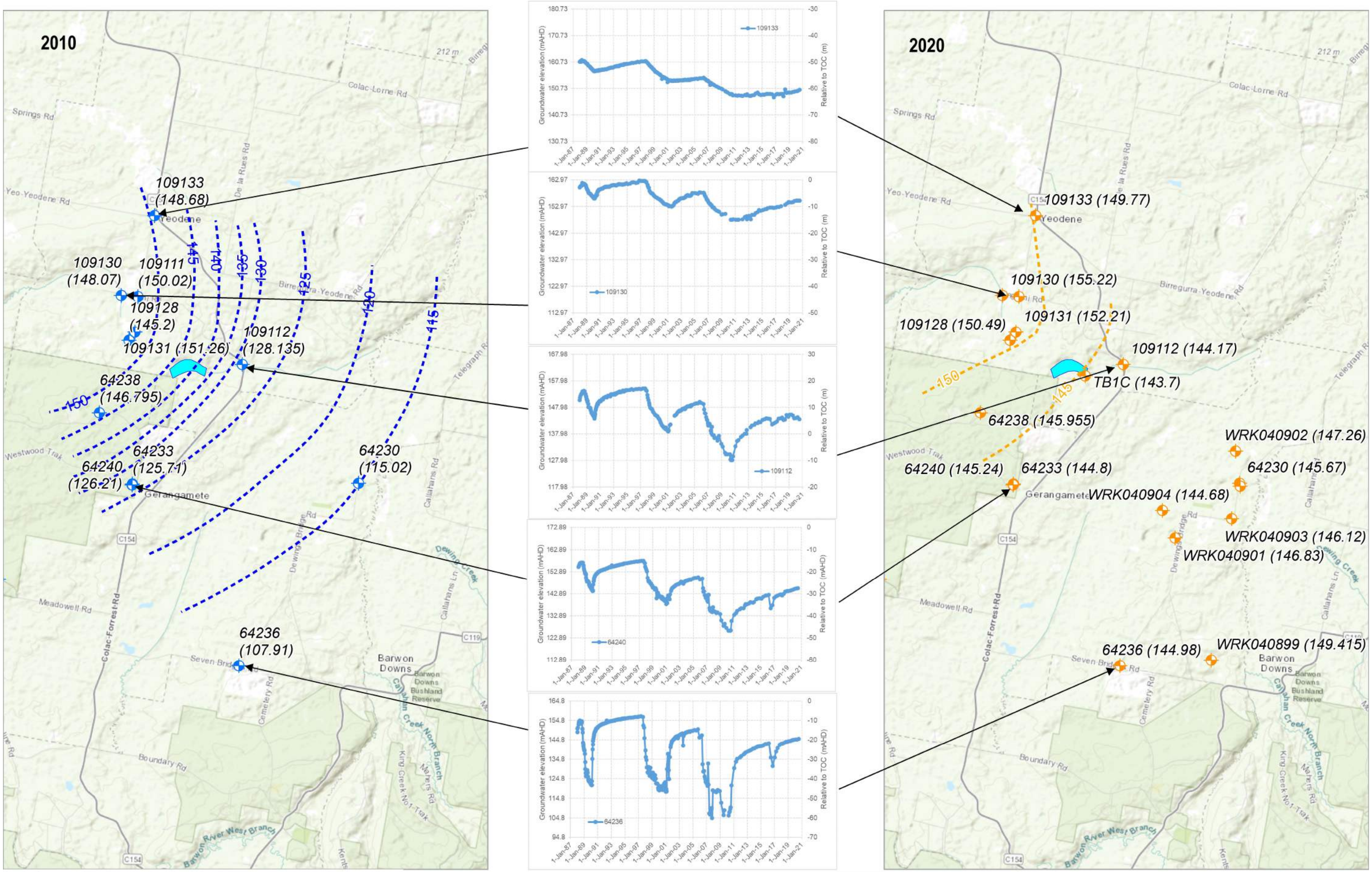
From the point of view of modelling, appropriate representation of piezometric heads in the underlying LTA is important as the nature of aquifer interaction influences the amount of through-flow and leakage into the QA of Big Swamp. Under the current condition, this component is likely to be small and is masked by much larger fluxes from surface water inundation. For this reason, maintaining the flow and inundation along Boundary Creek is the primary focus of the proposed remediation strategy. The interaction between the LTA and QA would be expected to vary over time depending on the future operation of the Barwon Downs borefield and climate that influences recharge into the LTA.

Key findings:

- The QA and LTA aquifer inter-connection along Boundary Creek and Big Swamp influences the amount of aquifer through-flow and baseflow into the QA of Big Swamp, which has an effect on the water balance and water table elevation in the swamp.
- Groundwater levels in the LTA have not yet fully recovered from the influence of pumping and drier climate. In the upstream end of Big Swamp, the QA is likely to be currently "losing" to the LTA following flood inundation events. The water table potentially declines to a level similar to the groundwater levels in the LTA during dry periods.
- From the point of view of modelling, the direction and magnitude of fluxes exchanged between the QA and LTA are important. These are expected to vary over time depending on the future operation of the borefield and climate.

Figure 2-11 Hydrograph of nested monitoring site TB1





Legend

- Groundwater bore (2010 RWL in mAHD)
- Groundwater bore (2020 RWL in mAHD)
- Groundwater contour in mAHD (2020)
- Groundwater contour in mAHD (2010)
- Location of Big Swamp

Paper Size ISO A3

0 1 2 3

Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 54

N

GHD

Barwon Water
Big Swamp Modelling for Detailed Design

LTA Groundwater Contours 2010 and 2020

Project No. 12536659
Revision No. B
Date 12/10/2020

FIGURE 2-12

N:\AU\Melbourne\Projects\31\12536659\GIS\Maps\Deliverables\31_12536659_04_DeepBoreContours_A3L_RevB.mxd
Print date: 08 Apr 2021 - 17:51

Data source: WMIS, bore locations and elevations, 2020; BW, groundwater levels, 2020; Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Created by: bsmyth (tworth)

2.4 Schematic conceptual model of key processes

Key hydrological and hydrogeological processes driving the behaviour of the Big Swamp aquifer system are summarised in simple schematic block diagrams.

Figure 2-13 shows the conceptualisation of the upstream end of Big Swamp, including the condition prior to the extraction of groundwater from the Barwon Downs borefield and recent drier climate, when the water table within the outcropping LTA was in hydraulic continuity with the QA.

Figure 2-14 shows the conceptualisation of the downstream end of Big Swamp under the existing condition, where the LTA is confined below the MTD.

Figure 2-13 Schematic hydrogeological conceptualisation – Big Swamp upstream

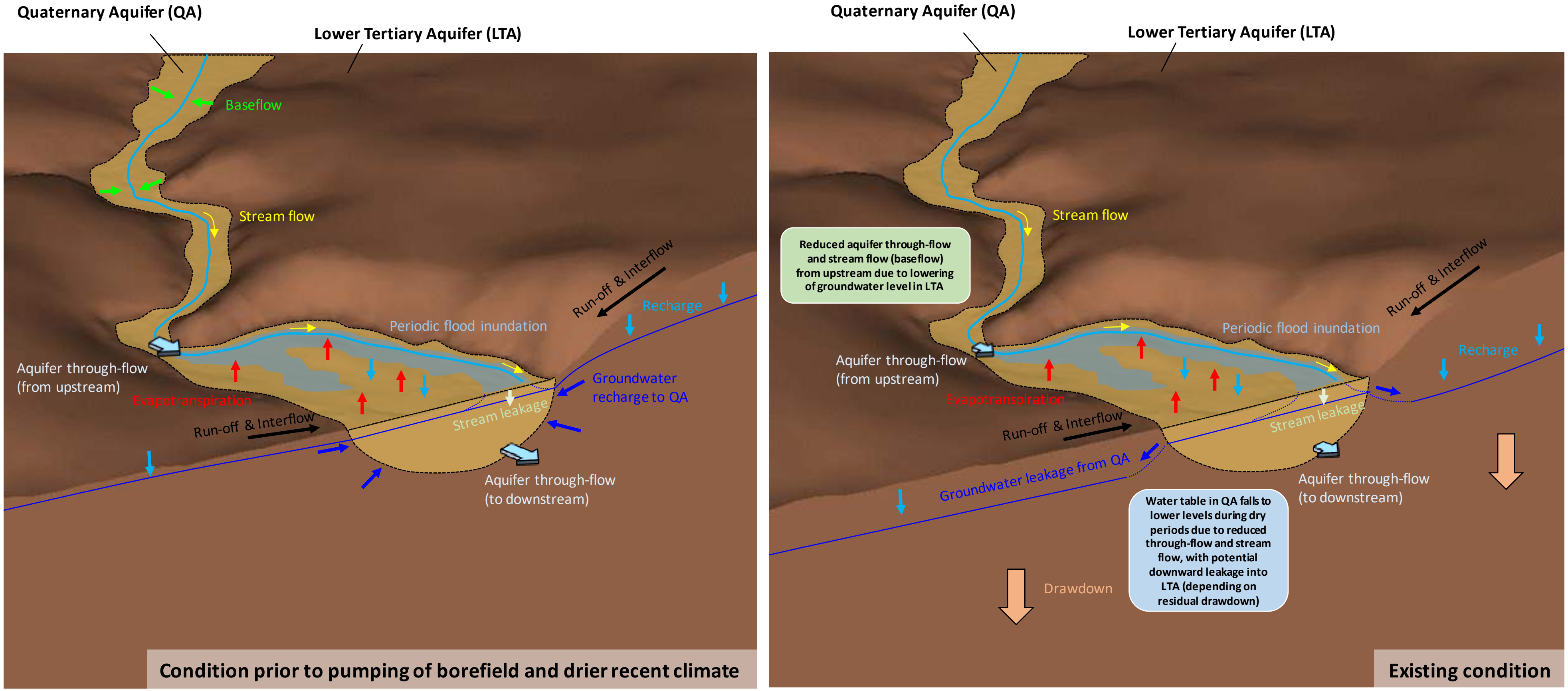
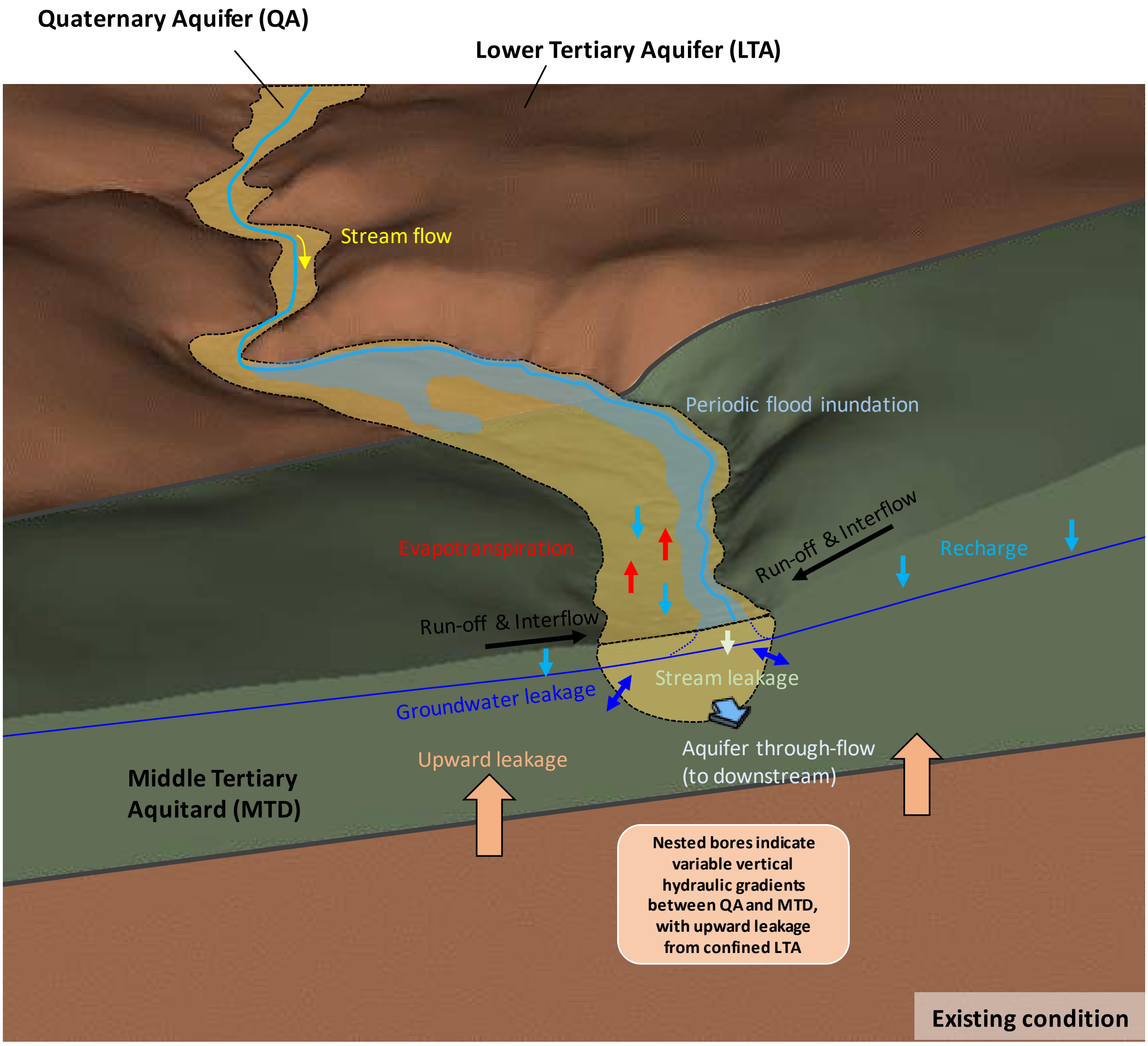


Figure 2-14 Schematic hydrogeological conceptualisation – Big Swamp downstream



3. Model design and construction

3.1 Modelling approach

3.1.1 Integration of surface water and groundwater processes

Hydrological and hydrogeological models can be coupled in several ways. In tightly coupled fully-integrated models, both the surface and subsurface flow equations are solved simultaneously using fine spatial grids and time steps. In loose coupling, external hydrological and hydrogeological models are run independently and outputs from each model are used to inform their respective inputs. The outputs exchanged depend on the types of models used e.g. infiltration calculated using 1D Richard's equation, deep drainage from rainfall-runoff models and infiltration estimated from ponding depths such as those calculated from flood models.

Although the capability of tightly coupled fully-integrated models is appealing, they are often plagued by numerical instability and excessive model run times. The benefit of their use is questionable given that simpler loosely coupled approaches can achieve similar outcomes, for example by using a stream flow routing boundary condition (coupled to groundwater at successive time steps) to accurately represent interaction between Boundary Creek and groundwater. A tightly coupled model would be problematic for this project, given the requirement for run-intensive procedures such as rigorous automated calibration, predictive uncertainty analysis and multiple scenario runs to inform the detailed design.

A complex, cumbersome approach based on tightly-coupled models is also counter to good modern modelling practice, in which the primary goal is to develop models that can simulate the processes of relevance to a sufficiently reliable degree whilst not expending efforts on details that have little material effects on model outcomes. In conjunction with this, the model should be numerically stable and efficient to enable uncertainty to be constrained through a rigorous history-matching process and to facilitate an understanding of uncertainty that underpins the decision-making process for which the model was commissioned to inform. While the loose coupling method is simpler, the benefits gained from improved numerical stability and more transparent exchange of outputs would assist in meeting the modelling objectives within the timeframe of the project.

In this project, the primary mechanism of maintaining the water table in Big Swamp would be via surface water inundation. The information exchanged between the hydrological and hydrogeological models would include the depth, extent and duration of inundation and associated infiltration rates that result in the observed water table response. These are discussed further in Section 3.1.3.

3.1.2 Modelling platforms

For hydrological modelling, TUFLOW has been chosen based on its extensive application to flood modelling studies in a wide range of environments and to maintain continuity with the previous hydrological modelling undertaken by Jacobs (2019a). A rainfall-runoff model is also used to provide inputs to the TUFLOW model.

For hydrogeological modelling, the appropriate modelling platform has been chosen based on careful considerations of the intended model use and updated hydrogeological conceptualisation presented in Section 0.

Broadly speaking, there are two commercially available groundwater modelling platforms that are widely used in Australia. These are the finite element code FEFLOW, developed and maintained by DHI, and finite difference code MODFLOW (and its variants), developed and maintained by the United States Geological Survey (USGS). Both codes have been extensively used and benchmarked, and have similar capabilities. In this sense, the choice of suitable modelling platform often comes down to the skill and experience of the modelling team, although there are subtle differences between the two codes that can influence their suitability.

For this project, an unstructured grid version of MODFLOW called USG-Transport version 1.5 (Panday, 2020) has been chosen as the most appropriate modelling platform. USG-Transport is based on the MODFLOW-USG code (Panday et al, 2013) developed by the USGS and includes several enhancements (such as adaptive time stepping) which are frequently updated by the code's lead developer. The preference for using a MODFLOW based code over FEFLOW is as follows:

- It is generally recognised amongst experienced modellers that extracting reliable and consistent local water balances can sometimes be challenging with FEFLOW due to the finite element formulation and post-processing methods. This is not a limitation with USG-Transport that uses the control volume finite difference formulation with prismatic cells, in which the flow balance is conserved locally on a cell-by-cell basis. The ability of the model to simulate reliable local water balance of the Big Swamp alluvial aquifer is of critical importance to this project.
- MODFLOW (and USG-Transport) is open source and all input and output files, as well as the source code, are visible to the user. This level of transparency and flexibility can be advantageous in some instances, for example when interfacing the model with third-party software such as PEST and its associated utilities for automated calibration and uncertainty analysis.
- MODFLOW has exiting packages such as Recharge, Evapotranspiration, River and Stream packages, which are particularly suited to simulating the effects of near surface hydrogeological processes that are critical to this project.
- MODFLOW based code has been successfully applied by GHD for Barwon Water's Anglesea Borefield Project, to model groundwater level, creek flows, a lake and water balance changes in the swampland and associated acid generation risks.

Although the previous modelling was undertaken in FEFLOW, transitioning into a MODFLOW-based code is not an impediment to the modelling process as the knowledge gained from the previous modelling remains applicable. Additionally, the updated conceptualisation has identified several model design aspects that require modifications to meet the modelling objectives and project timeframe. These modifications are necessary irrespective of the modelling platform chosen for the project and are discussed in more detail below.

3.1.3 Specific model design considerations

Specific model design considerations include the following:

- The rapid onset of rise in groundwater level following high stream flow events and generally thin unsaturated zone indicate that accuracies gained from incorporating the unsaturated flow processes and corresponding fine vertical resolution would be immaterial and do not outweigh the computational burden, increased model run time and additional parameters incurred. Reducing the model to only saturated flow has a follow-on benefit to run-intensive calibration and uncertainty analysis required for this project.

- Multiple model layers are not necessary to simulate the net response of the QA in Big Swamp, recognising that the monitoring bores are not designed to capture subtle variations that may exist vertically within the top several meters of the aquifer. This is not important to meet the main objective of the modelling, which is to quantify the water balance of the QA and whether or not the proposed remediation strategy can maintain the water table within the top metre. According to Jacobs (2019a), the justification for dividing the QA into multiple model layers within the FEFLOW model was to provide the fine vertical resolution required to model the unsaturated zone. However, the data suggest that the unsaturated zone is generally 1 to 2 m in thickness, placing the majority of these model layers below the water table. This means the model layers, as currently included in the FEFLOW model, do not actually serve their intended purpose.
- The MODFLOW packages available with USG-Transport simulate the hydrogeological processes and surface water-groundwater interactions in a manner that allows the relative contribution of each water balance component to be examined closely. The Stream Flow Routing (SFR) package can be used, with time-varying stage, to accurately simulate the interaction of Boundary Creek with groundwater based on the calibration to flow gauges, including stream loss along the length of Big Swamp observed during the dry period. This differs from a simple head boundary condition used in the FEFLOW model by Jacobs (2019a), which could provide limitless volumes of water to the groundwater model (even in periods when the creek may not have any water flowing down it) and does not account for loss of water down the creek (which is thought to occur in the upper reaches of the swamp in this project). In contrast, flow routing boundaries only simulate a head of water in the creek when there is water flowing and account for loss of water to the water table as the creek flows through the catchment.
- The infiltration associated with periodic surface water inundation can be simulated using the River (RIV) package, based on the water depth, extent and duration derived from the TUFLOW model outputs[1]. With the SFR and RIV packages the resistance to flow due to the creek bed material is implicitly accounted for by the bed conductance term. This means a 1 m thick top layer incorporated into the FEFLOW model to represent the creek bed sediments is no longer required.
- The time-varying recharge and evapotranspiration can be simulated using the recharge (RCH) and evapotranspiration (EVT) packages, to examine their contributions to the water balance of Big Swamp and effects on water table fluctuations that are key to acid generation processes. These sink and source terms can be derived from a simple water balance model such as LUMPREM (Doherty, 2020) and adjusted during calibration.
- The method of simulating the interaction between the QA and LTA requires careful consideration. Jacobs (2019a) attempted to simulate the distribution of piezometric heads within the LTA by adopting a large model domain and applying heads from the Barwon Downs regional model along the model boundary. The challenge with this approach is that the ability of the model to accurately account for the nature of inter-aquifer connection depends on its ability to accurately simulate the piezometric heads. This is not straightforward when the model domain only represents a portion of the regional flow field, where the distribution of piezometric heads depends on the geology and recharge and discharge dynamics over a much larger spatial area. This is demonstrated by the piezometric head simulated by the FEFLOW model at the nested site TB1, where the modelled head in the LTA is around 141 mAHD compared to the observed head of around

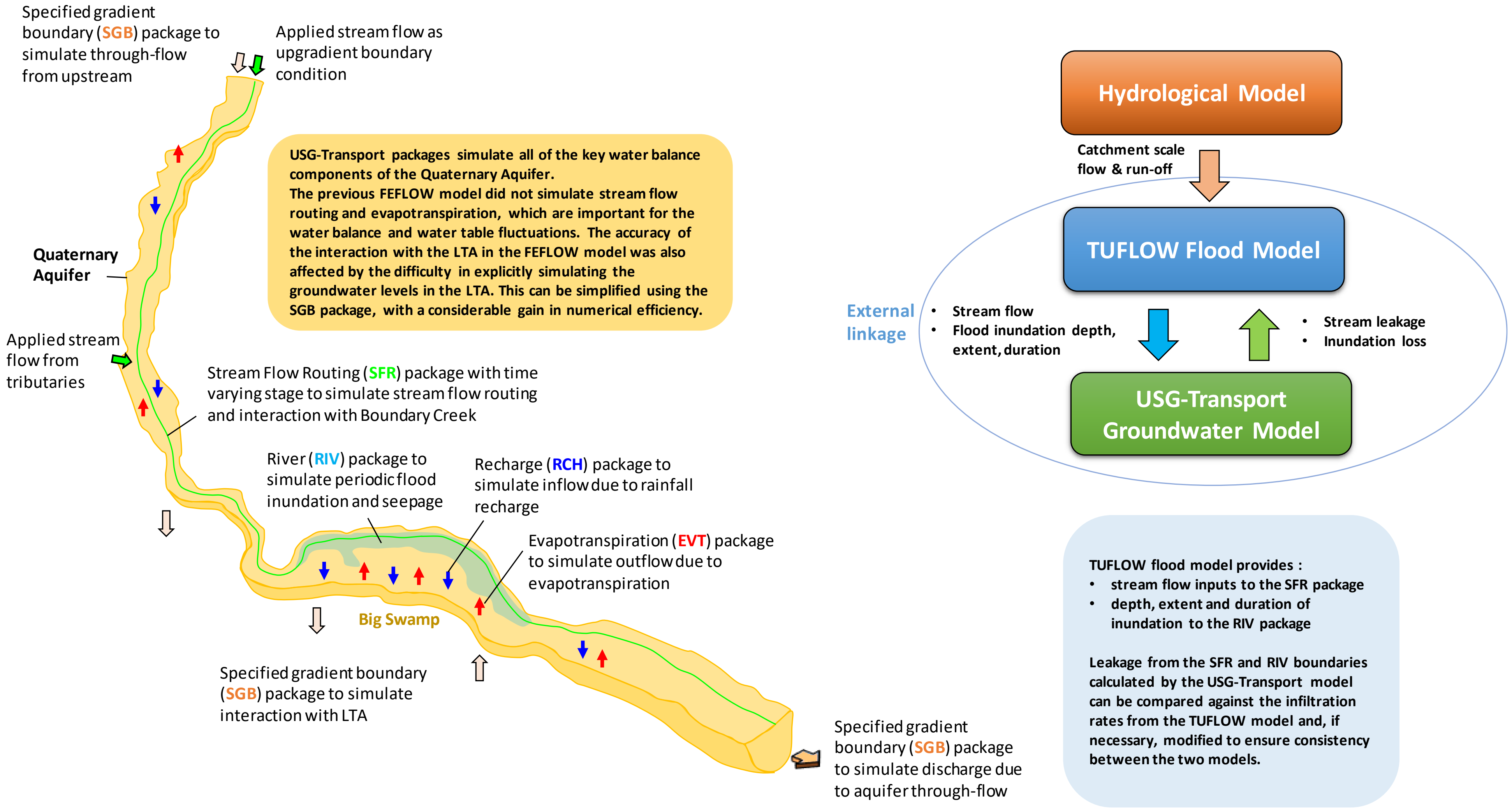
[1] Another reason for using this simple approach to overbank inundation is that it is not common over large areas or over long periods of time in this catchment. Hence, a more complex modelling approach is not warranted and takes the focus away from more critical issues such as uncertainty in water table depth variability in time and space, flow losses from the creek channel to the water table, and the potential acid generation processes.

144 mAHD and the model simulates a downward vertical hydraulic gradient (instead of the upward gradient implied by the data). In contrast, the FEFLOW model overestimates the piezometric heads in the upgradient LTA bores by around 3 m.

- An alternative approach to simulating the inter-aquifer connection is to use the Specified Gradient Boundary (SGB) available with USG-Transport. With the SGB, hydraulic gradients are specified as input and fluxes are calculated by the model in accordance with the gradients and resistance to flow represented by the hydraulic conductivity of model cells. In this study, the SGB can be prescribed along the base of the QA using the observed (and interpreted) difference in the LTA and QA heads. This ensures that the flux into and out of the QA is simulated in the correct direction based on the specified hydraulic gradient and resistance to flow represented by the vertical hydraulic conductivity of the QA. The hydraulic gradient can be varied during calibration to account for uncertainty in the distribution of LTA heads, with constrains placed such that the fluxes are always maintained in the correct directions. While this approach is simpler, it is more efficient than expending efforts to accurately simulate the heads in the LTA which may not be attainable at this scale (or at least to the accuracy required to maintain the correct directions of exchange). It is also possible to use head dependent flux boundary conditions such as the General Head Boundary (GHB), however, these boundaries require both the heads and conductance term to be specified as input and require more post-processing efforts to constrain fluxes or to ensure correct direction of fluxes. They would also require at least one more model layer beneath the QA and could artificially force heads through the base of the swamp.
- The SGB can also be applied along the upgradient and downgradient model boundary to simulate aquifer through-flow into and out of the model.

Figure 3-1 is a schematic representation of the groundwater (USG-Transport) model design. Also included in the figure is the linkage between the TUFLOW and USG-Transport models. The SGB can be extended to account for future conditions when the groundwater levels in the LTA recover to higher elevations, potentially resulting in a gaining condition over a larger area of the QA than currently expected.

Figure 3-1 Schematic representation of groundwater model design



3.2 Hydrological (GR4J) model design and construction

3.2.1 Overview

The purpose of developing the hydrological model is to estimate inflows from rainfall-runoff, which are used as inputs for the TUFLOW and USG-Transport models.

Big Swamp is situated on Boundary Creek, which has a large upstream catchment including McDonald's Dam. Downstream of McDonald's Dam, multiple tributaries join the creek near or within the swamp. Whilst gauged streamflow is available at various locations on Boundary Creek, the local catchment and tributary flows between the last upstream gauge (233229) and the downstream end of the swamp needed to be estimated. A rainfall runoff model has been developed for this area to estimate the flow volumes running into the creek using the software package e-water Source and the conceptual rainfall-runoff model GR4J. This model has been calibrated to the available flow data from the gauges along Boundary creek to generate appropriate flow volumes.

3.2.2 Model attributes

GR4J is a catchment water balance model that relates runoff to rainfall and evapotranspiration data on a daily timestep. It contains two storages and has 6 parameters, as outlined in Table 1.

Table 1 GR4J parameters and ranges

Parameter	Description	Default	Range
x_1	Capacity of the production soil (SMA) store	350 mm	1-1500
x_2	Water exchange coefficient	0 mm	-10.0-5.0
x_3	Capacity of the routing store	40 mm	1-500
x_4	Time parameter for unit hydrographs	0.5 days	0.5-4.0
k	Filter parameter given by the recession constant (as in observed catchment runoff depth model)	n.a.	0-1
C	Shape parameter (as in observed catchment runoff depth model)	n.a.	0-1

Source utilises the GR4J model to generate runoff from several sub-areas and can link and route these flows to get output hydrographs at various points within the model. Source also allows modelling of storages and offtakes which have been used in this model to represent McDonald's Dam.

Further details of GR4J as it is implemented in eWater Source can be found at: https://wiki.ewater.org.au/display/SD41/Rainfall+Runoff+Models+SRG.

3.2.3 Catchment delineations

The Boundary Creek catchment upstream of the Yeodene gauge (233228) has been divided into 15 sub-catchments based on topography (10 m contours) to represent where runoff would enter the creek. The area upstream of McDonald's dam is separated into several sub-catchments to allow direct comparison of flows at gauges to aid in calibration. The area within the TUFLOW model boundary is also separated out from the tributary catchments. Figure 3-2 shows the delineated sub-catchments.

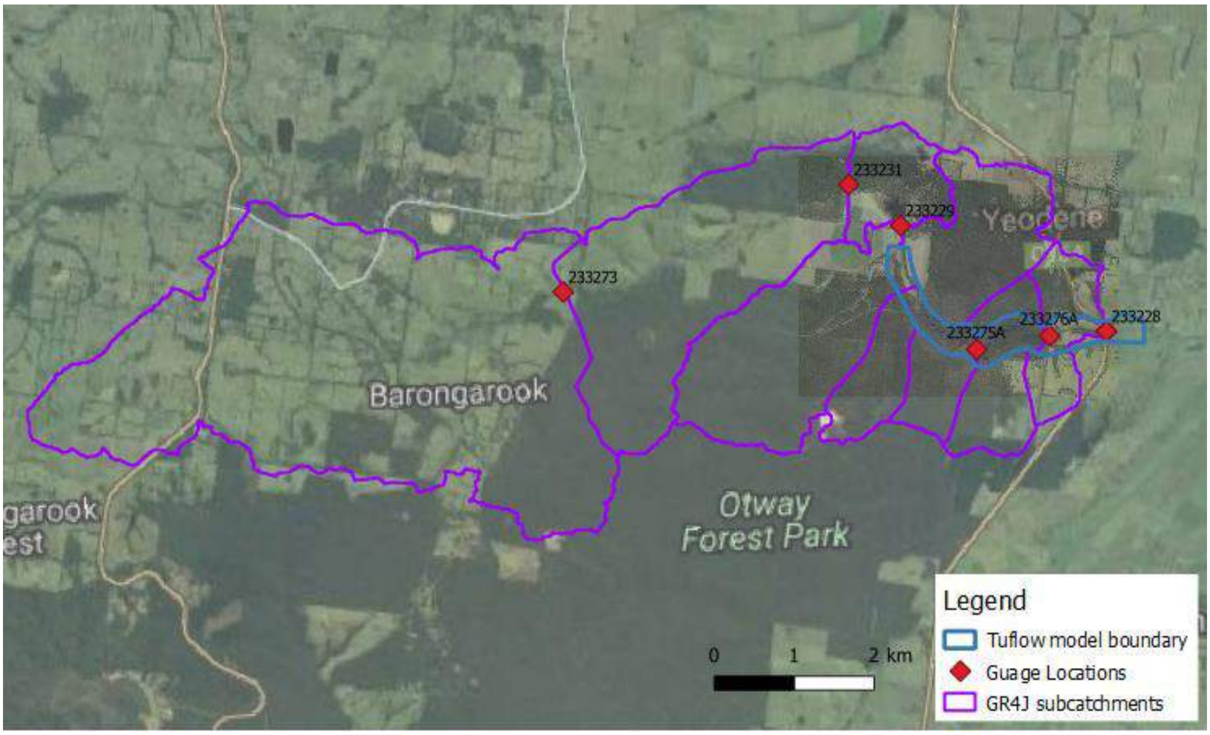


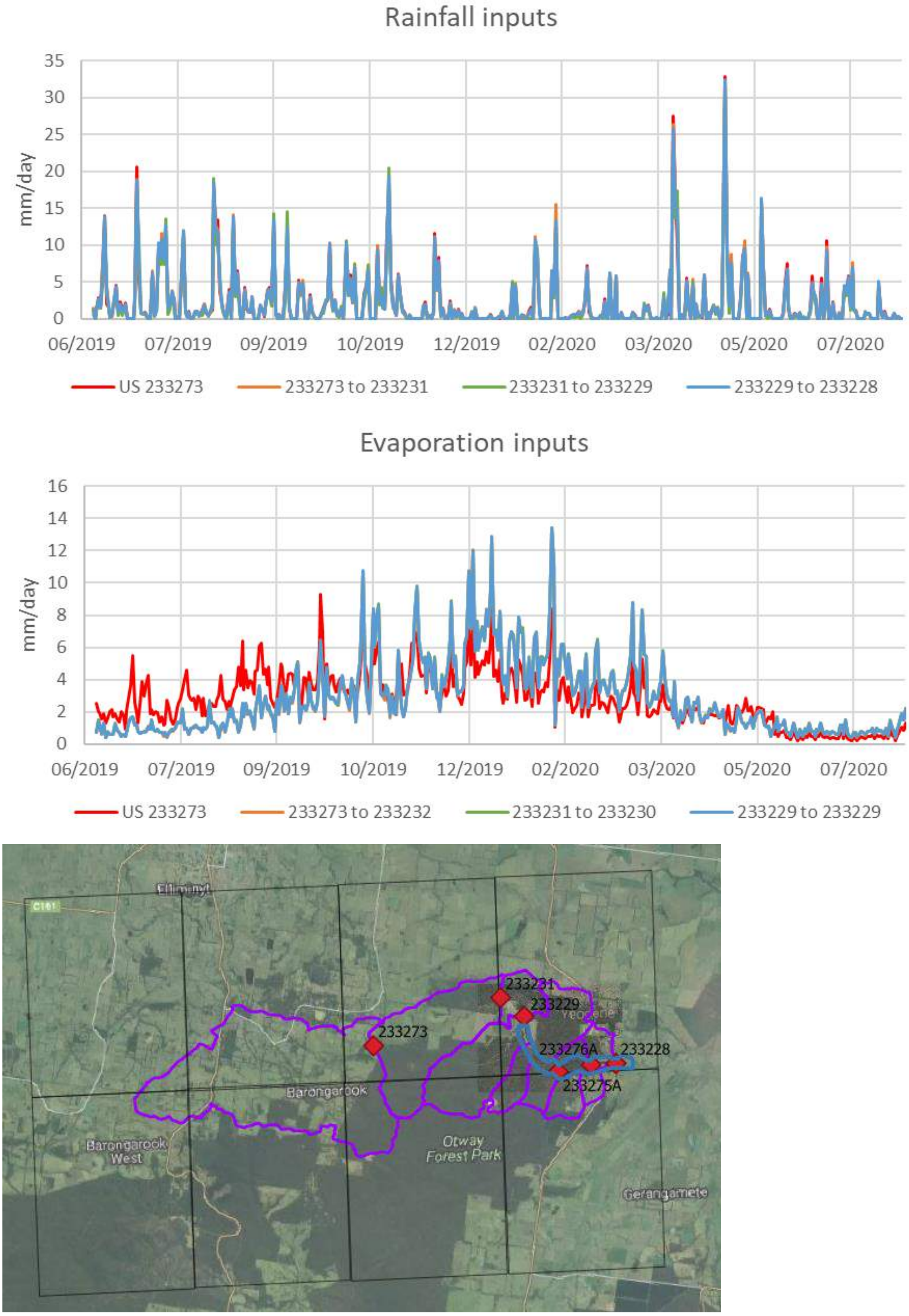
Figure 3-2 Sub-catchment boundaries

3.2.4 Climate data inputs

Due to a lack of complete climatic data for this catchment, daily rainfall and evapotranspiration data have been downloaded from the SILO database (https://www.longpaddock.qld.gov.au/silo/). This is a large data source which provides complete timeseries data for climatic variables using observed data and data infilling techniques. The gridded datasets for daily rainfall and daily Morton's potential evapotranspiration have been downloaded, which provide data interpolated to cover the entirety of Australia in a grid.

The area of interest to this study is covered by eight of these SILO grid cells, so all eight datasets are used, and an area weighted average of these has been calculated for the sub catchments. The weighted averages are based on how much of each of the catchment is inside each cell and separate rainfall and evapotranspiration timeseries are calculated for each of the following groups of catchments: Upstream of gauge 233273, between gauges 233273 and 233231, between gauges 233231 and 233229, and all catchments downstream of 233229. These timeseries are shown below in Figure 3-3.

Figure 3-3 Rainfall and evaporation input data to Source



3.2.5 Streamflow data inputs

There are several gauges with streamflow data available along Boundary creek, with locations shown in Figure 3-2

The site-specific gauges, managed by Barwon water, provide water surface level and flow rate data (limited to flows below to 12 ML/day) covering the period 7th June 2019 to 4th August 2020 at a 15-minute timestep. These provide information immediately upstream (Gauge 233275A) and downstream (Gauge 233276A) of Big Swamp.

Data from the other stream gauges have been downloaded from WMIS online at daily and 15-minute timesteps. These gauges varied in record length, but all had data covering most of the calibration period stated above. The gauges relevant to this study, listed in order from upstream to downstream, are: 233273, 233231(just upstream of McDonald's Dam), 233229 (just downstream of McDonald's Dam and 233228 (downstream of the swamp and at the end of the model).

To demonstrate the relative data quality and completeness of the four station gauges, Table 2 shows the percentage of data that is missing when data of poor quality (considered poor when quality code is above 150) is removed.

Table 2 Data missing for codes 150 and over during calibration period

233228	233229	233231	233273
17%	19%	16%	2%

A concern identified in the gauge data is that the flows at gauge 233229, downstream of McDonald's Dam are in many cases higher that the flows into the dam at gauge 233231, shown in Figure 2 4. This is unexpected as there is very little catchment area between the two gauges that could be causing this flow increase and dams generally also act to slow down the flows and flatten hydrographs slightly. It is likely there is some error in one of the gauges, however it is difficult to identify which one is more reliable. This adds some uncertainty into the modelling. A key improvement for future work on this location would be to complete an analysis of the data reliability of all the available gauges to better identify the most appropriate inflows.

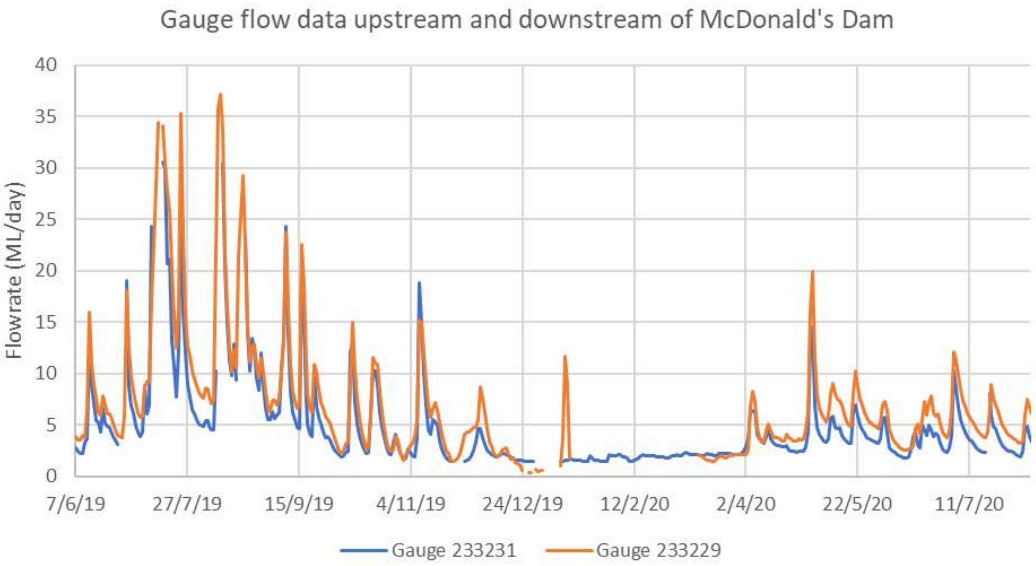


Figure 3-4 Comparison of flowrates at gauges 233231 and 233229

3.2.6 Model construction

Catchment linkages and routing

The topography shows clear gullies for almost all of the sub-areas that feed into the Boundary Creek along the TUFLOW model domain. This means it is possible to estimate approximately where along the channel each tributary flow is added. Source is then set-up to reflect this conceptualisation of added flows, with sub-catchment linkages shown in Figure 3-5.

For this model, straight through routing is adopted along all linkages, meaning the model only provides the runoff hydrographs and simply adds them together for downstream flow. Routing within Source has not been necessary as this is completed in TUFLOW.

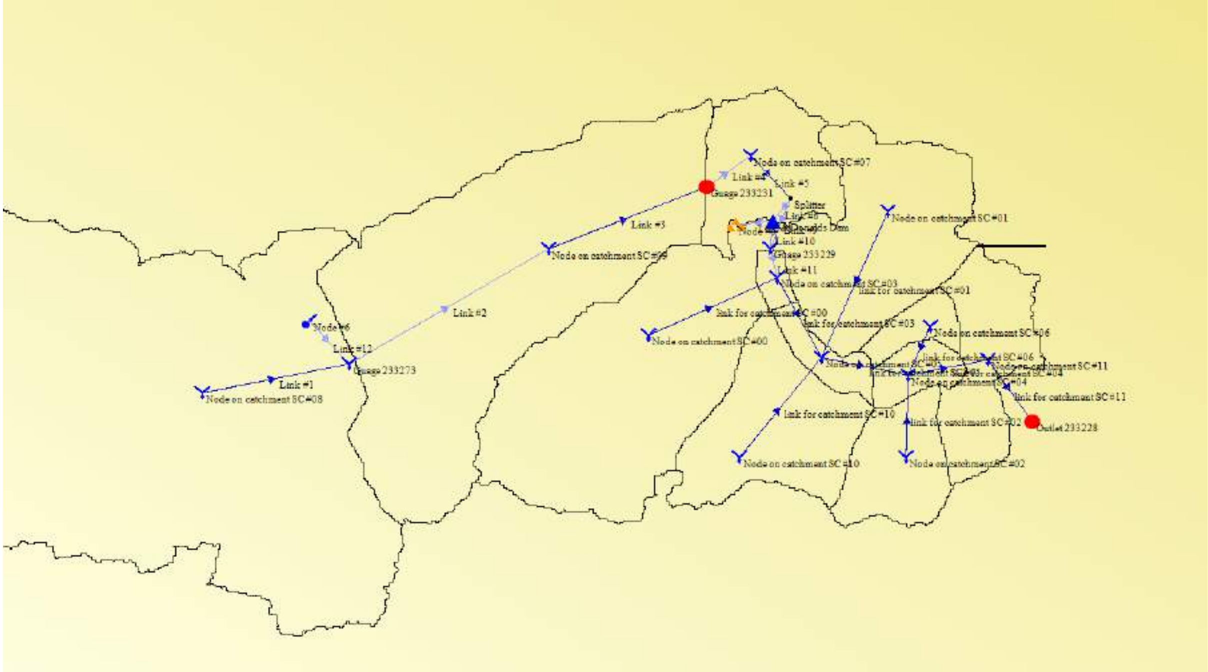


Figure 3-5 Catchment linkages

McDonald's Dam representation

McDonalds Dam has been explicitly modelled in Source using a storage node. There is some uncertainty around the exact operation of the dam that occurred during the calibration period. However, based on correspondence with Barwon Water, the dam operation is understood to be constrained by the following guidelines:

- Flows leave the dam via an outlet valve that has a capacity of 5 ML/day
- This valve is manually operated currently and is adjusted when flow changes are required.
- The dam fill period is 1 July to 31 October
- Outside the fill period, all flows must be passed by the dam.
- Dam extraction is licensed for 3 ML/day and 66 ML total per year.
- The spillway is an overflow weir.

This information still leaves some uncertainty as to when the dam filling and offtakes occurred. Therefore, the following assumptions have been made:

- The dam passes all incoming flows up to 5 ML/day throughout the year. When the flowrate exceeds 5 ML/day it will contribute to filling the dam.
- The dam offtake allowance of 66 ML/year is assumed to be extracted at a constant rate evenly distributing this offtake over the non-fill period. This results in a daily offtake of 0.273 ML for 31 October to 1 July.
- The dam has a capacity of 160 ML, when this is exceeded flows will be passed downstream via the spillway which is set at 167.17 mAHD.

This assumed behaviour has been modelled in Source using a flow splitter to divert incoming flow below 5 ML/d straight through the dam, a storage node to represent the dam, and a minimum flow requirement node to offtake 0.273 ML/d during the non-filling period.

The storage has been set so that the spillway would be overtopped at 160 ML. The dam spillway rating curve, as shown in Figure 3-6, has been generated using HEC-RAS.

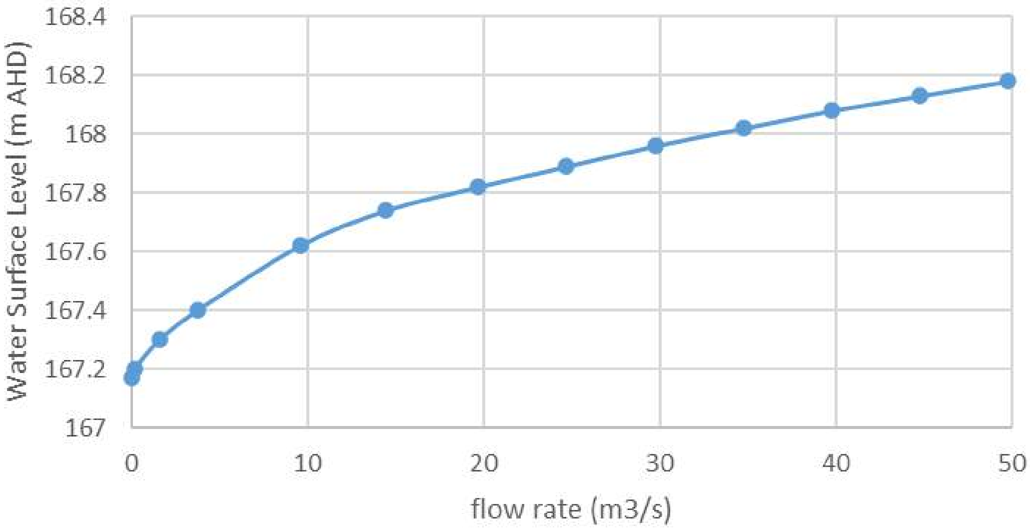


Figure 3-6 Dam spillway rating curve estimated for McDonalds Dam and entered into Source

Land use types

The catchment areas are considered to be made up of two land types: forest and farmland. The area of each land type in each sub-catchment is estimated by using satellite imagery to trace the areas of forest land and calculate the area. Only large blocks of forested land are considered forest and single trees or thin rows of trees have been included as farmland. The resulting land type areas for each sub-catchment are shown in Table 3. These areas are entered into the GR4J rainfall runoff model. Using two different land types allows the model to have two different parameter sets, to model the behaviour of the farmland and forest. The model then generates runoff proportionally to the areas. This is considered important when utilising the upstream gauge information in calibration, as differing land types are accounted for.

Table 3 Sub-catchment proportion of forest and farmland

Sub-catchment number	Total area (km^2)	Forest area (km^2)	Farmland area (km^2)	% forest	% farm
0	4.463	4.015	0.448	90	0.10
1	2.601	2.067	0.534	79	0.21
2	1.022	0.753	0.269	74	0.26
3	0.154	0.154	0	100	0.00
4	0.371	0.371	0	100	0.00
5	0.355	0.355	0	100	0.00
6	0.34	0.34	0	100	0.00
7	1.433	0.762	0.671	53	0.47
8	18.192	3.202	14.99	18	0.82
9	7.173	4.245	2.928	59	0.41
10	1.926	1.926	0	100	0.00
11	1.362	0.381	0.981	28	0.72

Supplementary flow

A supplementary flow of 2 ML/d has been added to the model upstream of gauge 233273. This has been applied as a constant inflow throughout the simulation period using an inflow node in Source.

3.3 Flood (TUFLOW) model design and construction

3.3.1 Overview

The primary purpose of developing the hydraulic model is to determine the areas and duration of inundation over Big Swamp and throughout the calibration (monitoring) period. For this project, TUFLOW version 2020-10-AA-iSP-W64 is used. TUFLOW is a hydrodynamic model used for simulating one-dimensional (1D) and two-dimensional (2D) flows. The model is based on the solution to the free-surface flow equations. The TUFLOW model consists of a 2D domain (TUFLOW) representing the topographic terrain surface, a 1D network (ESTRY) representing the pipe systems and a set of boundary conditions comprising the calculated GR4J and gauge input data hydrograph inflows and the downstream water levels.

The TUFLOW model has been derived from an existing model developed by Jacobs in 2019, with several enhancements to improve the representation of the study area. The base model has been developed to simulate existing conditions and calibrated to the available flow data from the gauges along Boundary Creek. The calibrate model has been used as the basis for testing several hydraulic barrier configurations to inform the design of the remedial system and provide inputs to the USG-Transport model.

3.3.2 TUFLOW model configuration

The TUFLOW model developed for the project is relatively simple, consisting mainly of boundary conditions and a digital terrain model. The major components of the model can be seen in Figure 3-7. Most of the flow comes into the model at the upstream boundary, which uses the gauge data from 233229 as an inflow hydrograph. The inputs from GR4J are added along the model at appropriate locations and the end of the model has a downstream HQ boundary. The main 1D components are two 1D weirs, set to model the v-notch weirs located at gauges 233275A and 233276A.

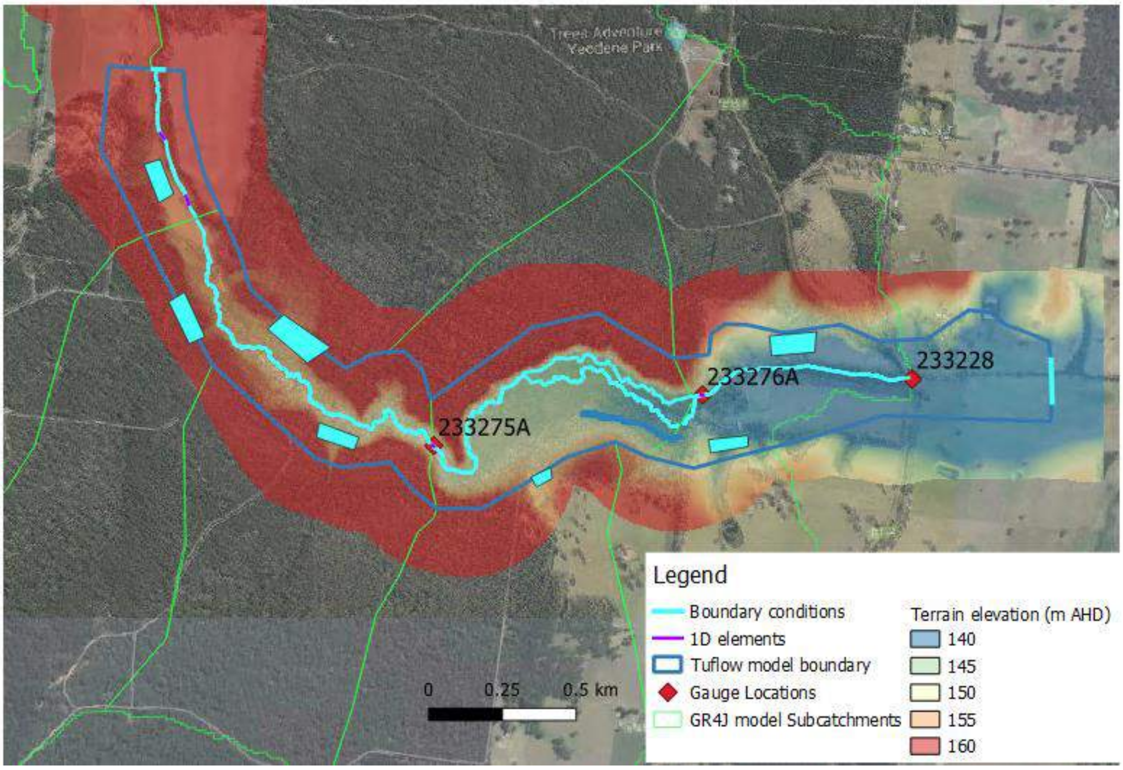


Figure 3-7 Tuflow model setup main components

3.3.3 2D domain

The 2D domain represents the ground surface, and hence the overland flow paths within the model. The digital terrain/elevation model (DEM) has been generated from LIDAR data, which has been processed to create a TIN surface from all the points identified in the metadata as being ground. Using this DEM, grid cells are formed, covering the model domain at a 4 m by 4 m resolution. Each grid cell is made up of nine internal points, with the elevation for each point derived from the DEM. The 2D domain created through this process has been used to model all overland flow paths.

There is currently a high degree of uncertainty in this terrain data, due to the presence of very dense vegetation. It appears that in many cases the top of vegetation, or in some locations the surface of the water, has been read by the LIDAR and included as a ground point. To demonstrate the inaccuracies in the terrain data in some locations, Figure 3-8 shows a sample of the terrain along the main channel. The spikes in the ground surface are clearly visible. This has been problematic along the channel, as bumps in the ground prevented surface water from continuing down the channel and caused the water to spill out and travel downstream via the floodplain. The ground surface along the channel has been improved using terrain shaping to connect the low points along the line and erase high points that are clearly not representative of ground surface. This has been achieved using a thin gully line strung between elevation points in TUFLOW. The outcome of this improvement is also shown in Figure 3-8, where the shaped DEM is smoother than the original. However, it is also clear that the bumps have not been entirely erased by this process.

A thick gully line connecting the low points has also been used to shape the area within the fire trench to ensure that surface water is properly diverted down under the existing conditions. This modification has been incorporated after the initial iteration of USG-Transport model calibration, as the break out (spilling) of surface water from the fire trench was thought to have overestimated the inundation and hence the modelled groundwater levels at bore BSBH08. It has been assumed that the fire trench acts as a channel, only to re-join Boundary Creek at the end of Big Swamp. It should be noted that whether or not surface water could break out from the fire trench is not clear from the terrain data and satellite imagery, therefore there remains some conceptual uncertainty in the actual hydraulic behaviour of the fire trench.

Whilst the terrain has been improved along the gully lines (including the main channel and fire trench), the entire 2D area of Big Swamp has not been treated to remove the highpoints. By using TUFLOW's new sub-grid sampling (SGS) feature, it is expected that the errors associated with this noisy elevation data will be reduced. Sub-grid sampling allows the TUFLOW model to run on a 4 m grid, whilst still using points spaced at 1 m intervals to determine if water can pass through a cell. Sub-grid sampling permits surface water to flow through parts of cells that would be wet, which could mean that most of the time surface water would still be able to flow around these localised terrain spikes.

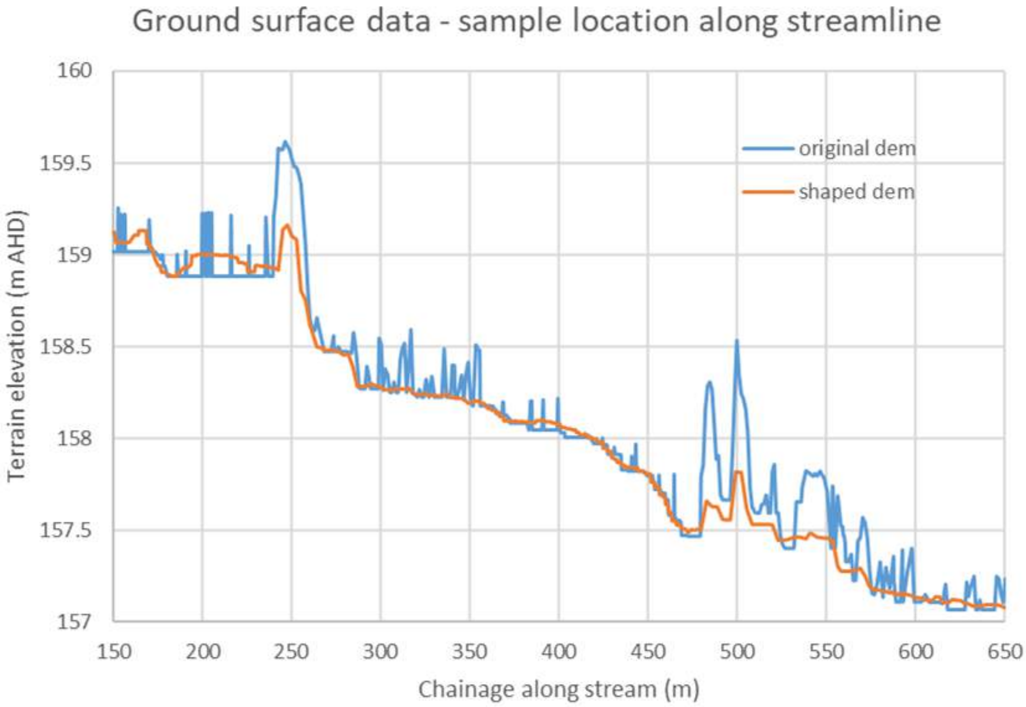


Figure 3-8 Sample of digital elevation model along main channel

3.3.4 1D elements

1D elements have been used in this model to represent the v-notch weirs that exist at gauges 233275A and 233276A. These weirs are represented as m-channels, with a stage-discharge relationship defined by the rating curve used to convert level data to flow data. The invert levels of the m-channels are set to the surveyed invert levels of the two gauges, at 149.421 and 140.393 mAHD for gauges 233275A and 233276A respectively. A thin z-shape line drawn across the channel is used to force the flow to travel through the m-channel only up until it reaches the level of the z line, where it can then flow freely over the top of it. The z-line levels have been set to the level of the top of the v-notch weir plates which are assumed to be 0.4 m above the invert levels, at 149.821 and 140.793 mAHD for gauges 233275A and 233276A respectively.

There are several 1D culverts included in the upstream parts of the model. These pipes were incorporated into the original model developed by Jacobs and have been retained for this project. The information used to configure these culverts have not been verified by GHD.

3.3.5 Model boundary conditions

Inflow boundary conditions

The inflows to the model consist of the main streamflow and the tributary sub-catchment flows.

The upstream flow in the main channel is taken from recorded data at gauge 233229. The gauge data has been filtered to remove flows with poor quality codes above 150. Much of the poor-quality data is due to extrapolation of level data beyond the extent of the rating curve. To address this issue, an additional high flow rating curve has been generated by a TUFLOW run with a steadily increasing flow rate. This rating curve is then used to infill missing data where the level indicated high flows.

At lower flows, the poor-quality data from gauge 233229 needed to be used. There is also one period of time between 23 December 2019 and 12 March 2020 where data from the upstream gauge 233231 needed to be used to infill, as gauge 233229 shows some anomalous behaviour during this time, with a spike in flows that appears erroneous given the absence of such a spike in every other gauge. This occurs over the same time as the rating curve for the gauge is changed, and therefore assumed to be an issue associated with this change. The original recorded gauge data for 233229 and the infilled timeseries, as well as the quality codes and a comparison to gauge 233231, is shown in Figure 2 3. The higher quality codes indicate poorer quality data, so these periods are where infilling has been applied.

The runoff generated by the sub-catchments outside the TUFLOW model boundary are applied as 2d “sa” polygons, located in the gullies where surface water would naturally flow in. The runoff generated by the sub catchments inside the TUFLOW model boundary (directly along the channel) is applied along the streamline using a series of streamline “sa” polygons.

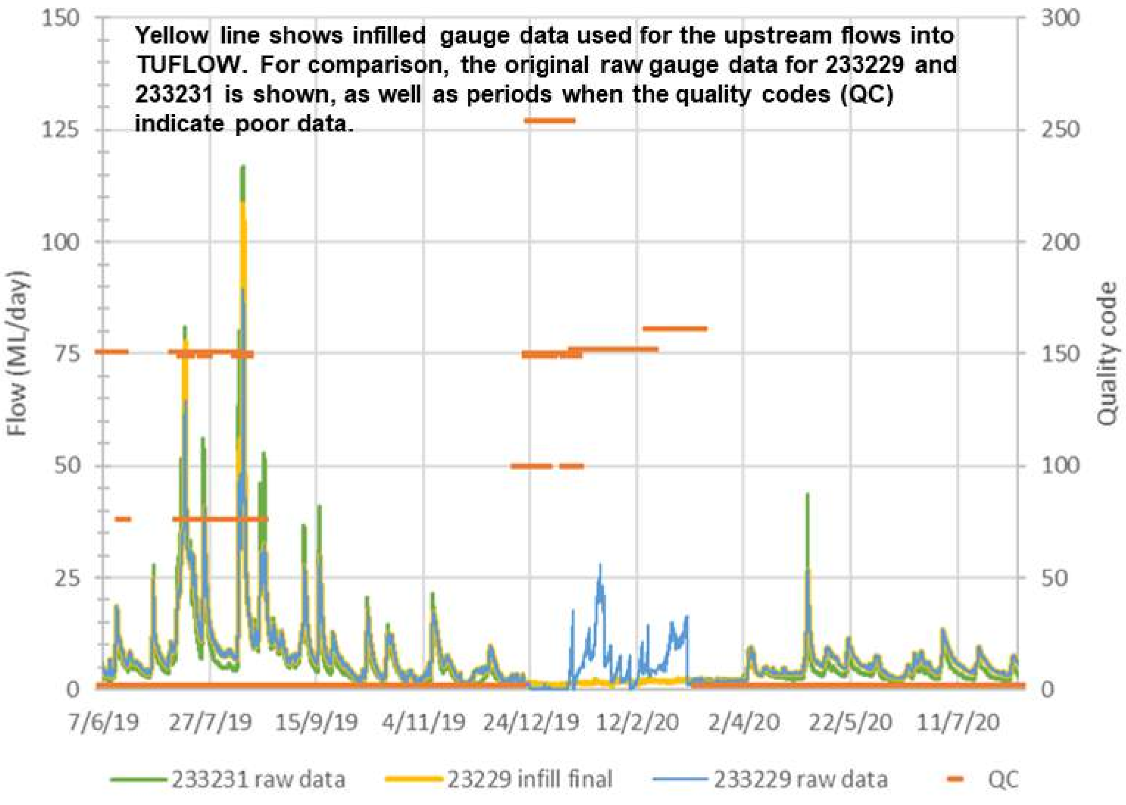


Figure 3-9 Infilled gauge data used for the upstream flows into Tuflow

Downstream boundary condition

The downstream boundary is located at the downstream code boundary of the model and consists of a HQ type boundary line.

Evaporation losses

Evaporation losses have been represented in the model as a constant loss that is lumped in with the infiltration loss.

The initial approach involved applying evaporation as a negative rainfall using an sa_rf polygon in TUFLOW. However, this feature only has the ability to remove a fixed volume of water from wet cells covered by the polygon. This means in dry periods, when very few cells are wet, the effective depths of water evaporated were around seven times higher than in the periods when more cells were wet. Alternatively, the soils function and the initial loss-continuing loss model can be used in TUFLOW to remove evaporation as a fixed depth from wet cells. However, this does not allow this loss to vary in time, as the evaporation forcing varies with the seasons. The limitations associated with these two options means a decision needs to be made between simplifying either the spatial or the temporal variations of evaporation.

After some testing of different options available, a decision has been made in this project to represent evaporation via the soil loss term by adding the average evaporation (about 4 mm/d) to the soil infiltration term. This ensures that evaporation is increasing as surface water spreads out and ponds over a greater area, which is considered to be important when simulating the effectiveness of hydraulic barrier configurations. Figure 3-10 shows the variation in evaporative demand over the period of historical observations, including a ten-day moving average to better show the seasonal average conditions. Evaporation varies from 1 to 8 mm/d between winter and summer. By using a time-constant average value, there are upwards of 4 mm of error in the applied daily evaporation. This is a limitation of the model, as TUFLOW does not currently have the capability for a better representation of these longer term conditions as it is primarily designed for short term event-based modelling. Nonetheless, this is considered a relatively minor issue given the much higher soil infiltration losses estimated from the USG-Transport model and large uncertainties associated with these losses.

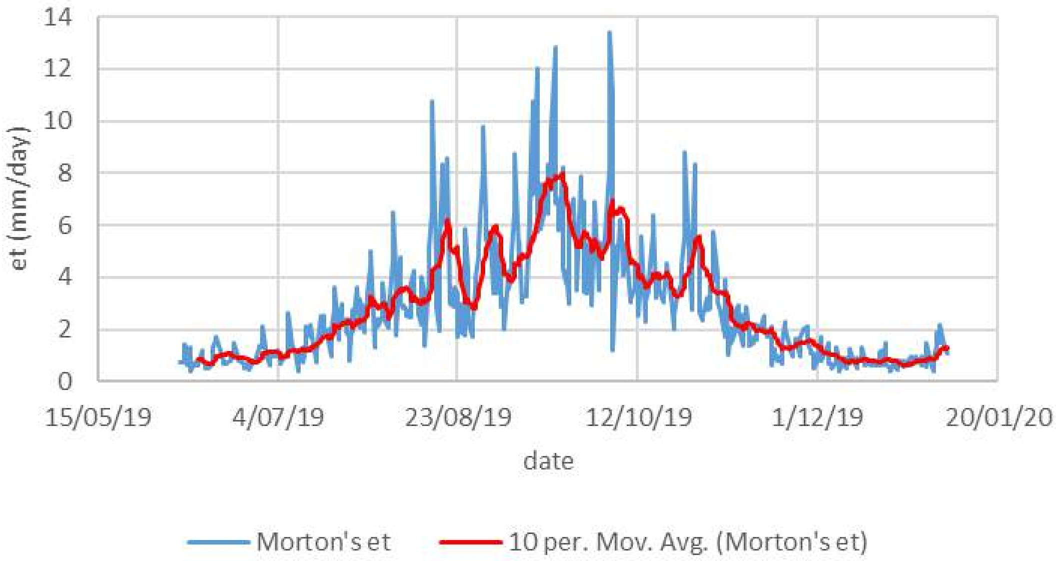


Figure 3-10 Evaporation forcing during monitoring period

Infiltration losses

Soil infiltration losses are accounted for using the soils function in TUFLOW, and the initial loss – continuing loss model. By setting the initial loss to zero and setting the continuing loss to a value in mm/d for each timestep, TUFLOW removes a fixed depth of water equal to the applied infiltration rate only from the wet cells. This capability has been verified using sub-grid sampling in several test model runs, to ensure that specified depths of water are correctly lost from the partially wet parts of the cell.

Due to the uncertainties and variability in the soil infiltration rates simulated by the USG-Transport model, several soil infiltration rates have been tested in the TUFLOW model. These used 35 mm/d infiltration along the main channel, with infiltration in other ponded areas set to 10, 25 and 40 mm/d. These soil loss values also include an average value of around 4mm/d of evaporation, which means the effective soil infiltration rates are 6, 21 and 36 mm/d. The calibrated model currently uses 25 mm/d soil infiltration loss, which is discussed further in Section 4.1.

Note that the use of Green-Ampt soil losses was initially the preferred option for estimating soil infiltration in TUFLOW. However, TUFLOW does not include any way for the soil moisture to be reduced. This means once the soil is saturated during the first wet period, it would remain saturated for the rest of the simulation, leading to incorrect representation of the drying and wetting cycles.

3.3.6 Material roughness

The Manning's n values used to specify the roughness of the ground surfaces are shown in Figure 3-11. These values have been selected based on typical values for each land use type and are unchanged from the previous modelling undertaken by Jacobs. The land use types are broadly consistent with the evapotranspiration zones applied to the USG-Transport model, which is discussed in Section 3.4.2.

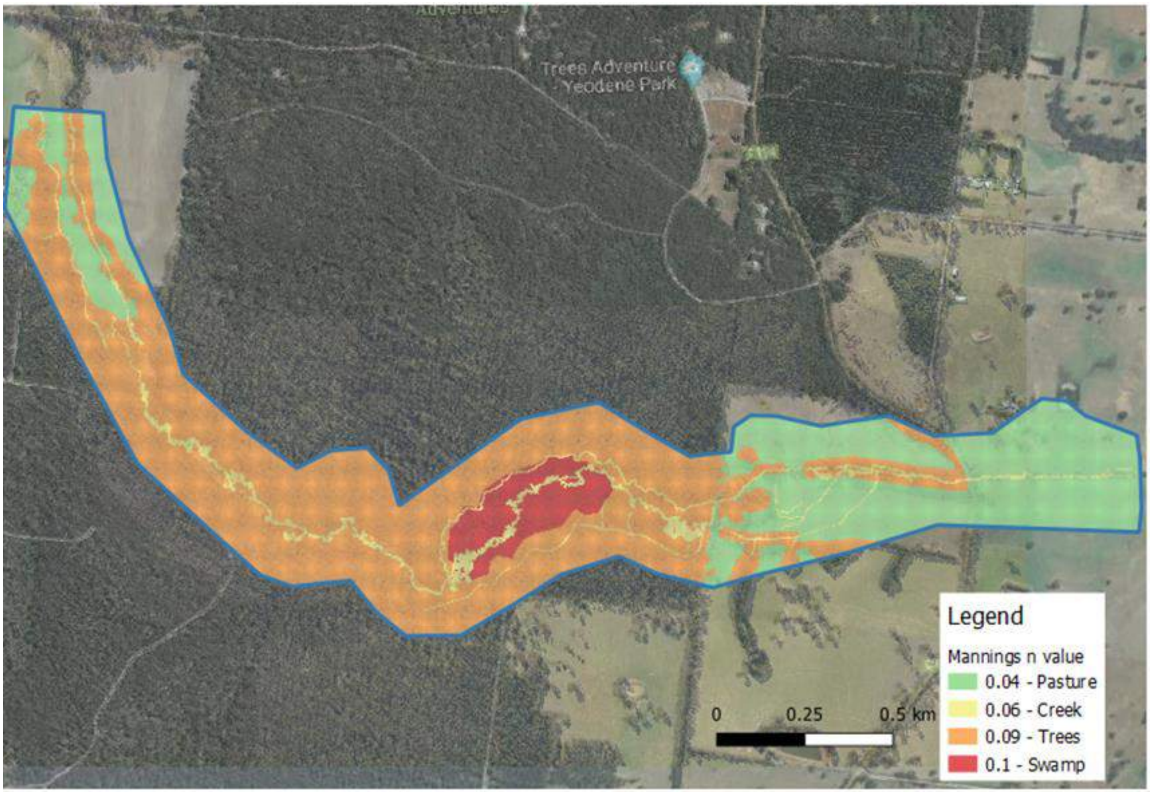


Figure 3-11 Manning's n values

3.4 Groundwater (USG-Transport) model design and construction

3.4.1 Model domain and structure

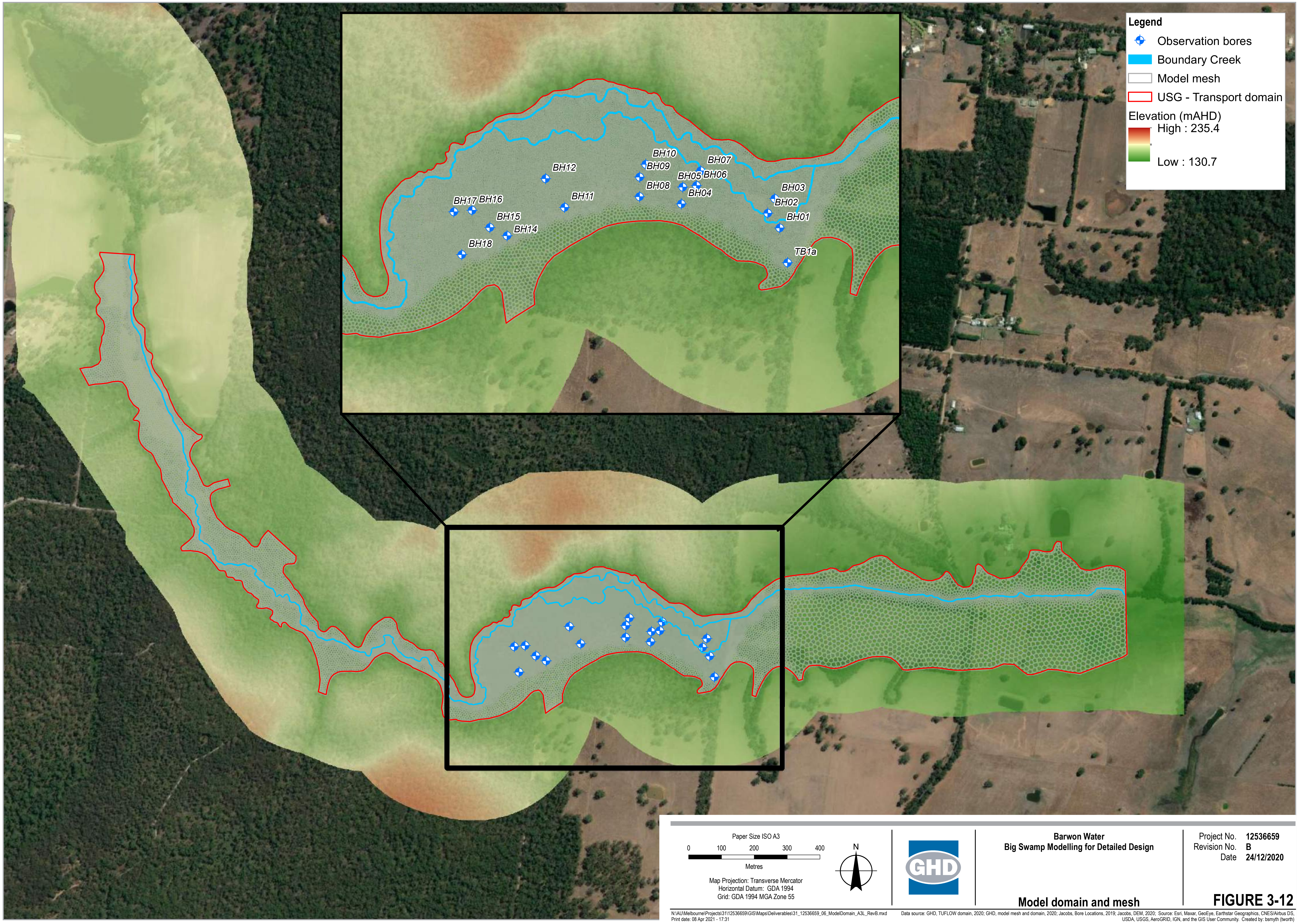
The USG-Transport model domain is based on the revised extent of the QA, taking into consideration the geological map, borehole logs and topography. This is broadly consistent with the QA extent of the FEFLOW model, with modifications to better reflect the presence of alluvial sediments along minor channels/tributaries (such as those encountered at the nested site TB1 and bores TB2b and TB2c drilled further upstream). The domain is defined along the entire length of the TUFLOW model to maintain consistent spatial extents and to facilitate the exchange of information between the two models (including the surface flow/run-off terms applied along their boundaries). The domain covers Reach 2 of Boundary Creek, and approximately a third of Reach 3 downstream of Big Swamp.

The USG-Transport model uses an unstructured mesh, with Voronoi (tessellated) cells that are considered numerically ideal for meeting the requirements of the controlled volume finite difference formulation (a line connecting the centres of two adjacent cells intersects the shared face at or close to a right angle). The mesh is refined in critical areas where the accuracy is considered important. These include much of the wetland area, where the bores are located and overland (inundation) flow is expected, with cell lengths reducing to around 3 m. The bores are used as constrained points to align the Voronoi cell centres to the location of each bore. The mesh is also refined along Boundary Creek, with constrained points spaced at roughly 2 m apart, producing a series of cells connected along the creek alignment with a length of around 2 m and width of around 3 m (broadly consistent with the typical channel width). This is based on the alignment of Boundary Creek delineated from the most accurate DEM and includes the primary channel and secondary channel that diverges within Big Swamp.

The model top is based on the processed DEM used in TUFLOW, which is derived from lidar and has been spot checked against the surveyed bore and gauge elevations. The thickness of the QA is assumed to be around 8 m in the most upstream end of the model, increasing linearly along Boundary Creek and reaching a thickness of around 12 m at the location of nested site TB1 (based on the depth of QA interpreted from the borehole logs). The QA is also assumed to thin towards the edge, where it pinches out against the outcropping bedrock to form a channel-filled geometry.

The QA is split into two model layers, to enable partially penetrating hydraulic barriers to be simulated in the model if required. There are 38,806 cells per layer and 77,612 cells in total.

Figure 3-12 shows the model domain and unstructured mesh, including mesh refinement in the area of Big Swamp and along Boundary Creek. Figure 3-13 shows the 3D view of the model domain, including the model top elevation. The model top elevation is also shown in Figure 3-14, along with the QA thickness.



Model domain and mesh

FIGURE 3-12

Figure 3-13 3D view of groundwater model domain

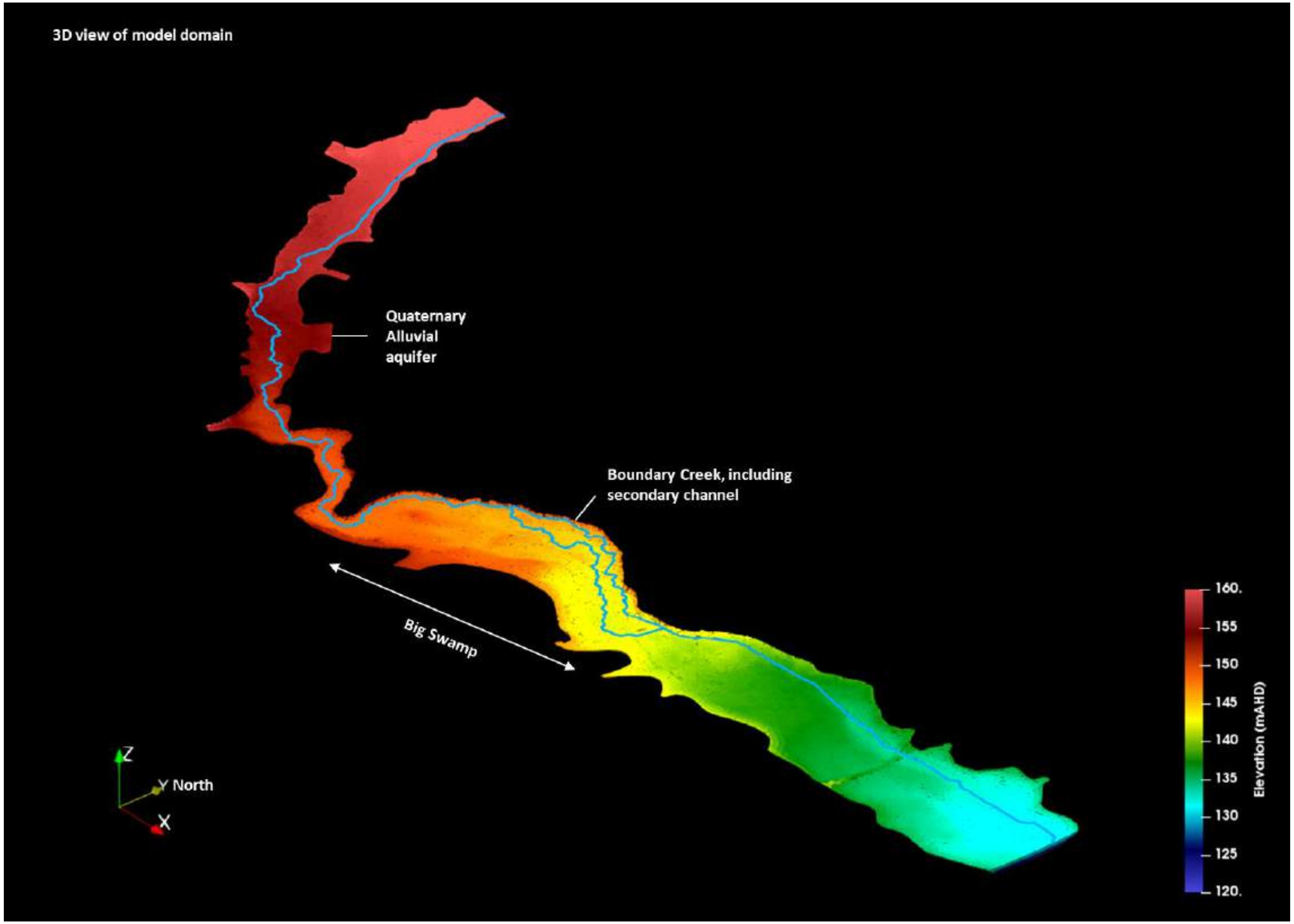
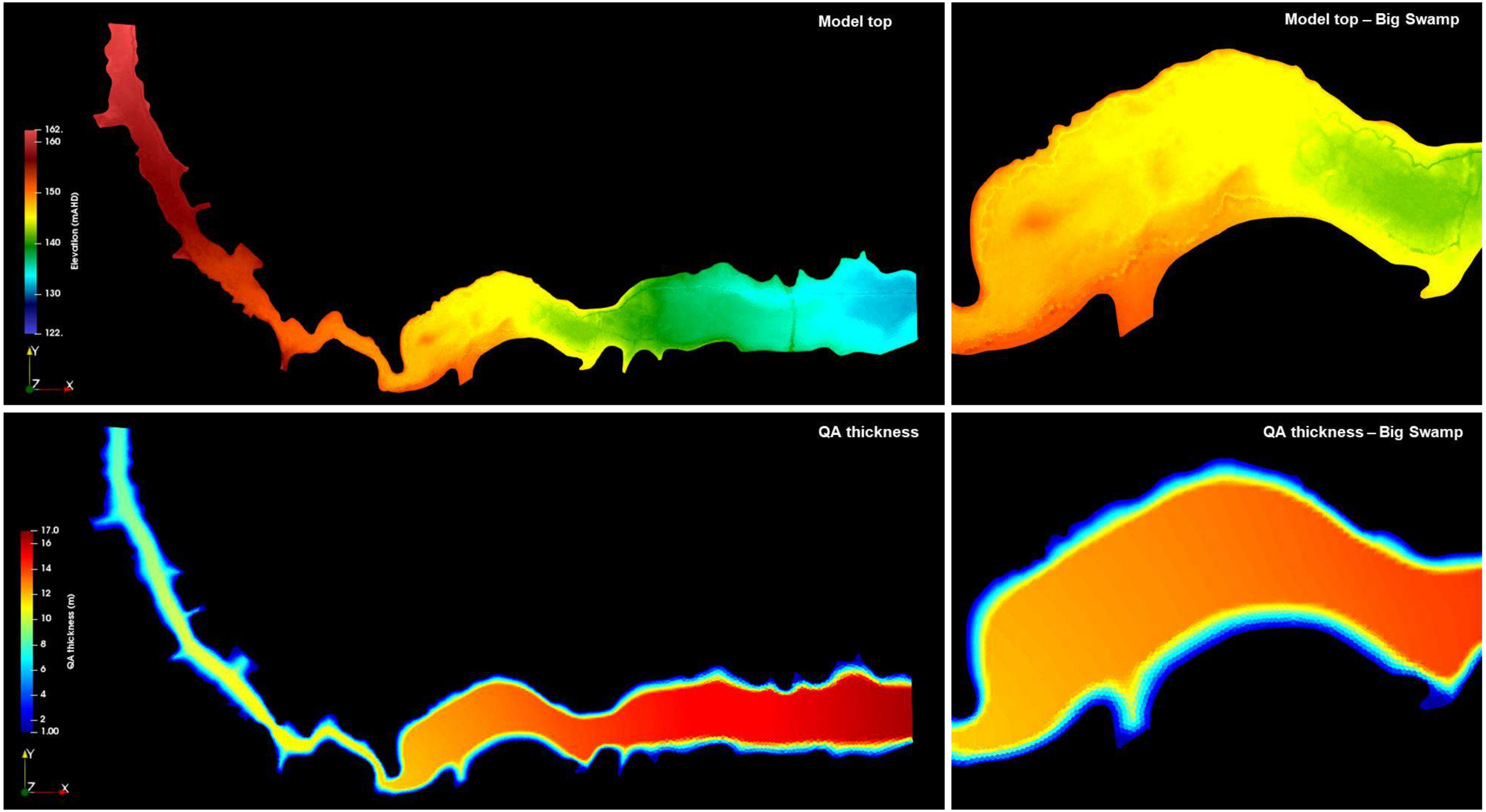


Figure 3-14 Model top and QA thickness



3.4.2 Model boundary conditions

River boundary condition

USG-Transport's River (RIV) package is a head-dependent flux boundary condition, which is used in this study to simulate infiltration due to surface water inundation/overland flow. The surface water depths and extents derived from the TUFLOW flood model are used to parameterise the RIV stage and map the location of RIV cells. As the TUFLOW model is solved using much finer time steps than the length of USG-Transport model stress periods, the water depth and extents from TUFLOW are spatially and temporally averaged over each stress period to derive time-varying RIV boundary condition. This means both the RIV stage and number of RIV cells vary for each model stress period to represent the dynamic nature of surface water inundation process.

The RIV conductance term is rigorously calculated for each RIV cell using the cell area, RIV bed hydraulic conductivity and RIV bed thickness (assumed to be 0.5 m based on the typical thickness of surficial material comprising clayey silt with loose fine sand and rootlets, as recorded in borehole logs).

The RIV cells are absent along Boundary Creek, which is simulated using the Stream boundary condition.

Stream boundary condition

USG-Transport's Stream Flow Routing (SFR2) package is used to simulate Boundary Creek and its interaction with groundwater. With the SFR boundaries, the volume of water available for interaction with the modelled groundwater system is limited to that which has accumulated from upstream within the defined stream channel network (from baseflow, and/or any runoff and artificial discharges, less any diversions). In dry times, there may be no or little water flowing down the stream network, thus avoiding unrealistic leakage of water into the model from these boundaries. This capability is particularly important for this project, as the flow loss observed between gauge 233275A and 2332756A is critical for understanding the stream leakage rates and therefore the effectiveness of supplementary flow regimes in maintaining flow downstream. The model can also be calibrated to both stream flows and stream stage, which aids in narrowing the uncertainty in modelled water balance.

In this study, time-varying stream stage is calculated using Manning's equation with a rectangular wide channel. The channel widths are varied from 1 to 3 m during calibration, based on a typical range of widths estimated from DEM. The Manning's roughness is also varied during calibration from 0.05 to 0.2, with the lower end of the range representing tortuous channels with vegetation (as commonly encountered in swamps).

SFR bed elevations are defined using the processed DEM, with enforced topographic fall down the stream network. The bed elevations at the location of flow gauges 233275A and 2332756A have been corrected against the surveyed gauge zero elevations to ensure accurate computation of stream stage. Stream length within each model cell is calculated rigorously based on the stream geometry derived from DEM. Hydraulic conductivity of the bed material (and hence the stream bed conductance) is adjusted during model calibration. Stream bed thickness is set to 0.5 m, consistent with the RIV boundary condition.

For the calibration period, a total of 14 stream segments are used to assign inflow from downstream of McDonald's Dam and various tributary points along the length of Boundary Creek (see Figure 3-16). These flow terms are derived from the GR4J hydrological model, ensuring consistency with the flow terms applied to the TUFLOW model. The daily flow from the GR4J model have been averaged over the length of model stress periods. Where the secondary channel diverges from the primary channel within Big Swamp, a diversion is created to direct flow into the secondary channel. This is based on the flow split derived from the TUFLOW model, which equates to roughly 20% of flow diverted to the secondary channel.

For the predictive simulation, additional stream segments and diversion have been incorporated to simulate the diversion of flow into the swamp to redistribute flow. This is discussed further in Section 5.3.

Recharge and evapotranspiration

Recharge and evapotranspiration are simulated using USG-Transport's Recharge (RCH) and Evapotranspiration (EVT) packages. The initial estimates of time-varying recharge and evapotranspiration have been derived using a simple water balance model called LUMPREM (Doherty, 2020) which uses daily climate data and unsaturated zone parameters to derive deep drainage, runoff and evapotranspiration. The outputs from LUMPREM are sensitive to the assumed unsaturated zone parameters such as soil moisture store, soil hydraulic conductivity, crop factor and recharge delay which are often not known. Nonetheless, the LUMPREM outputs based on initial parameter estimates can provide a hydrologically sensible starting point for parameterising time-varying recharge and evapotranspiration, which can be subsequently varied during model calibration.

The daily rainfall data from the nearest rainfall gauge 233250 and the daily pan evaporation data from the nearest SILO point are used as climate inputs to the LUMPREM model. The typical plant root zone is assumed to be shallow (1 m), with a soil porosity of 0.3 and vertical soil hydraulic conductivity of 0.02 m/d (an order of magnitude lower than the average from slug tests). A simple time constant crop factor of 0.8 has been assumed.

A total of four zones are used to parameterise the EVT package's extinction depth. This defines the maximum depth below land surface above which the water table must occur before evapotranspiration is removed from the groundwater model. The evapotranspiration rate varies linearly from nil if the water table level occurs at or below the extinction depth, up to the defined maximum rate if it occurs at or above the land surface. The EVT zones for parameterising the extinction depths are based on the echo-hydrological zones developed by Ecological Australia (2019) and broad inspection of aerial imagery, and include:

- Zone 1, defined over woodlands where deep-rooted vegetation/trees are likely to be accessing groundwater (including various Eucalyptus species). Within Big Swamp, this includes Damp Woodlands and Main Channel eco-hydrological zones. The plausible range of extinction depth is assumed to be 1 to 5 m.
- Zone 2, corresponding to the Swamp Plain eco-hydrological zone comprising shallow rooted vegetation (such as Riparian Fern Scrub) the require a near-constant waterlogged condition. The extinction depth is assumed to be shallow, ranging from 0.3 to 1 m.
- Zone 3, corresponding to pasture/grass areas outside of Big Swamp where the extinction depth is expected to be shallow. As per Zone 2, the extinction depth is assumed to be shallow, ranging from 0.2 to 1 m.
- Zone 4, defined along the perimeter of the model where the QA is thin and the extinction depth is constrained to prevent unrealistic EVT i.e. to prevent the extinction depth extending below the bottom of model. The extinction depth for this zone is assumed to range from 0.1 to 1 m.

Recharge and EVT are set to zero over the location of RIV and SFR cells. As the number and location of RIV cells vary dynamically, the location and number of zero RCH and EVT cells also vary from one stress period to the next.

Specified gradient boundary condition

USG-Transport's Specified Gradient Boundary (SGB) package is used to simulate the component of through-flow into and out of the model and vertical flow to and from the underlying LTA. The SGB provides efficient means of allowing fluxes into and out of the model based on hydraulic gradients, cross-sectional area perpendicular to the direction of flow and anisotropy ratio relative to the horizontal hydraulic conductivity in x-direction. The positive SGB terms represent flow into the model and negative SGB terms represent flow out of the model.

For aquifer through-flow into and out of the model, positive and negative SGB terms are assigned along the northern (upgradient) and eastern (down gradient) boundary of the model respectively. The SGB term is calculated for each cell based on the cross-sectional area and horizontal hydraulic gradients estimated from the regional piezometric contours of the LTA, which are varied during calibration within a plausible range.

For the vertical flow component, the SGB terms have been calculated using the following steps:

- Firstly, an interpreted surface of piezometric heads was derived using the recent measurements of groundwater levels in the LTA bores 109130, 109128 and TB1C and the horizontal hydraulic gradients between them. This provides a piezometric surface that accurately matches the measured groundwater levels at the location each bore.
- The vertical hydraulic head difference is then computed on a cell-by-cell basis using the interpreted LTA heads and heads in the QA. Because the latter is also not known everywhere in the model in advance, a reference depth to water has been calculated from the bores within the swamp. This is subtracted from the model top to derive approximate QA head for each model cell. As the shallow groundwater levels are highly dynamic, the reference depth (and hence the heads in the QA) is varied over time based on the range of groundwater depths recorded at the bores over each model stress period (which is varied during calibration). While simplified, this provides highly efficient means of allowing the direction and magnitude of vertical fluxes to vary spatially and temporally such that their effects on the observed groundwater levels and trends can be closely examined. The vertical hydraulic head differences are divided by the half aquifer thickness to calculate hydraulic gradients.
- The vertical hydraulic gradient at each model cell is multiplied by the cell area and an anisotropy ratio (kz/kx), which vary spatially. This means the SGB term computed for each model cell is unique and reflects the spatial differences in vertical hydraulic gradients, cell area and anisotropy ratio. Where/when the heads in the LTA are lower than the QA heads, negative SGB terms are used to compute fluxes out of the QA and vice versa.

The interpreted surface of the LTA heads indicate that the LTA becomes artesian in the downstream part of the swamp. This corresponds to the interpreted extent of the MTD, which is thought to occur approximately in the middle of the swamp based on the regional geological map. Although there is uncertainty in the exact location of this boundary, the development of an artesian condition is consistent with the confining effect of the MTD which limits the hydraulic connection between the LTA and QA, as seen at the nested site TB1. The early testing of the model also indicated excess upward flow into the model when the SGB terms are prescribed in the artesian/MTD area, which is not supported by the available data. For this reason, no SGB terms have been assigned over the interpreted area of the MTD.

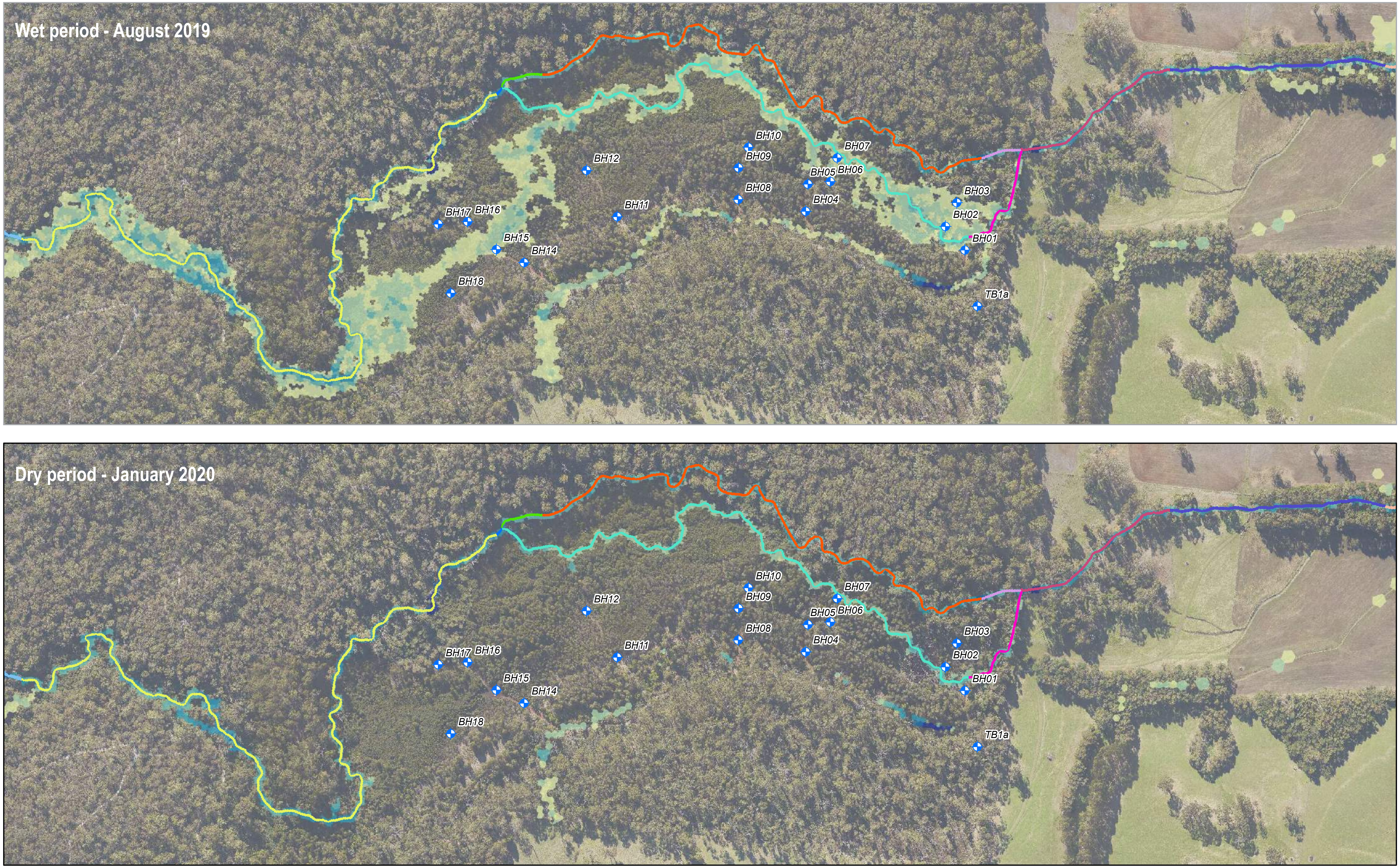
In the current SGB configuration, the LTA heads are assumed to be constant during the period of model simulation (14 months). This is supported by very little variation in the LTA heads observed over this period (see Figure 3-19), which is small compared to the seasonal variations in the QA heads. For future model use, the effect of changes in the LTA heads can be easily incorporated to the SGB terms by varying the LTA heads and recalculating the SGB terms.

Figure 3-18 and Figure 3-19 provide further information on the configuration of the SGB terms.

Drain boundary condition

USG-Transport’s Drain (DRN) package is used to simulate the presence of narrow fire trench along the southern boundary of Big Swamp. The DRN elevation is based on the lowest DEM intersected by the DRN cell and the conductance term is calculated accurately using the length of fire trench intersecting each DRN cell and a width of 2 m. The DRN hydraulic conductivity is derived from the RIV bed hydraulic conductivity used to parameterise the surficial material.

During wet periods, the TUFLOW model simulates ponding of surface water in the fire trench. This means the DRN cells switch on and off dynamically depending on whether or not RIV cells are active in a given stress period.



Legend

Observation bores

SFR Segment

SFR Segment	SFR Segment	RIV ponding depth (m)
4	7	0.02 - 0.1
5	8	0.1 - 0.2
6	9	0.2 - 0.3
	10	0.3 - 0.4
	11	0.4 - 0.5
	12	0.5 - 0.6
	13	
	14	

Paper Size ISO A3

0 25 50 75 100

Metres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

GHD

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SFR and RIV boundary conditions

FIGURE 3-15

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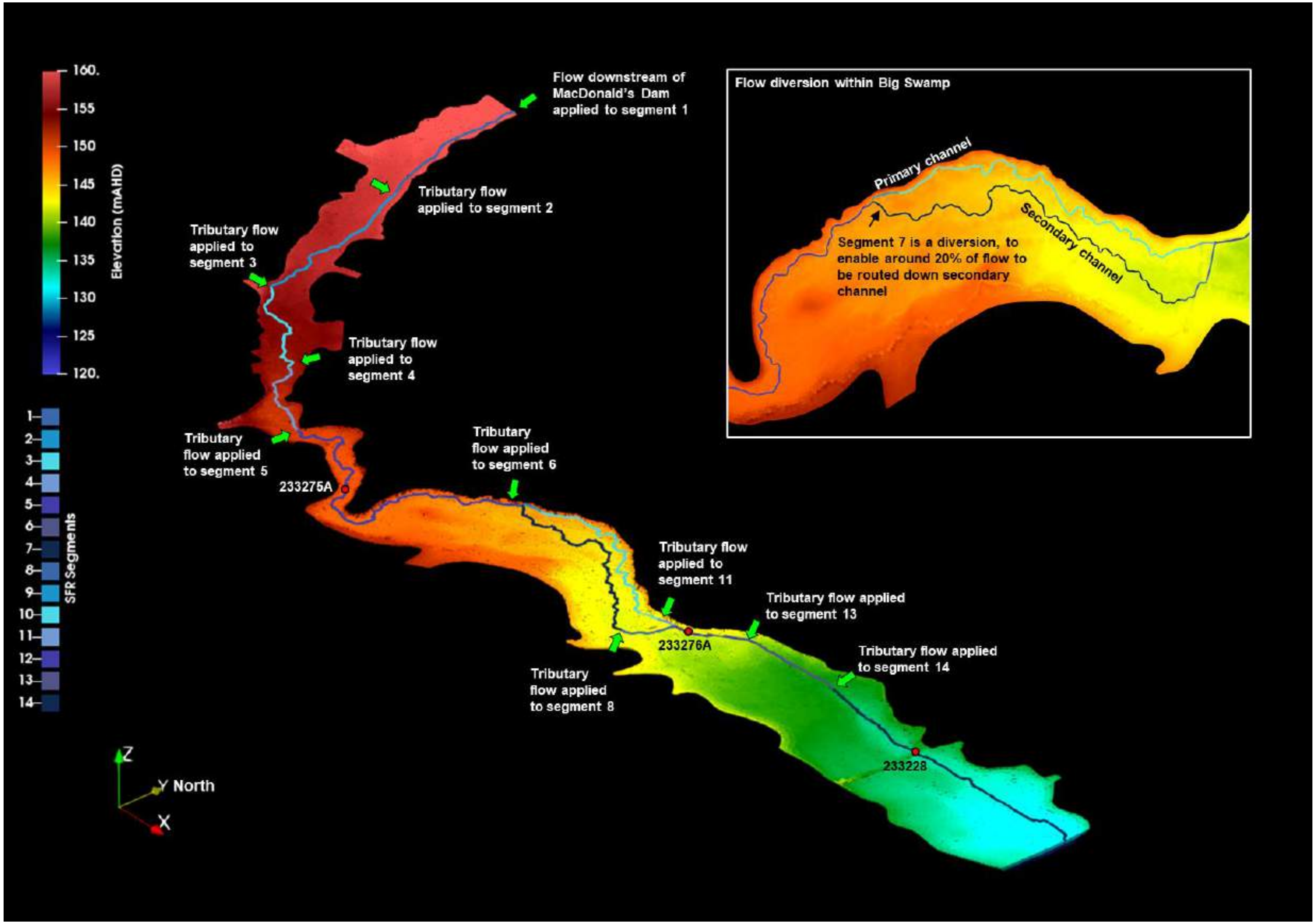
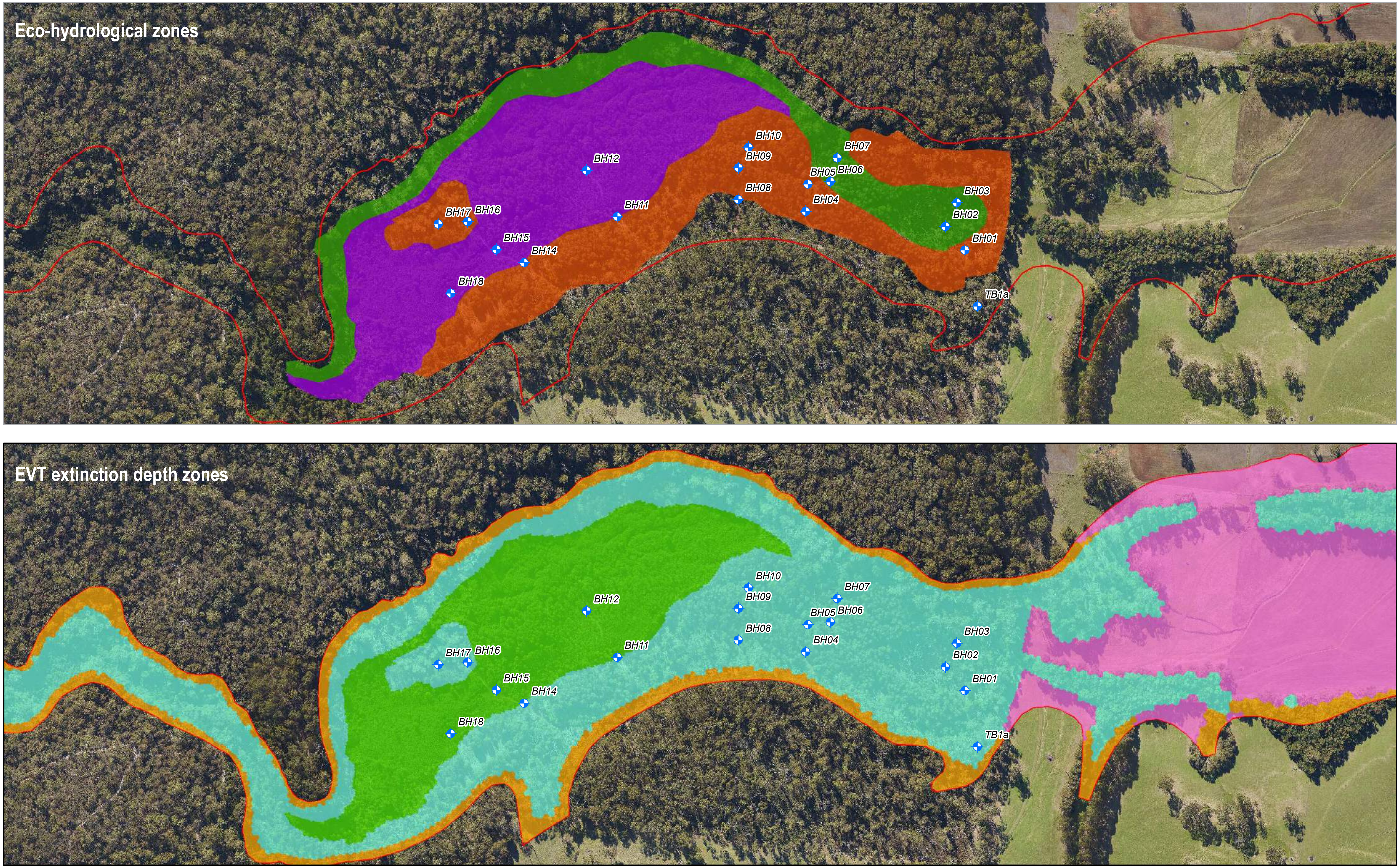
Print date: 08 Apr 2021 - 17:29

Data source: Jacobs, Bore Locations, 2019; GHD, RIV and SFR boundary conditions, 2020; BW, Imagery, 2019; . Created by: bsmyth (tworth)

Figure 3-16 SFR segments and inflows





Legend

- Observation bores
- USG - Transport domain

Eco-hydrological zones
- Damp woodlands
- Main channel
- Swamp plain

EVT extinction depth zones
- 1
- 2
- 3
- 4

Paper Size ISO A3
0 25 50 75 100
Metres
Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

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EVT extinction depth zones

FIGURE 3-17

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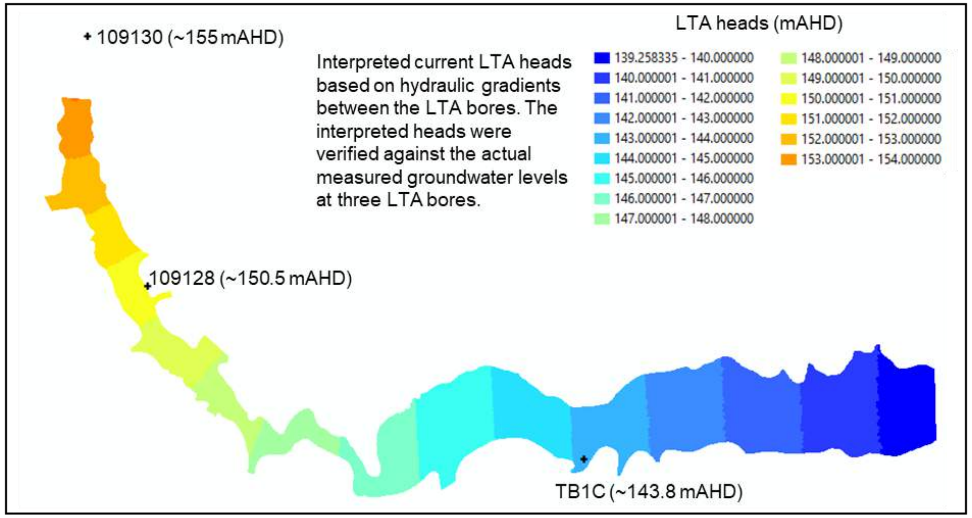
Print date: 08 Apr 2021 - 17:28

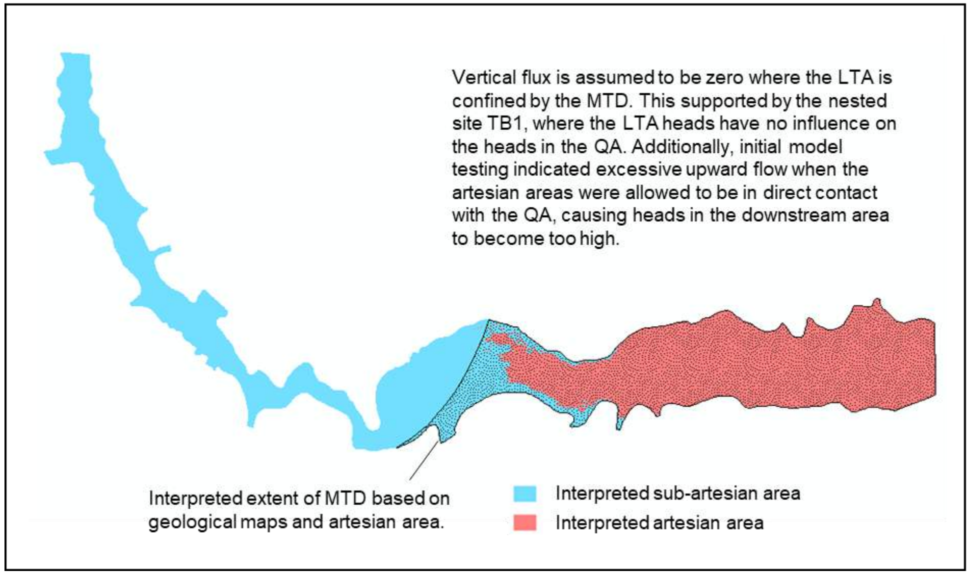
Data source: Jacobs, Bore Locations, 2019; GHD, REVT extinction depth zones, 2020; Ecological Australia, eco-hydrological zones, 2019; BW, imagery, 2019; . Created by: bsmyth (tworth)

Figure 3-18 SGB set up – part 1



Specified gradient boundaries (SGB) are parameterised in the following manner:

- Along the up gradient and down gradient boundaries, positive and negative horizontal SGB terms are prescribed to represent the component of through-flow into and out of the model, respectively. The SGB terms are applied to both layer 1 and 2 and are calculated by multiplying the hydraulic gradient by the cross-sectional area of each voronoi cell.
- Elsewhere, vertical SGB terms are prescribed to simulate the component of vertical flow into and out of the QA. The vertical head difference is calculated by subtracting representative water levels in the QA from the interpreted heads in the LTA. Because appropriate water levels are not known everywhere in the QA prior to modelling, these were adjusted during calibration within the expected range of water level (creating a surface of reference depth to water from which reference water level is calculated on a cell-by-cell basis). The vertical gradient is calculated between the base and mid-point of the QA (head difference divided by the half thickness of QA). As the QA water levels are highly dynamic, the minimum and maximum reference water depths have been calculated for each stress period based on the observed water levels from bores in the area where the QA is in contact with the LTA. The vertical SGB terms are then calculated on a cell-by-cell basis using the surface area and kz/kx anisotropy ratio of each voronoic cell.
- Where the MTD is present and limits the vertical hydraulic connection between the QA and LTA, no SGB terms have been prescribed. This is based on the limited hydraulic connection observed at the nested monitoring site TB1.
- The LTA heads are assumed to be steady during the calibration period based on the observed data; however, this simple approach allows the effects of future changes in the LTA heads to be easily incorporated into the model by shifting the LTA heads and recalculating the SGB terms.



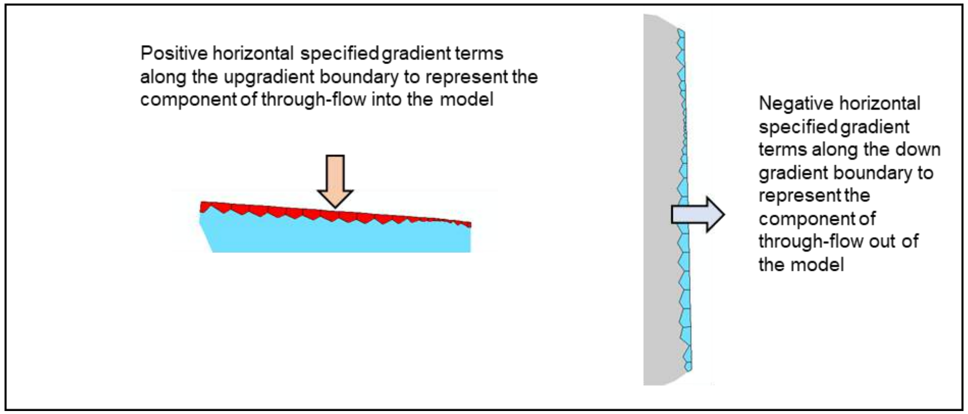
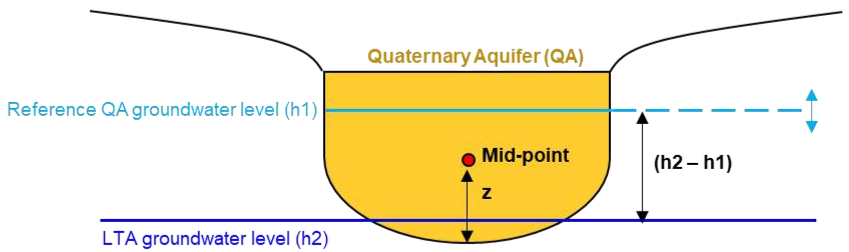


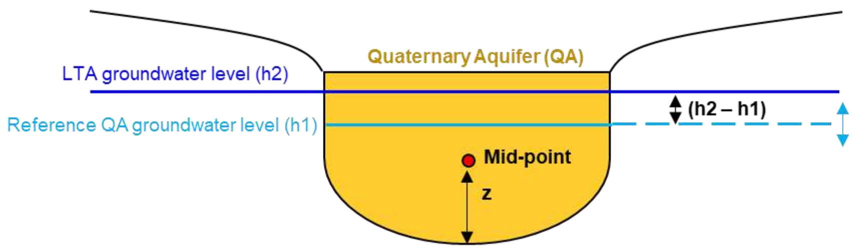
Figure 3-19 SGB set up – part 2

Losing condition



Z gradient = (h2 – h1) / z = negative gradient indicating vertical flow out

Gaining condition

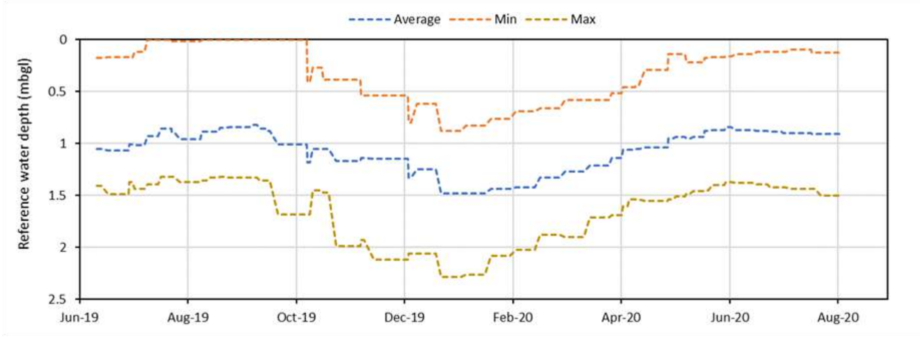


Z gradient = (h2 – h1) / z = positive gradient indicating vertical flow in

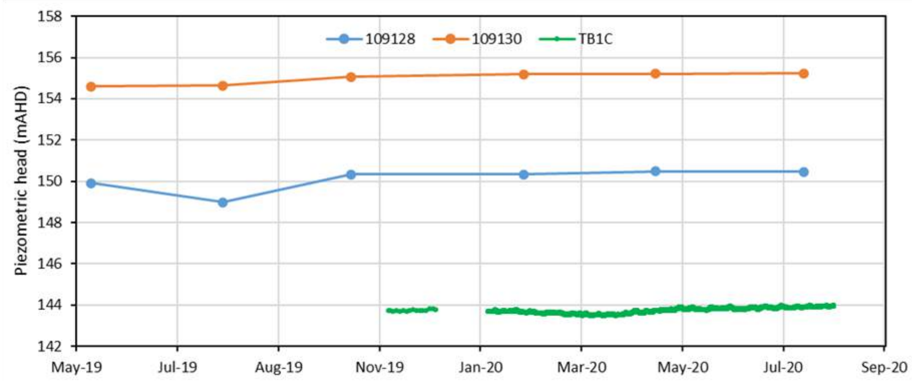
Reference water level has been allowed to shift during calibration within a range defined by the water levels of upstream bores where the QA is in contact with the LTA.

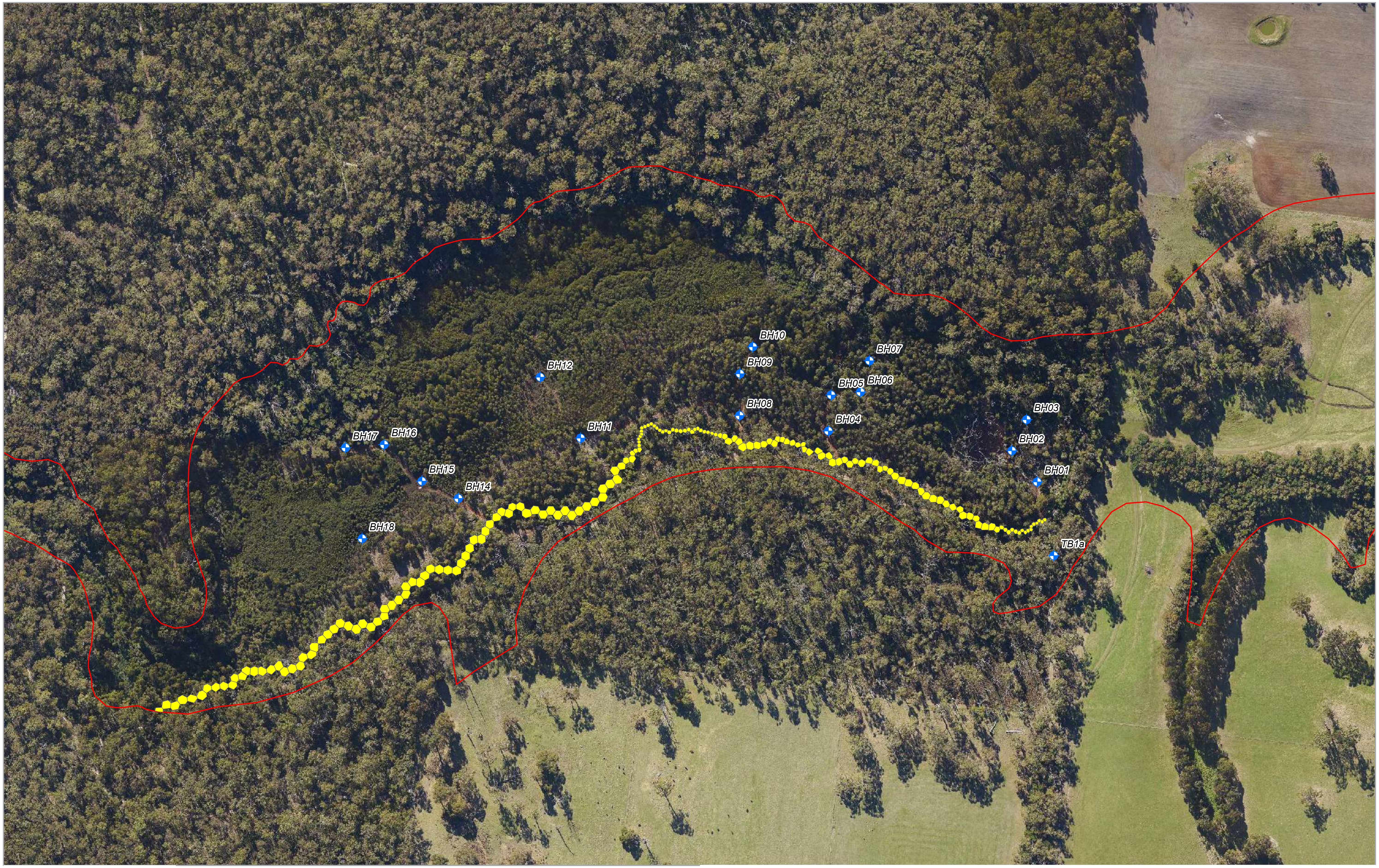
Where the QA is thin (towards its edges), the reference levels can fall below the mid-point or bottom of the QA during calibration. When this occurs, the reference levels are assumed to be equal to the mid-point of the QA to prevent unrealistic gradients.

The chart below shows the average, minimum and maximum water depths calculated over time from the bores. The reference water levels have been allowed to vary within this range to provide some flexibility to adjust the rate and direction of vertical fluxes during calibration.



The chart below shows recent measurements of LTA heads. With the exception of a slight dip in July 2019 at 109128, the LTA heads over the last 12 months have been effectively constant. The SGB terms therefore assumes constant LTA heads for the 14-month monitoring period.





Legend

- Drain boundary condition
- Observation bores
- USG - Transport domain

Paper Size ISO A3

0 25 50 75 100

Metres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

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Drain boundary conditions

FIGURE 3-20

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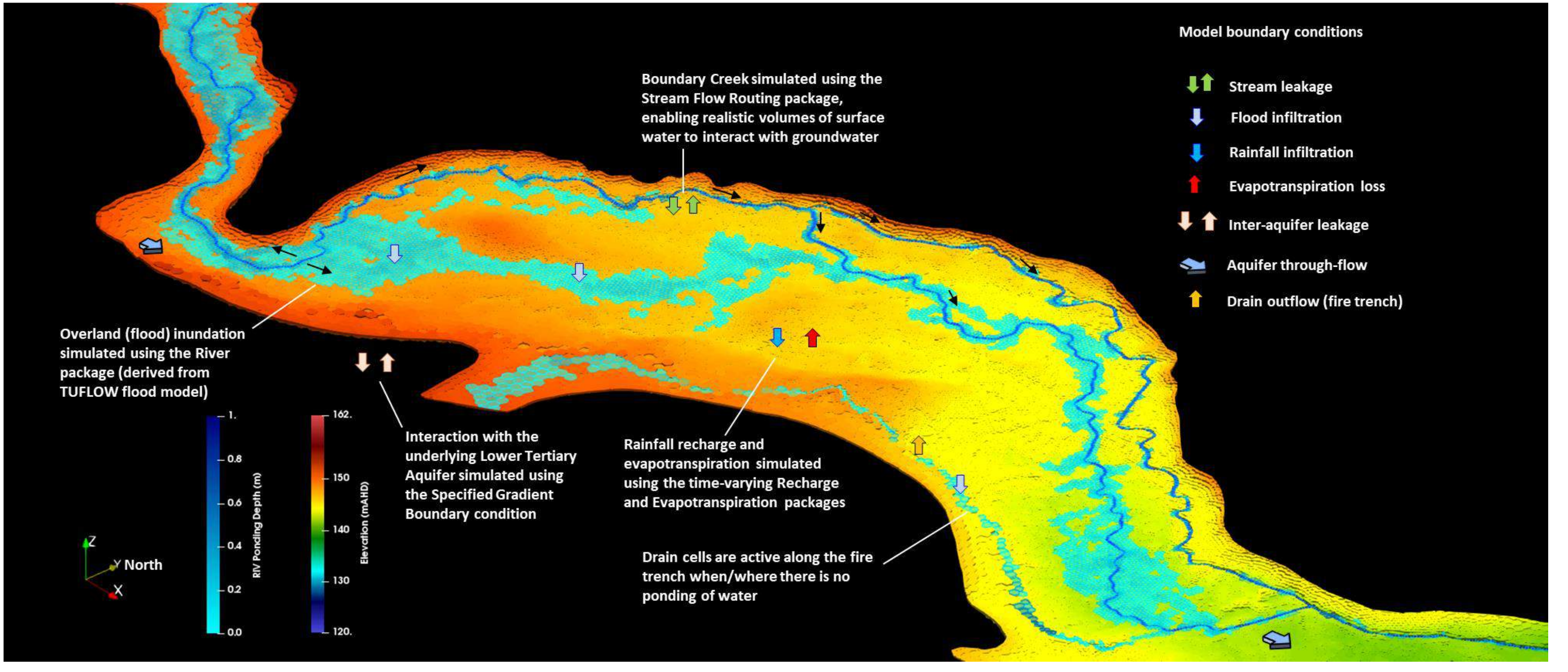
Print date: 08 Apr 2021 - 17:27

Data source: GHD, model domain, 2020; Jacobs, Bore Locations, 2019; BW, imagery, 2019; . Created by: bsmyth (tworth)

Figure 3-21 Model boundary conditions and processes – existing condition

Model boundary conditions for August 2019 wet period



3.4.3 Model parameterisation

The USG-Transport model is highly parameterised, with a total of 611 adjustable parameters used to introduce local scale variability in material properties required to replicate the observed groundwater levels, trends, steam flow and their spatial differences within Big Swamp.

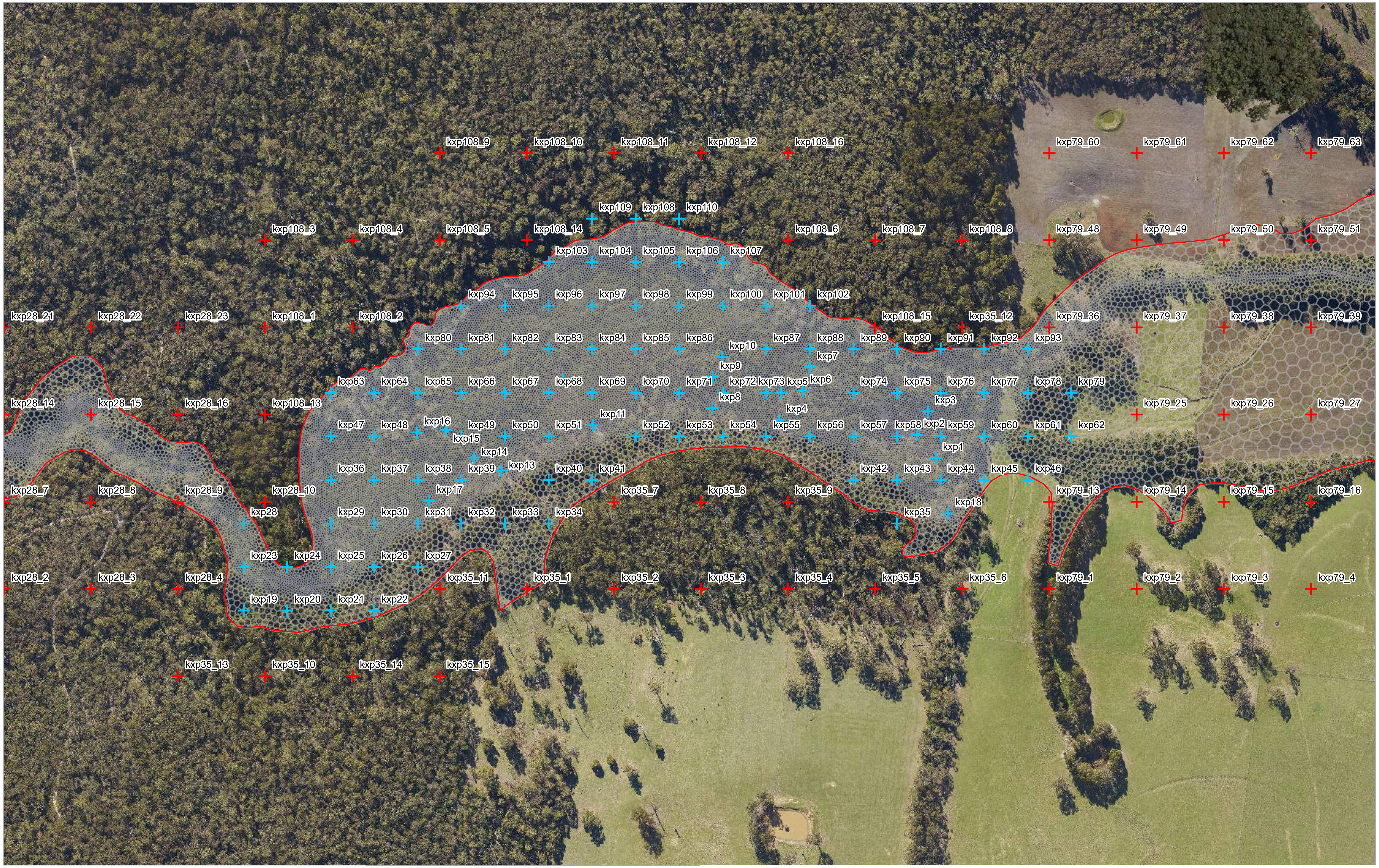
For horizontal and vertical hydraulic conductivity, RIV bed hydraulic conductivity and specific yield, local scale variability within Big Swamp is simulated using pilot points. For each of these parameters, a total of 110 adjustable pilot points are used, which include pilot points located at each observation bore and the surrounding area on a 50 m by 50 m grid. For the upstream and downstream areas of the model outside of the swamp, parameter values are varied uniformly using gridded pilot points tied to one of the adjustable pilot points. Similarly, tied pilot points are used to the north and south of the swamp to minimise spurious interpolation of parameter values towards model edges. Figure 3-22 shows the location of adjustable and tied pilot points used for horizontal hydraulic conductivity. The same pilot point locations are used for the vertical hydraulic conductivity, RIV bed hydraulic conductivity and specific yield.

For the SFR bed hydraulic conductivity, a total of 80 pilot points are distributed along the alignment of Boundary Creek at roughly 40 m spacing within Big Swamp, increasing up to around 200 m regionally. The SFR bed hydraulic conductivity is linearly interpolated between the pilot points along Boundary Creek. The SFR width and Manning’s roughness are also parameterised separately for each of the 14 SFR segments.

The SGB cells used to simulate vertical fluxes are parameterised using a model-wide reference water depth, from which the representative QA heads are calculated. The reference water depth is varied for each model stress period to simulate the temporal variability.

Time-varying recharge and EVT rates are applied uniformly over the entire model domain, albeit with zero rates assigned where SFR and RIV cells are present.

The model parameters are discussed further in Section 4.4 in the context of model calibration.



Legend

Hydraulic conductivity pilot point
- log
- tied
- Observation bores

- USG - Transport domain
- Model mesh

Paper Size ISO A3
0 25 50 75 100
Metres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

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GHD

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Horizontal hydraulic conductivity pilot points

FIGURE 3-22

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Print date: 08 Apr 2021 - 17:27

Data source: GHD, model domain, mesh and pilot points, 2020; Jacobs, Bore Locations, 2019; BW, imagery, 2019; . Created by: bsmyth (tworth)

4. Model calibration

4.1 Calibration approach and iterations

Model calibration is a process by which model parameter values are altered within realistic bounds until the model outputs fit historical measurements, such that the model can be accepted as a reasonable representation of the physical system of interest (Barnett et al. 2012). In this study, the calibration period commences in June 2019 and extends to August 2020, capturing approximately 14 months of data.

As discussed in Section 3.1.1, the integrated modelling requires outputs from the GR4J model to inform the flow inputs to both the TUFLOW and USG-Transport models, and outputs from the TUFLOW model to inform the boundary condition of the USG-Transport model. Because the rate of infiltration assumed in the TUFLOW model cannot be well constrained until running the USG-Transport model, iterations are required to ensure a degree of consistency between the two models. This means the calibration process has been staged as well as iterative.

The method in which infiltration (leakage from flooded areas) is accounted for by the TUFLOW and USG-Transport models is different, and simplifications are therefore necessary when seeking consistency. While TUFLOW provides several options for simulating infiltration, the time-constant net loss term has been most effective in limiting infiltration specifically to flooded areas that vary over time. In reality, the infiltration rates vary over time as well as spatially, with the USG-Transport model indicating greater infiltration when/where the water table is deeper and little to no infiltration once the aquifer becomes fully saturated.

Following several iterations, a time-constant net loss of 25 mm/d was assumed over the flooded areas in TUFLOW and a higher net loss of 35 mm/d was assumed along and within the vicinity of Boundary Creek. The USG-Transport model was then recalibrated using the flood inundation extents and depths computed by this version TUFLOW model. The calibrated USG-Transport model currently simulates a typical infiltration (RIV leakage) rate of around 30 mm/d when normalised against the entire ponded (RIV cell) areas within Big Swamp. This is within the 25 to 35 mm/d range assumed in TUFLOW and is considered reasonable given the approximate nature of infiltration in TUFLOW. Additionally, a portion of infiltration (RIV leakage) computed by the USG-Transport model is lost from the swamp in the downstream area where the water table equilibrates with the flood level and there is net discharge of groundwater accumulated from further upstream. This may provide further justification for assuming a lower net loss in the TUFLOW model than that computed by the USG-Transport model. However, given the level of calibration ultimately achieved in the USG-Transport model, these differences and assumptions are not considered to limit the application of the models to informing the design of the preferred remediation system (the intended model use). Further discussions on parameter assumptions and water balance are provided for each model in the following sections.

4.2 GR4J model calibration

4.2.1 GR4J model calibration approach

The rainfall runoff model has been calibrated with the primary aim of simulating the inflows from the sub-catchments along the length of the TUFLOW model. Due to the swamp gauges (233275A and 233276A) lacking flow data at high and moderate flow rates and having relatively short record lengths, the GR4J model has been calibrated to the flow data of other gauges along Boundary Creek. The flow data from the two swamp gauges have been used for model validation.

There are four relevant gauges with data available to aid in calibration: 233273, 233231(just upstream of McDonald's Dam), 233229 (just downstream of McDonald's Dam) and 233228 (downstream of Big Swamp and at the end of the model). The daily flow data for each of these gauges has been filtered to exclude unacceptably extrapolated or compromised data. For the WMIS quality code system, this means excluding data with codes of 150 and above. An automatic calibration tool in Source has been used, utilising a shuffled complex evolution algorithm and the Nash-Sutcliffe Error (NSE daily) as an objective function to evaluate the degree of fit between the observed and modelled values.

4.2.2 Calibration challenges

Ideally, a split sample approach would be undertaken, in which the model is calibrated to match the gauge data from the first half of the simulation period, and the performance of the model is then validated by comparing the model outputs to the gauge data from the second half of the simulation period. This approach resulted in a very poor fit to the data, with NSE objective function values of around 0.03 being achieved. The use of different objective functions, with greater calibration iterations, and even altering the rainfall runoff model to the Australian Water Balance model did not improve the calibration outcomes to an acceptable level when using the split sample approach.

Further analysis of the gauge data found some anomalies, most notably a shift in gauge 233229 where the flow to level relationship shifts around 22 March 2019 and 28 May 2019. The rainfall data from SILO also did not exactly match the gauge hydrographs, leading to further difficulties in getting the modelled response to match that of the gauges. Given these issues, the calibration of the GR4J model has been limited to the period of historical observations (7 June 2019 to 5 August 2020). This targeted calibration resulted in a much more acceptable degree of fit with NSE values in the range of 0.67 to 0.82, adequately capturing the peaks and troughs in the hydrographs.

While this approach is appropriate for the purpose of informing the calibration of the TUFLOW and USG-Transport models, the absence of consistent relationships between the rainfall data and gauged runoff over a much longer period of several years means the GR4J model is not capable of reliably estimating runoffs for synthetic climate data. This limitation, resulting from either the inadequacy of the rainfall-runoff models to capture the complex behaviours in this area or due to the inconsistencies in the gauge data, should be taken into consideration if the future use of the models is extended to include examining the influence of different climatic conditions.

4.2.3 GR4J calibration results

The GR4J model calibration involved three runs, each targeted at certain sub-catchments to mimic the flow observed at a particular flow gauge. These included:

- Calibration of all sub-catchments to simulate downstream flow to match gauge 233228 data (downstream of Big Swamp and at the end of the model).
- Calibration of the top sub-catchment to simulate flow at gauge 233273 (furthest upstream).
- Calibration of the top two sub-catchments to simulate flow at gauge 233231(just upstream of McDonald's Dam).

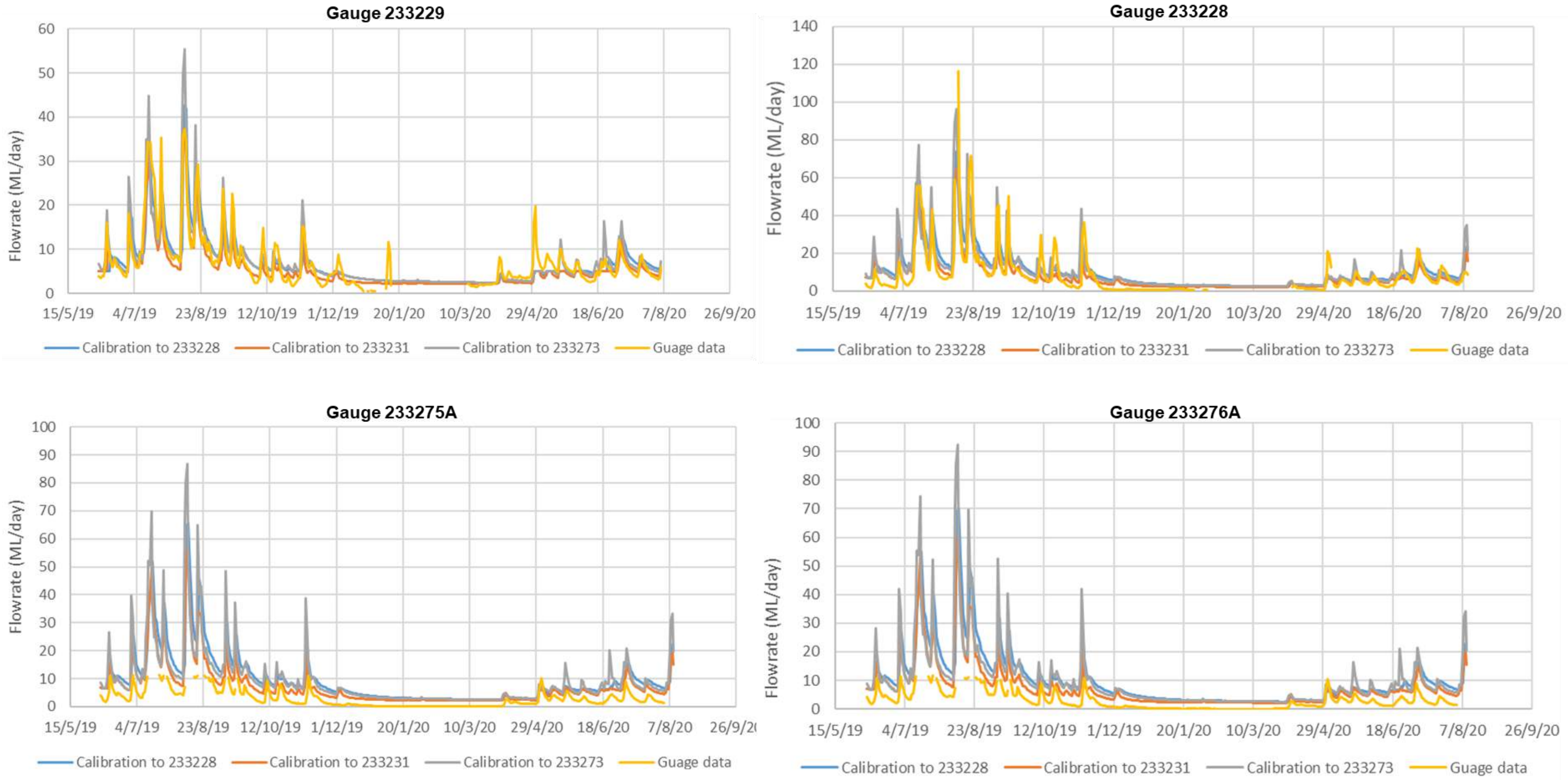
The automatic calibration was completed using the NSE daily objective function. The number of shuffles in the shuffled complex evolution algorithm was increased to ensure calibration outputs converging on a consistent set of parameters, by examining the top 50 calibration sets and whether or not the NSE objective function had converged to a consistent value. This was achieved for most parameters, although slight variations were observed in some parameter values, indicating low model sensitivity to minor changes to sub-set of parameters.

When a rainfall-runoff model is calibrated on a sub-catchment basis, a common approach to deriving the most optimal set of parameters is to calculate the average of the parameter values estimated from each calibration run. In this case, however, the parameter values from the three calibration runs were quite variable and the average of these parameter values resulted in a poor overall fit to the gauge data. Based on the objective function, the best calibration has been achieved at gauge 233228, followed by 2332231 and then 2332273, with NSE values of 0.83, 0.77 and 0.68 respectively. However, calibration to the downstream gauge 233228 is problematic for this project due to the potential for double accounting flow losses in the GR4J and TUFLOW models.

The GR4J model works by using rainfall and evaporation data to determine the runoff volumes and these runoff hydrographs are added together by Source to obtain the flow in the main channel. Once the flow is in the main channel, no routing or losses are applied. In reality, a significant portion of flow along Boundary Creek is lost to infiltration and evaporation as water travels downstream, particularly across Big Swamp. Since the GR4J model cannot account for this loss, calibrating to the downstream gauge would underestimate tributary inflows as they would be reduced to match the downstream hydrograph that already experienced these losses. This means any further infiltration simulated subsequently in the TUFLOW model would be in addition to flow losses that have already been compensated by the reduced tributary inflows. For this reason, the parameter set derived from calibration to the most upstream gauge 233273 has been chosen as the best calibrated parameters, which is least affected by the bulk of infiltration and evaporation losses that occurs further downstream (through the TUFLOW model domain). Additionally, the parameter values from gauge 233273 calibration appear to best mimic the filling and overtopping of McDonald’s Dam that occurs around May 2020, which is poorly replicated in the other two calibration runs.

Figure 4-1 compares the GR4J model outputs from the three calibration runs against the flow data at key gauges used to inform the TUFLOW and USG-Transport models. These include gauge 233229, located downstream of McDonald’s Dam which provides the upstream flow boundary to the TUFLOW and USG-Transport models, gauge 233228 located downstream of Big Swamp and the two swamp gauges 233275A and 233276A. For each hydrograph, the calibration run referred to as “Calibration to 233273” (grey line) represents the outputs from the final set of calibrated parameters. Although there are differences, the hydrographs from the three calibration runs are broadly consistent. On this basis, and for other reasons provided above, the use of calibrated parameters from the upstream sub-catchments to simulate the behaviour of the downstream sub-catchments is considered appropriate for this project.

Figure 4-1 GR4J modelled flow hydrographs at key gauges



4.3 TUFLOW model calibration

4.3.1 Stream flow and stage calibration

The TUFLOW model calibration has been undertaken for the entire period of historical observations, commencing on 7 June 2019 and ending on 6 August 2020. The TUFLOW model has been run using three different soil infiltration rates of 10, 25 and 40 mm/d, as discussed in Section 3.3.5.

The calibration involved comparing the flow rates and water levels simulated by the TUFLOW model against those observed at gauges 233275A, 233276A and 233228. The first iteration of the TUFLOW model resulted in simulated water levels that were significantly lower than those observed at the two swamp gauges (233275A and 233276A). This led to the refinement of the model, including simulating the v-notch weirs as m-channels. Figure 4-2 compares the modelled flow hydrographs against the observed hydrographs at the three gauges. Also included in the Figure are hydrographs focusing on the low flow period, when little to no flow was observed. The hydrographs indicate that the TUFLOW model is capable of replicating the temporal variations (trends) in flow, with the modelled and observed timing of peaks and troughs matching reasonably well. However, there are some discrepancies between the modelled and observed flow rates, with the TUFLOW model generally overestimating flows at gauges 233275A and 233276A, particularly during the dry/low flow period, and periodically underestimating flows at 233228.

The differences between the modelled and observed flows are potentially related to uncertainties in the reliability of the gauge data, resulting in inaccuracies in the inflow terms derived from the GR4J model which are passed onto the TUFLOW model e.g. inflows overestimated by the GR4J model resulting in generally overestimated flows at gauges 233275A and 233276A.

Where the flow is overestimated at gauge 233276A but underestimated at 233228 further downstream, this could be due to either too much infiltration loss or insufficient tributary inflow added between the two gauges. Neither of these two possibilities are considered likely given that the differences are seen with the infiltration rate as low as 10 mm/d and the GR4J inflows consistently overestimate flow at gauges 233275A and 233276A, suggesting that any inflows applied between 233276A and 233228 are likely to be also overestimated. Another possibility is errors in estimating flows at either 233275A and 233276A or 233228; however, a comprehensive investigation into the reliability of the gauge data, including those used to inform the GR4J model, is not part of the current scope.

The calibration of the USG-Transport model described in Section 4.4.4 also indicates that the flow recorded at these gauges, at least during the low flow period, is sensitive to the accuracy of surface water – groundwater interaction simulated along Boundary Creek, which would be difficult to simulate in a hydraulic model like TUFLOW. These limitations may be further affected by other model design considerations, such as the 4 m grid cell size adopted in the TUFLOW model to improve model run times, which may lead to inaccuracies along parts of the Boundary Creek where the channel width is potentially as small as 1 m (refer to Section 6.1.2).

Figure 4-3 shows hydrographs of the modelled and observed stage/water levels. There is generally good agreement between the modelled and observed values, particularly at gauge 233228 where the modelled levels are within 10-30 mm of the observed levels for most of the calibration period, with the only major deviation occurring during the dry period when the level was observed to drop by 0.6 m and the creek became dry (which did not occur in the model potentially due to higher than actual inflows). At gauges 233275A and 233276A, the TUFLOW model generally underestimates the level at high flows and overestimates the level at low flows although the discrepancies are generally within 100 mm of recorded levels (with up to about 150 mm discrepancies during the highest peak and the driest point of the calibration period).

While there are some discrepancies between the modelled and observed values, these are generally within the expected range of accuracy. Importantly, the calibrated TUFLOW model is able to simulate the seasonal dynamics (wetting and drying cycles) of the swamp, at spatial and temporal resolutions appropriate for informing the boundary conditions of the USG-Transport model.

4.3.2 Interface with USG-Transport model

The primary outputs of the calibrated TUFLOW model required for the USG-Transport model are the flooded extents and depths for each of USG-Transport model's stress periods (refer to Section 4.4.1). Because the TUFLOW model uses a fixed grid, whilst the USG-Transport model uses a flexible mesh, a large number of PO points have been used to extract water levels from the TUFLOW model at the centroid of every single USG-Transport model cell. As TUFLOW only records its output on a cell-by-cell basis, this leads to more than one USG-Transport model cell extracting results from the same TUFLOW cell in some places. An example of the relationship between the two model meshes is shown in Figure 4-4.

The USG-Transport model requires an average water depth for each cell whereas calculating an average depth from TUFLOW is not straightforward due to level differences that occur internally within each cell. Figure 4-5 presents a single TUFLOW cell when sub-grid sampling is applied. TUFLOW reports the water surface level when any point within the cell is wet, meaning that when the cell is only partially wet, the water surface level can be below the average elevation of the cell. The ground level used to calculate the water depth could use any one of the minimum, average or maximum elevation in the cell. For this project, the minimum cell elevation is used as the ground surface for calculating the water depth. Therefore, the water depth reported by TUFLOW is the maximum water depth simulated anywhere within the cell. The rationale for selecting the maximum elevation is to avoid registering partially wet cells as dry, which could happen when water depths occur in the lower part of the cells. In this sense, the ponded depths extracted from the TUFLOW model are likely to be an overestimate, although a threshold is applied subsequently in the USG-Transport model to filter out any wet cells where the ponding depth is less than 0.02 m (see Section 3.4.2).

To match the length of stress periods used by the USG-Transport model, the ponded depths from for all timesteps of the TUFLOW model that occur within the same stress periods are averaged. This results in an average water depth for each USG-Transport model cell for each one of its 50 stress periods.

4.3.3 Calibration of infiltration rates

As discussed in Section 4.1, the TUFLOW model uses a simple time-constant soil infiltration loss whereas the infiltration (leakage) rates calculated by the USG-Transport model are more complex, varying both spatially and temporally. To minimise the need for a very large number of iterations, a time-constant infiltration rates of 35 and 25 mm/d are applied along Boundary Creek and flooded areas of the calibrated TUFLOW model, respectively. The spatially and temporally averaged infiltration rate from the USG-transport model is around 30 mm/d, which is within the range of soil infiltration losses applied to the TUFLOW model. While it would be possible to expend more time and effort to closely match the infiltration losses of the two models, this is unlikely to materially improve the outcomes of the modelling given that an appropriate level of calibration has already been achieve with the USG-Transport model (see Section 4.4.4) and the ponded depths simulated by the TUFLOW model are relatively insensitive to the infiltration rates over the range of 10 to 40 mm/d, as discussed further in Section 6.1.

Figure 4-2 TUFLOW modelled and observed flow hydrographs

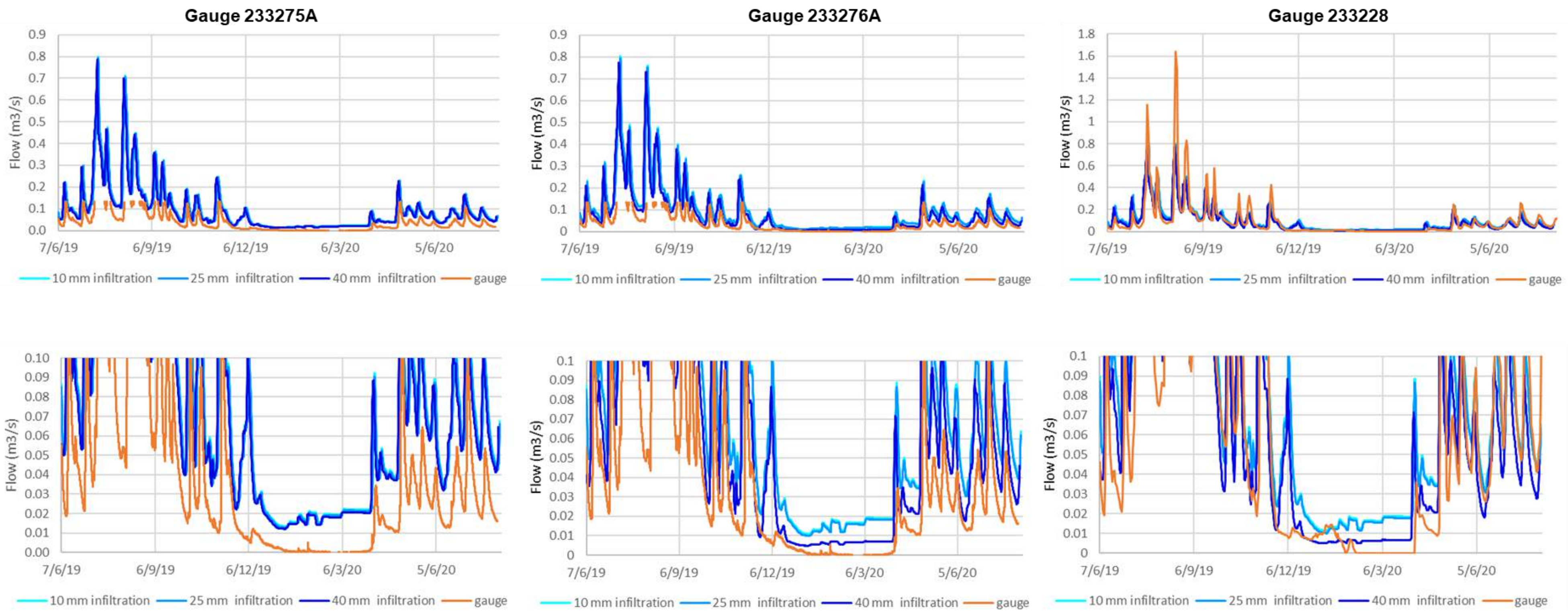
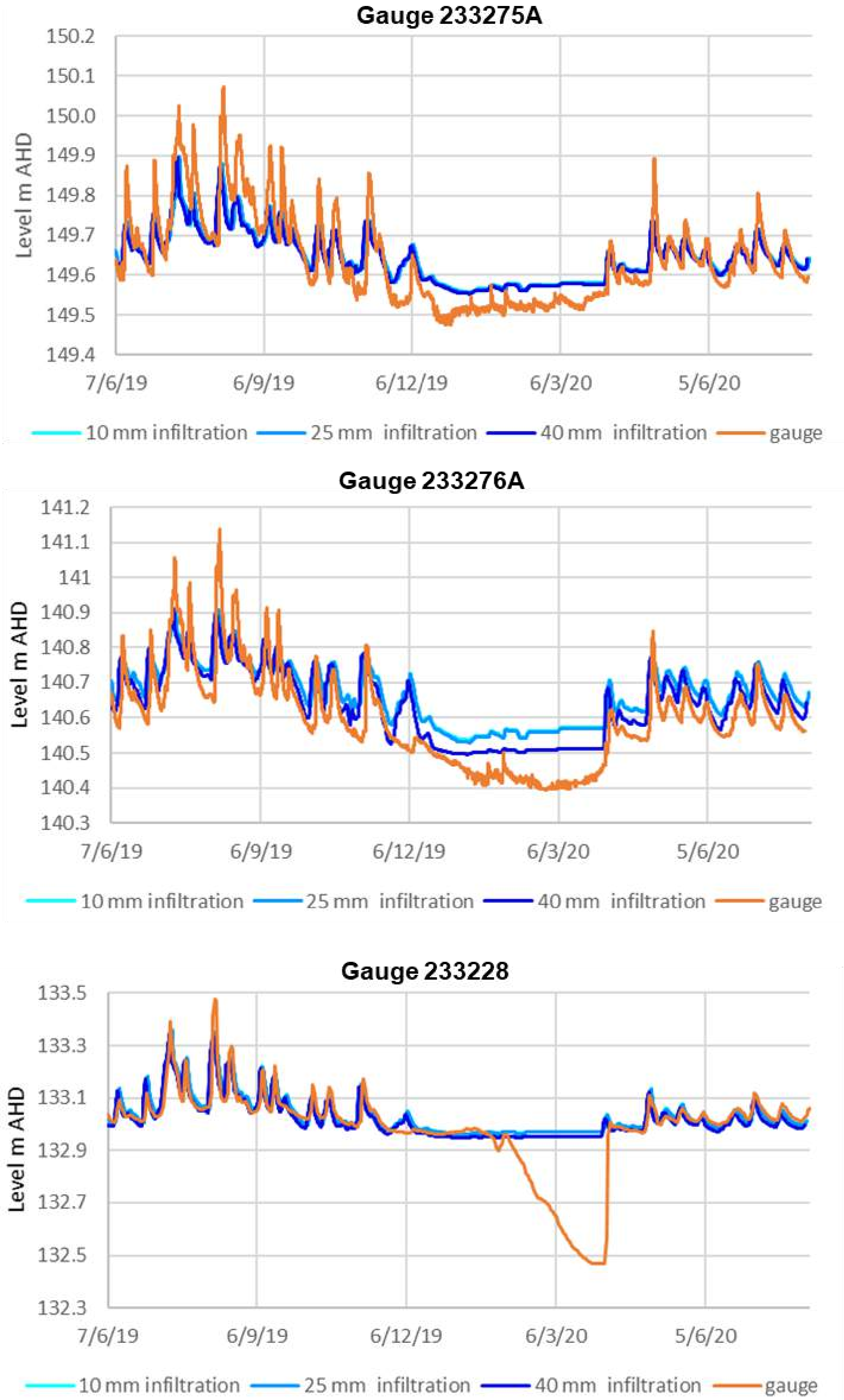


Figure 4-3 TUFLOW modelled and observed stage hydrographs



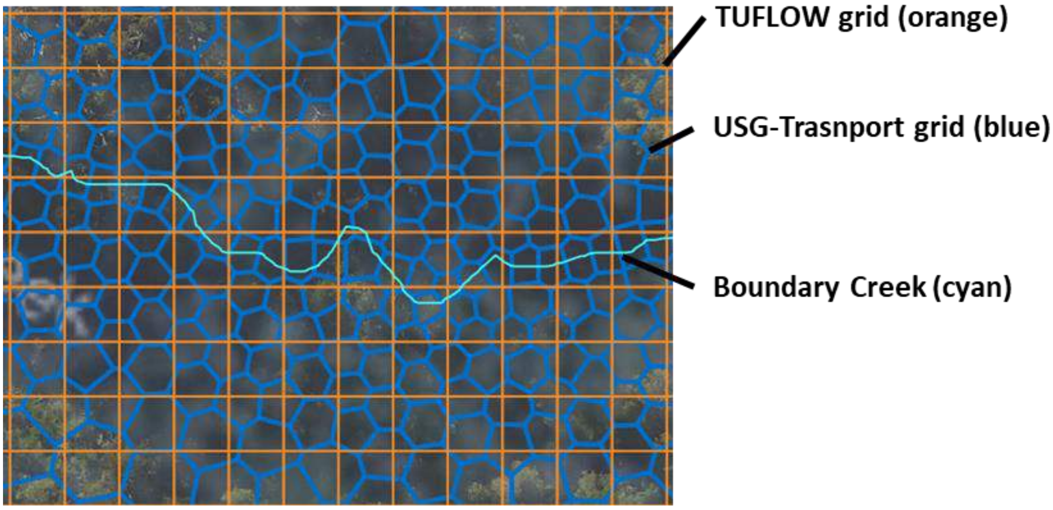


Figure 4-4 Relationship between TUFLOW grid and USG-Transport mesh

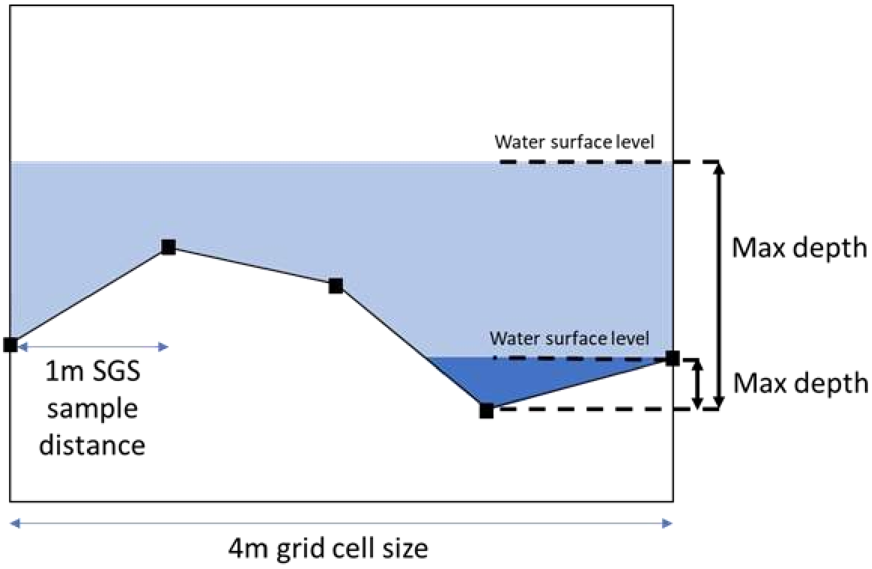


Figure 4-5 TUFLOW cell with sub-grid sampling

4.4 USG-Transport model calibration

4.4.1 Stress periods

The transient calibration uses a total of 50 stress periods to simulate 21 distinctive flow events and intervening drier periods. The stress period length varies from around 1.2 to 24.8 days, including eight 14-day stress periods over the dry period from December 2019 to April 2020 when there was negligible flow and inundation.

A steady-state simulation provides initial heads to the transient simulation. The steady-state model utilises average inundation extents and depths derived from a week-long conditioning run undertaken in TUFLOW, to provide a sensible starting point for the transient model. Similarly, average recharge and evapotranspiration have been derived from LUMPREM using climate data from several months preceding the start of transient calibration, which have been scaled during calibration to place the initial heads at sensible elevations.

4.4.2 Calibration targets

The calibration targets for the USG-Transport model include:

- Piezometric heads measured in a total of 18 monitoring bores constructed within Big Swamp. For the purpose of calibration, hourly measurements have been converted to average daily targets resulting in up to 419 targets per bore and a total of 7,339 head targets.
- Piezometric head differences, representing the change in piezometric head from the initial reading (temporal trend) calculated from the 7,339 head targets. There are 7,321 head difference targets in total.
- Horizontal head differences between a pair of monitoring bores, representing the spatial differences in observed heads and how they vary over time. Head difference targets have been derived from a total of 15 pairs of bores, as summarised in Table 4. There are 6,451 horizontal head difference targets.
- Stream stage at gauge 233275A and 233276A, converted to mAHD targets using the recently surveyed gauge zero elevation and averaged over the length of each stress period. There are 100 stream stage targets in total.
- Stream flow at gauge 233275A and 233276A, converted to m3/d to be consistent with the USG-Transport model flux unit. The flow targets are averaged over the length of stress periods, excluding periods when the flow is above the gauge capacity. Logarithmic flow targets are used due to the wide range of flow rates and to ensure that low flow targets from dry periods remain visible during calibration. There are 80 stream flow targets.
- Stream flow differences between gauge 233275A and 233276A for the dry period, when the flow differences represent the loss of surface water to the groundwater system, which is of critical importance to understanding how effective supplementary flow could be in maintaining flow downstream. There are four flow difference targets for four stress periods within the dry period, when low flows were recorded.

Table 4 Horizontal head difference targets

Bore 1	Bore 2	Direction	NO. Targets
BSBH18	BSBH17	North to south	364
BSBH18	BSBH14	East to west	364
BSBH14	BSBH16	North to south	419
BSBH16	BSBH12	East to west	419
BSBH14	BSBH11	East to west	419
BSBH12	BSBH11	North to south	419
BSBH12	BSBH10	East to west	419
BSBH11	BSBH08	East to west	419
BSBH08	BSBH10	North to south	419
BSBH10	BSBH07	East to west	419
BSBH08	BSBH04	East to west	419
BSBH04	BSBH07	North to south	419
BSBH07	BSBH03	East to west	419
BSBH04	BSBH01	East to west	419
BSBH03	BSBH01	North to south	419
TB1A	BSBH01	North to south	271

4.4.3 Calibration procedure

Calibration workflow

Calibration has been undertaken rigorously using PEST-based automated procedures in a highly parallelised computing environment. This involved several iterations, with the outputs from each calibration iteration providing the basis for modifying the observation weights and groups to guide the calibration effort, as well as exploring different calibration techniques. The key stages of calibration included:

- Initial calibration using PEST++ (PEST++ Development Team, 2020) and its Iterative Ensemble Smoother (IES) technique, which provided insights into areas of the model where calibration was challenging and adjustments to observation weights and groups required to make certain targets more visible.
- Targeted calibration using PEST_HP (Doherty, 2017) with Singular Value Decomposition (SVD) and 224 superparameters to improve calibration in critical areas. This procedure was repeated using the final flood inundation depths and extents computed by TUFLOW after updating the infiltration (net loss) term to better match the leakage rates computed by the USG-Transport model.
- Final calibration using PEST_HP with all 611 adjustable parameters to fine tune the model, particularly in areas where further improvement could not be attained using the SVD-assisted calibration.

The highly iterative calibration procedure required in excess of several tens of thousands of model runs. This run-intensive procedure was made possible by prioritising numerical stability and run time efficiency in the model design while retaining complexity where details are considered important (such as spatial parameter variability and surface water – groundwater interactions).

The automated calibration utilised a number of PEST utilities to facilitate pre- and post-processing of model data, including:

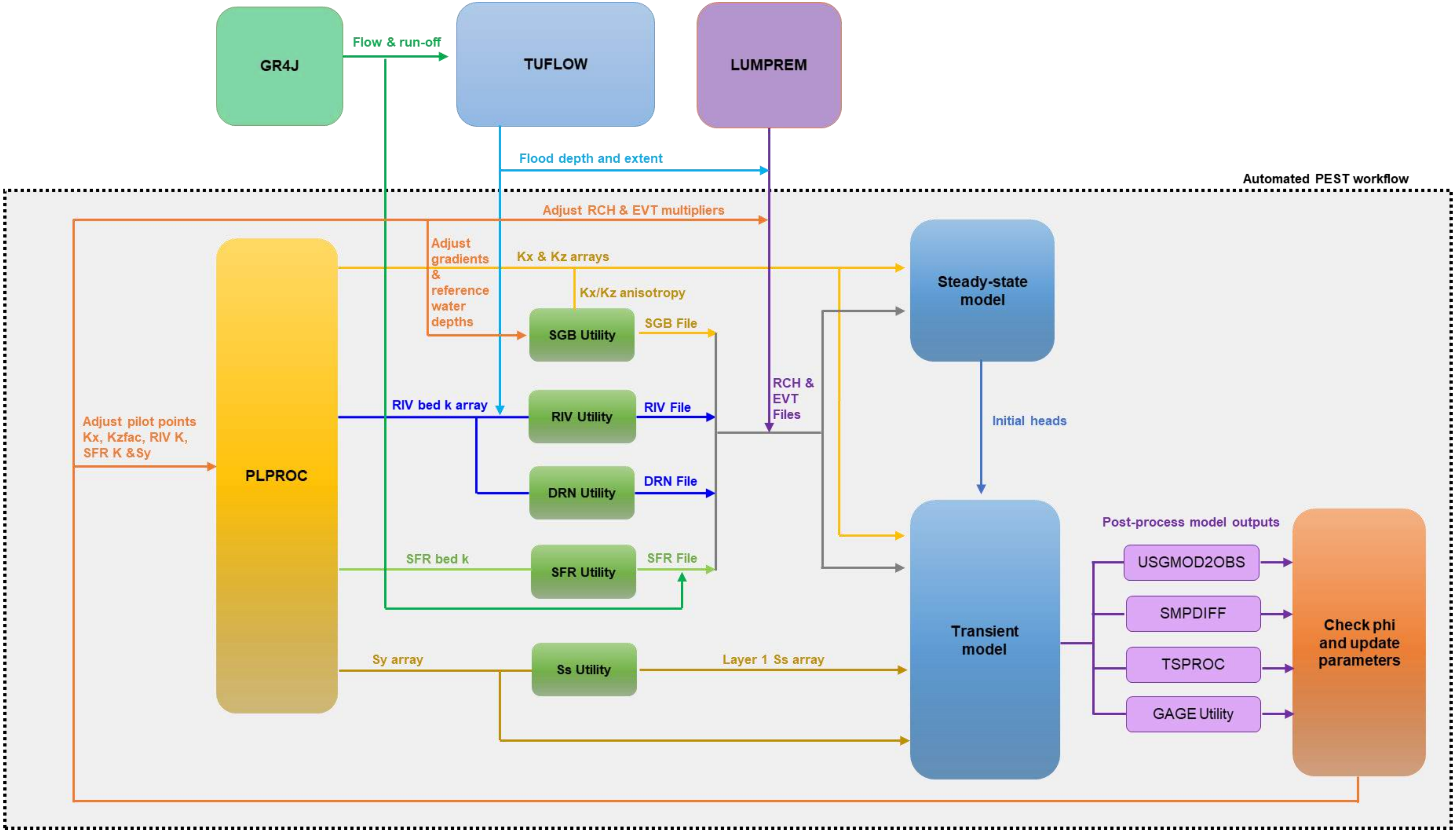
- PLPROC that undertakes spatial interpolation of parameters from pilot points to the model mesh, in this case to generate spatially varying arrays of horizontal and vertical hydraulic conductivity, RIV and SFR bed hydraulic conductivity and specific yield.
- TSPROC that undertakes calculations, filtering and interpolations on multiple time series data. This was used to calculate observed and computed horizontal hydraulic head differences between monitoring bores.
- USGMOD2OBS that extracts computed hydraulic heads at the time and location of observations and SMPDIFF that converts the computed hydraulic heads into temporal hydraulic head differences (trends) at the location of observations.

In addition to the PEST utilities, project-specific utilities have been prepared in Fortran and Python to write model input files based on parameters adjusted by PEST and to post-process model outputs. These include utilities that:

- write the RIV files based on the flood depths from TUFLOW and updated conductance terms calculated from the gridded RIV bed hydraulic conductivity array processed by PLPROC and area and bed thickness of each RIV cell.
- write the SFR file based on linearly interpolated SFR bed hydraulic conductivity generated by PLPROC.
- write the DRN file with updated conductance terms calculated from the gridded RIV bed hydraulic conductivity array processed by PLPROC.
- write the SGB terms based on the updated reference water depth for each stress period and the anisotropy ratio for each model cell calculated from the horizontal and vertical hydraulic conductivity arrays generated by PLPROC.
- write the specific storage array for layer 1, using layer 1 thickness and specific yield array generated by PLPROC.
- read the SFR outputs generated by the GAGE package and convert the model flows into logarithmic flows as well as calculating flow differences between gauge 233275A and 233276A.

A single batch file was prepared to run PEST and associated utilities in sequential order and to process model outputs. Figure 4-6 provides a graphical representation of the automated calibration workflow.

Figure 4-6 PEST automated calibration workflow



Observation groups

During calibration, it became necessary to group the head, head difference and flow targets into several different observation groups so that the calibration effort can be targeted at areas where the model calibration was initially deficient or where the model performance was considered particularly important (such as the dry period stream flow). This was achieved iteratively, resulting in the following observation groups:

- Group 1 head and head difference observation groups (Head1 and Hdiff1), which include the 2019 wet period observations for all bores and the whole 14-month observations for downstream bores BSBH01 to BSBH03 (bores that generally remained well calibrated throughout the calibration process and required no special grouping).
- Group 2 head and head difference observation groups (Head2 and Hdiff2), which include the dry period observations from January to end of March 2020 for upstream bores BSBH11 to BSBH18. These observation groups were generated to make the distinctive falling and rising trend observed during the dry period in the upstream bores visible to PEST.
- Group 3 head and head difference observation groups (Head3 and Hdiff3), which include the observations from April 2020 for upstream bores BSBH11 to BSBH18 to focus on the rising trend observed following the dry period.
- Group 4 head and head difference observation groups (Head4 and Hdiff4), which include the whole 14-month observations for bores BH04 to BSBH07 where the calibration performance remained slightly poorer than at other bores.
- Group 1 flow observation group (Flow1), which includes all flow targets except for the critical dry period.
- Group 2 flow observation group (Flow2), which includes flow targets during the critical dry period from January to end of March 2020.

For horizontal head difference, flow difference and stage targets, all observations have been grouped into their respective groups (Xdif, Flodif and Stage groups, respectively).

Calibration parameters

As discussed in Section 3.4.3, a large number of pilot points are used to simulate spatial variability in hydraulic conductivity, RIV and SFR bed hydraulic conductivity and specific yield. The vertical hydraulic conductivity has been calibrated using pilot points of anisotropy ratio between horizontal and vertical hydraulic conductivity (referred to as kz factors herein). The anisotropy ratio is converted to vertical hydraulic conductivity using PLPROC.

For recharge and EVT, simple model-wide factors are used to shift the recharge and EVT rates derived from LUMPREM up or down.

Table 5 provides a summary of model parameters adjusted during calibration. The initial parameter values are based on the prior knowledge and initial testing of the model performance. The automated calibration has been undertaken in the regularisation mode, utilising these initial values (as well as pilot point covariance matrices) as prior information to minimise parameter variability unless deemed necessary by PEST.

Table 5 Summary of calibration parameters

PEST Parameter ID	Parameter type	Initial	Min	Max	Comment
kxp1 to kxp110	Kx	0.2 – 0.8 m/d	0.01 m/d	5 m/d	Range based on slug tests
kzfp1 to kzfp110	Kz factor	0.08 – 0.15	0.0001	1	Maximum at 1 to prevent Kz > Kx
rivkp1 to rivkp110	RIV bed Kz	1 m/d	0.001 m/d	5 m/d	Based on slug tests (as per Kx), with a lower minimum to account flow in vertical direction
sfr_pp_kz0 to sfr_pp_kz80	SFR bed Kz	1 m/d	0.001 m/d	10 m/d	As per above, but with a higher maximum to account for potential local presence of sand along channels
syp1 to syp110	Sy	0.1	0.03	0.3	Range based on literature for clay, silt and sand
ss1	Ss	5×10^{-6} m^{-1}	1×10^{-6} m^{-1}	1×10^{-5} m^{-1}	Range based on literature
rchfac1 to rchfac2	Recharge	0.5	0.05	1	Maximum factor equals LUMPREM recharge
evtfac1 to evtfac2	EVT	1	0.6	1.1	Initial factor equals LUMPREM groundwater EVT
exdp1 to exdp4	Extinction depth	0.3 – 2 m	0.1 m	5 m	Maximum 5 m applies only to zone 1, elsewhere 1 m used
gradx1 to gradx2	gradient	0.005	0.003	0.005	Horizontal gradient for through-flow SGB term
sgb1 to sgb50	water depth	0.82 - 2.15 m	0.001 m	2.26 m	Range varies for each stress period, with minimum effectively equal to 0 m water depth (wet period)

- Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, Sy – specific yield, Ss – specific storage, EVT – evapotranspiration.
- Parameters rchfac1 and evtfac1 are used for the steady-state model and rchfac2 and evtfac2 are used for the transient model. The maximum rchfac1 and rchfac2 are constrained at 1, as LUMPREM recharge was considered already towards the upper end of plausible range.
- The range for EVT extinction depths are 1 to 5, 0.3 to 1, 0.2 to 1 and 0.1 to 1 for zones 1,2,3 and 4 respectively.
- The reference water depths for SGB parameters sgb1 to sgb50 varies for each stress period based on the range of average depth to water recorded at upstream bores (where the QA is in contact with the LTA)

4.4.4 Calibration performance

Head calibration

Figure 4-7 shows the scatter plot of the observed and computed heads, which provides a useful indication of the overall quality of model calibration. The Scaled Root Mean Squared (SRMS) error is around 3% and the Root Mean Squared (SRMS) error is around 0.2 m. This means the computed heads are generally accurate to within 0.2 m of the observed heads.

The quality of calibration can be further demonstrated using hydrographs of observed and computed heads for the 18 monitoring bores used in calibration, as shown in Figure 4-8 and Figure 4-9. While larger discrepancies between the observed and computed heads can be seen in some bores such as BSBH06, the degree of fit for critical upstream bores such BSBHBH12, BSBH14 and BSBH15 is considered high and the model is able to adequately replicate the overall seasonal trend, including the falling trend at the start of the dry period and the subsequent rising trend observed in the middle of the dry period in upstream bores. The latter is of particular interest, as it occurs during a period when there is negligible inundation and recharge. The model calibration indicates that this is due to upflow from the SGB cells (LTA) which occurs when the water table falls to a critical level and results in a temporary reversal in vertical hydraulic gradient.

Figure 4-10 shows the contours of computed heads for the wet (August 2019) and dry (Jan 2020) periods. The overall flow direction is to the east, with a steeper hydraulic gradient (contour spacings) in the wet period. The model simulates a local low point near Boundary Creek (to the west of BSBH17 and BSBH18), which is due to locally elevated hydraulic conductivity at this location where the effects of vertical fluxes are more pronounced (in this case, downward leakage). Uncertainty analysis presented in Section 6.2 considers realisations of the model with much lower hydraulic conductivities in this area, where the degree of connection with the underlying LTA is less certain due to the absence of observation data.

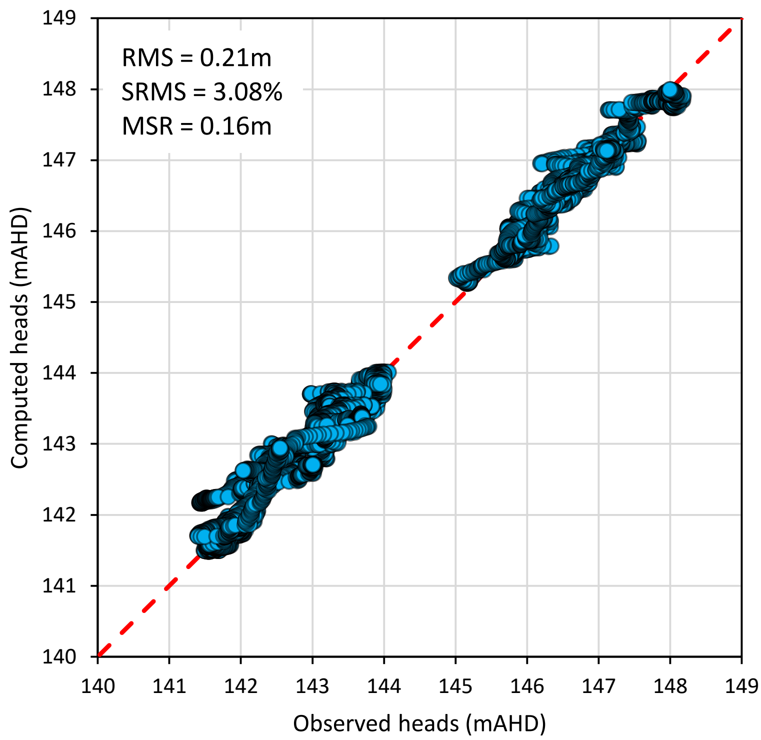


Figure 4-7 Scatter plot of observed and computed heads

Figure 4-8 Calibrated bore hydrographs – BSBH01 to BSBH09

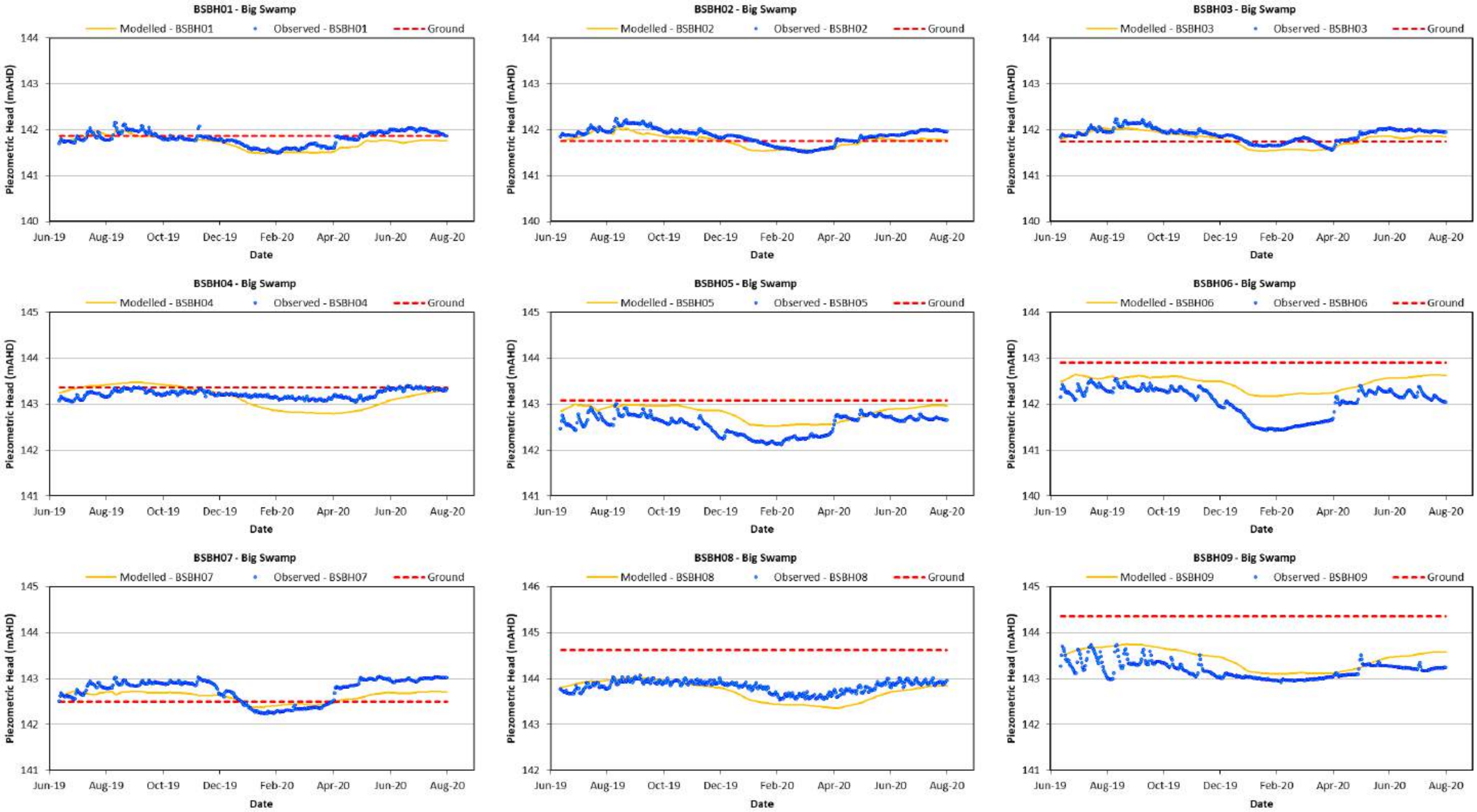
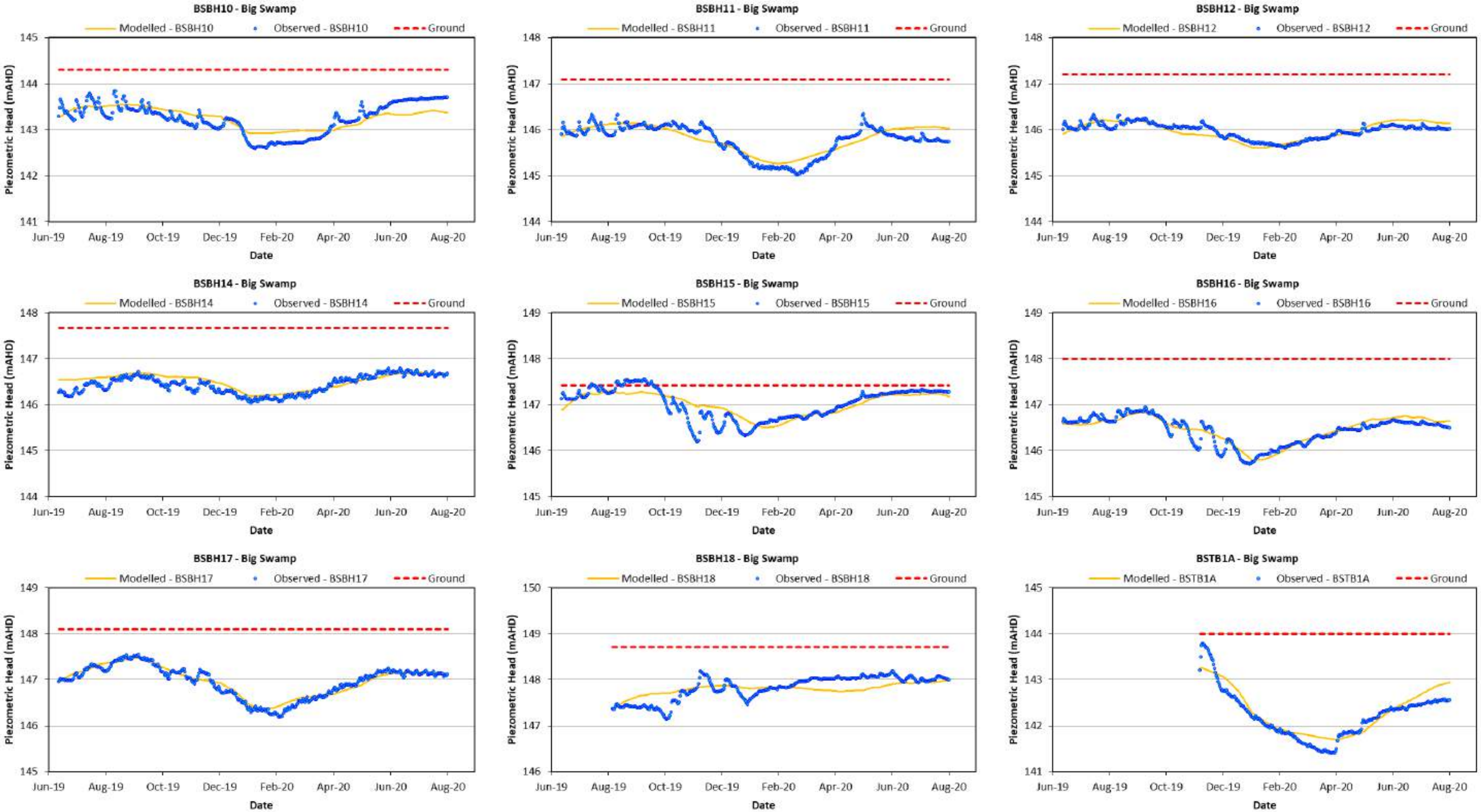
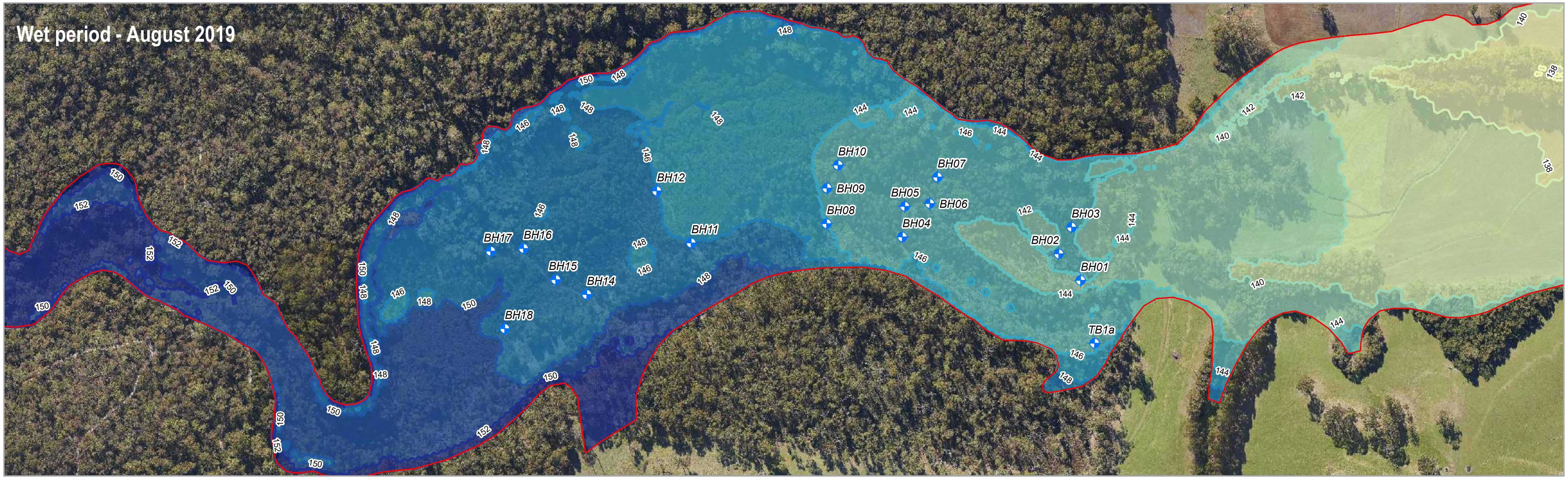
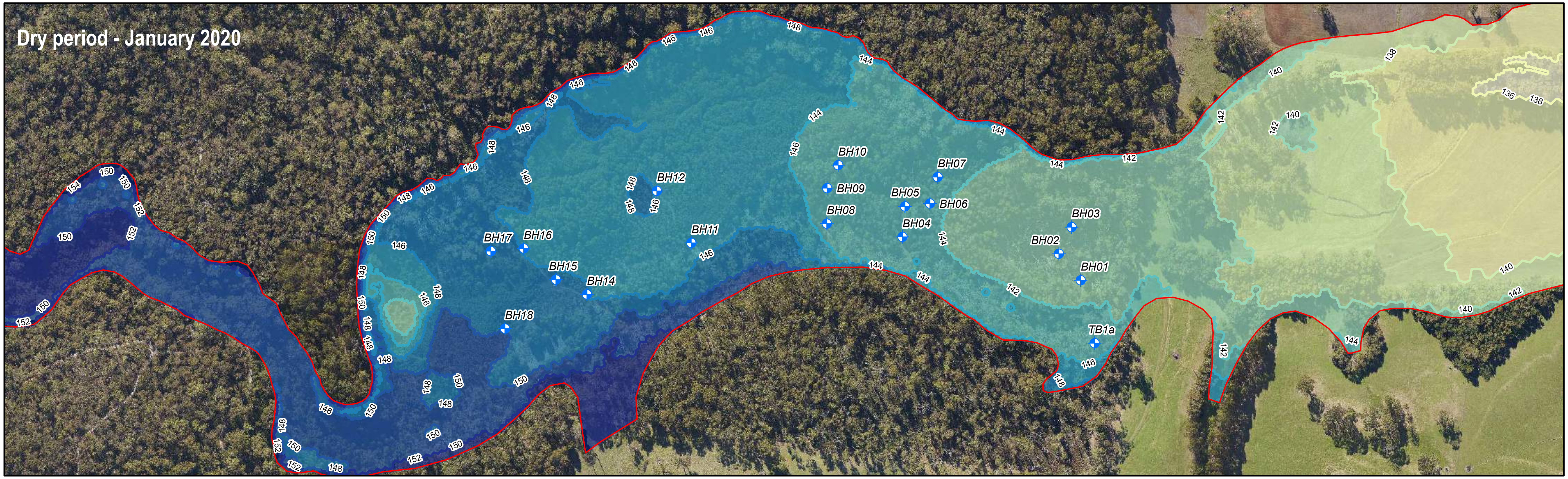


Figure 4-9 Calibrated bore hydrographs – BSBH10 to TB1A







Legend

- Observation bores
- Modelled groundwater contour (mAHD)
  - 134 - 136
  - 136 - 138
  - 138 - 140
  - 140 - 142
  - 142 - 144
  - 144 - 146
  - 146 - 148
  - 148 - 150
  - 150 - 152
  - 152 - 154
- USG - Transport domain

Paper Size ISO A3

0 25 50 75 100

Metres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

GHD

Barwon Water
Big Swamp Modelling for Detailed Design

Project No. 12536659
Revision No. B
Date 24/12/2020

Modelled groundwater contours

FIGURE 4-10

N:\AU\Melbourne\Projects\31\12536659\GIS\Maps\Deliverables\31_12536659_11_ModelGWcontours_A3L_RevB.mxd
Print date: 08 Apr 2021 - 17:26

Data source: Jacobs, Bore Locations, 2019; GHD, modelled groundwater contours, 2020; BW, imagery, 2019; . Created by: bsmyth (tworth)

Stream stage and flow calibration

The model calibration also focused on replicating the observed stream stage and flow, particularly during the dry period when the reduction in stream flow has been observed at downstream gauge 233276A. This is considered of critical importance because understanding the effectiveness of supplementary flow regimes depends on the ability of the model to adequately simulate the flow loss/stream leakage during dry periods when the system is most stressed. Figure 4-11 compares the observed and computed stream stage at the two gauges, which are generally accurate to within 0.1 m of each other.

Figure 4-12 compares the observed and computed stream flow at the two gauges. The critical dry period is highlighted in green. The figure indicates that the observed and computed flows match well during this dry period, including zero flow recorded at gauge 233276A in February and March 2020.

Figure 4-11 Calibrated stream stage

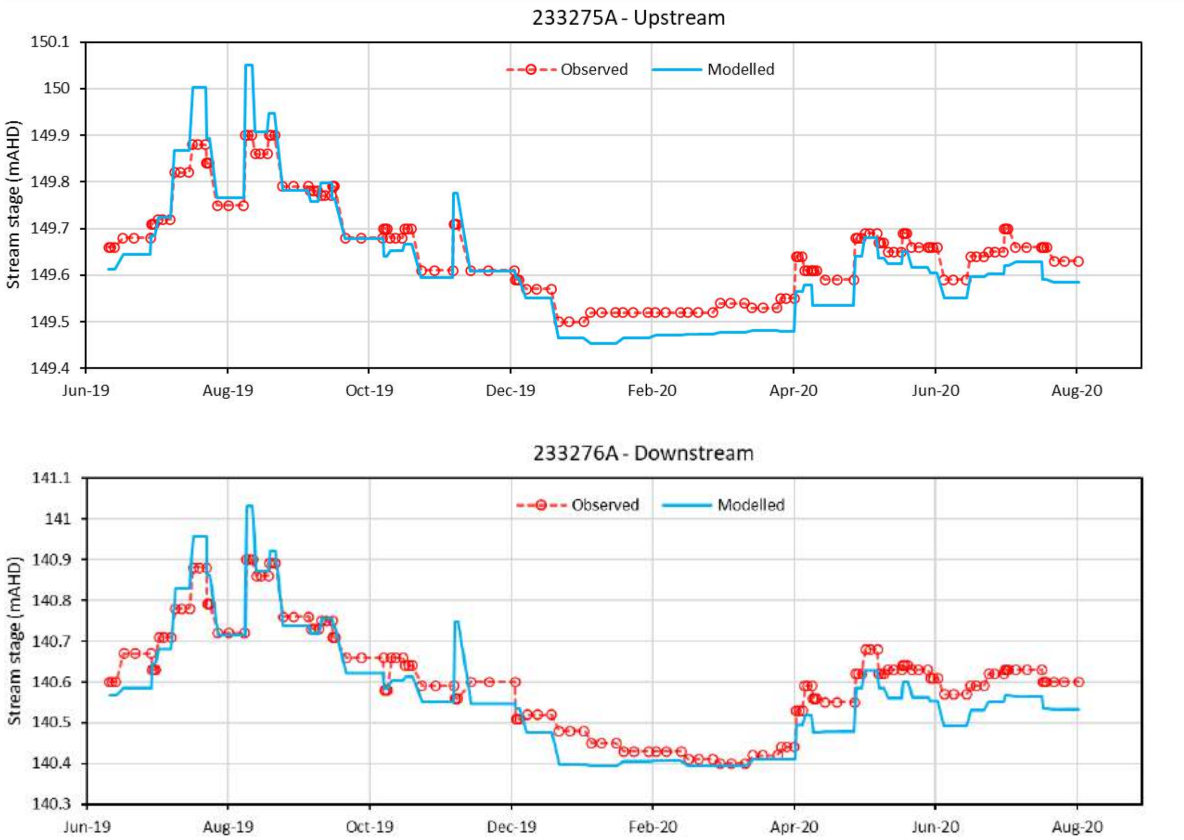
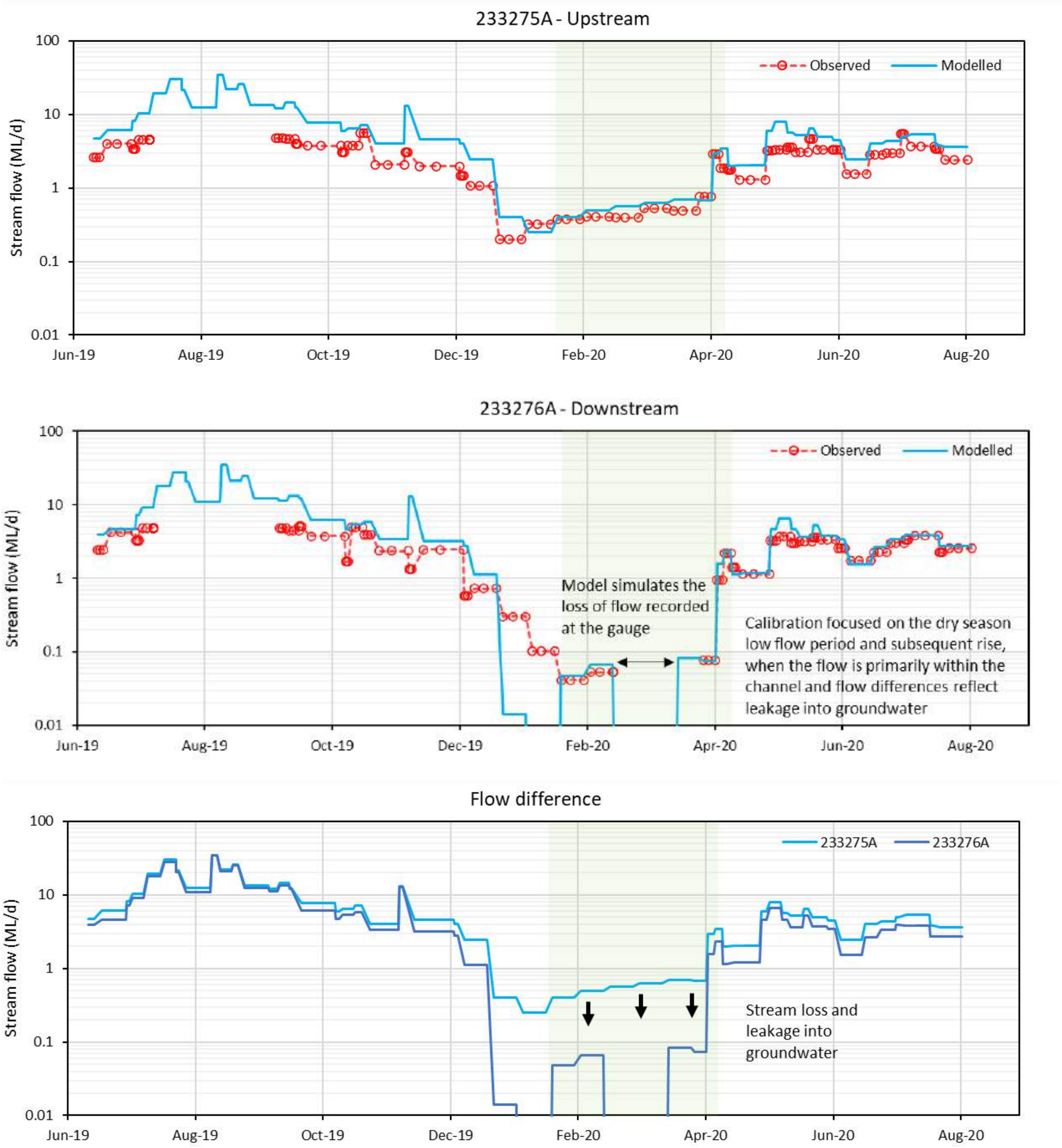


Figure 4-12 Calibrated stream flow hydrographs



4.4.5 Calibration parameters

Calibrated parameter values

The calibrated model parameters are presented graphically in Figure 4-13 to Figure 4-16. The spatial variability derived from the interpolation of pilot points parameters is presented in Figure 4-17 to Figure 4-19

The calibrated horizontal hydraulic conductivity within Big Swamp is around 1.3 m/d on average, although this is skewed by localised areas of elevated hydraulic conductivity. The median hydraulic conductivity of around 0.5 m/d is considered more representative, which is broadly consistent with the range of values derived from slug testing and the calibrated hydraulic conductivity from the previous FEFLOW model. The average and median vertical hydraulic conductivity is 0.2 and 0.01 m/d, respectively.

The calibrated RIV bed hydraulic conductivity within Big Swamp has average and median values of 1.5 and 1 m/d, respectively. The calibrated specific yield has an average value of 0.14 and is similar to the median value of 0.1.

The recharge factor for the transient model (rchfac2), is calibrated at around 0.7, which means the calibrated transient recharge is around 70% of the initial estimate derived using LUMPREM (although higher than the initial value of 0.5 set at the start of calibration). The average calibrated recharge is still considered towards the upper end of a realistic range, equating to around 40% of average rainfall over the calibration period; however, as recharge is only applied to dry areas, it has a relatively small net contribution to the model water balance compared to fluxes from Boundary Creek and flooded areas (see Section 4.4.6).

Figure 4-13 Calibrated parameters and their range – zone-based parameters

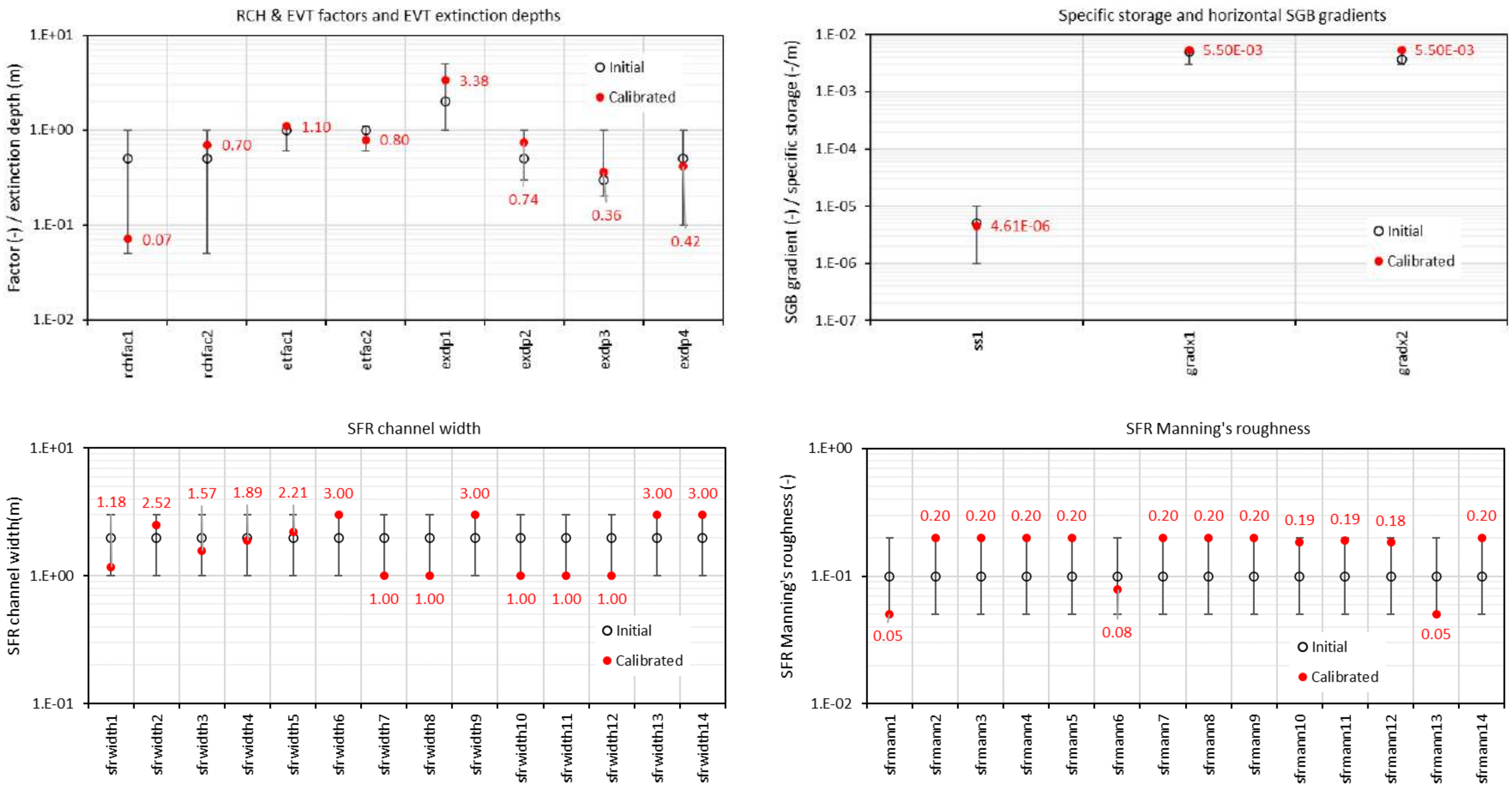


Figure 4-14 Calibrated parameters and their range – horizontal and vertical hydraulic conductivity pilot points

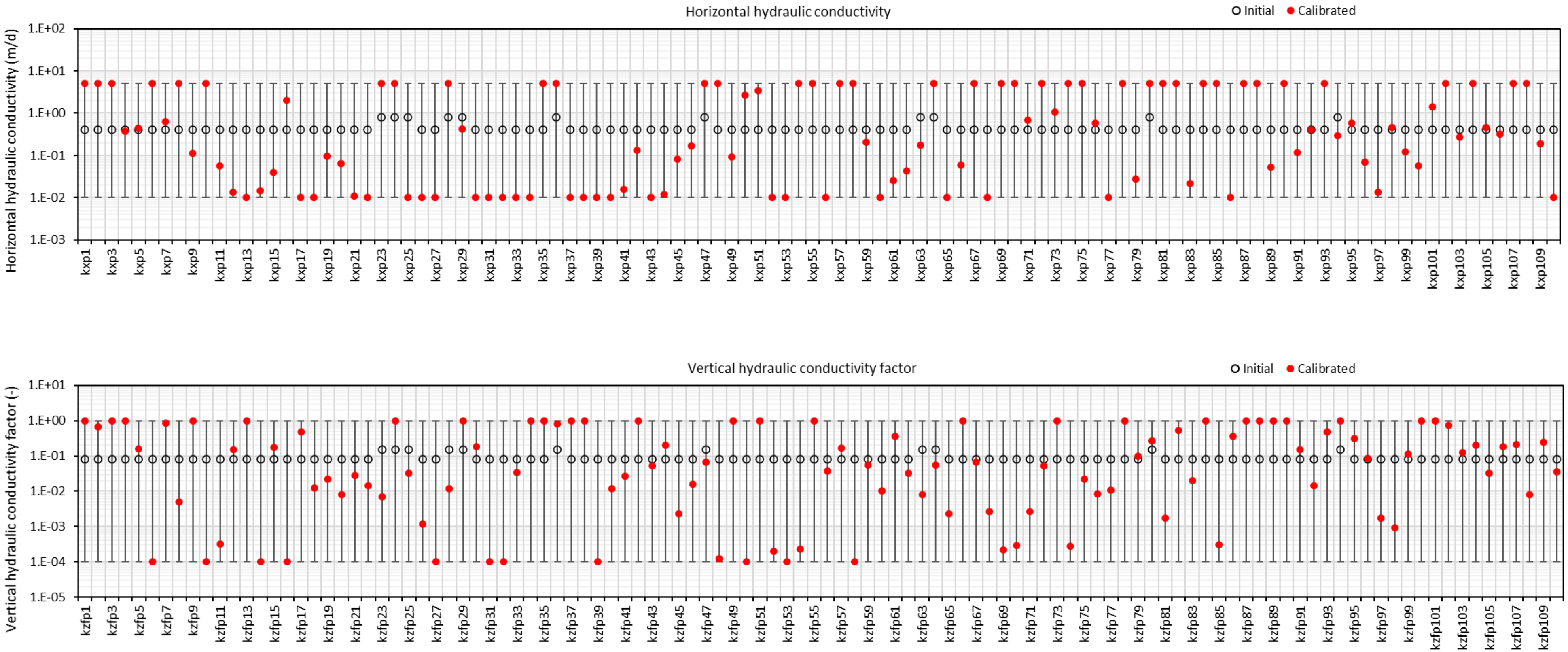
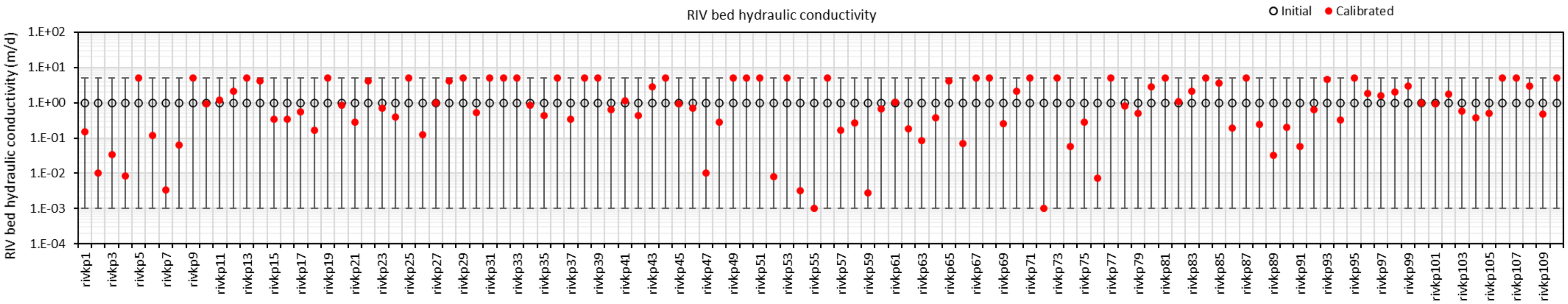


Figure 4-15 Calibrated parameters and their range – RIV and SFR bed hydraulic conductivity pilot points



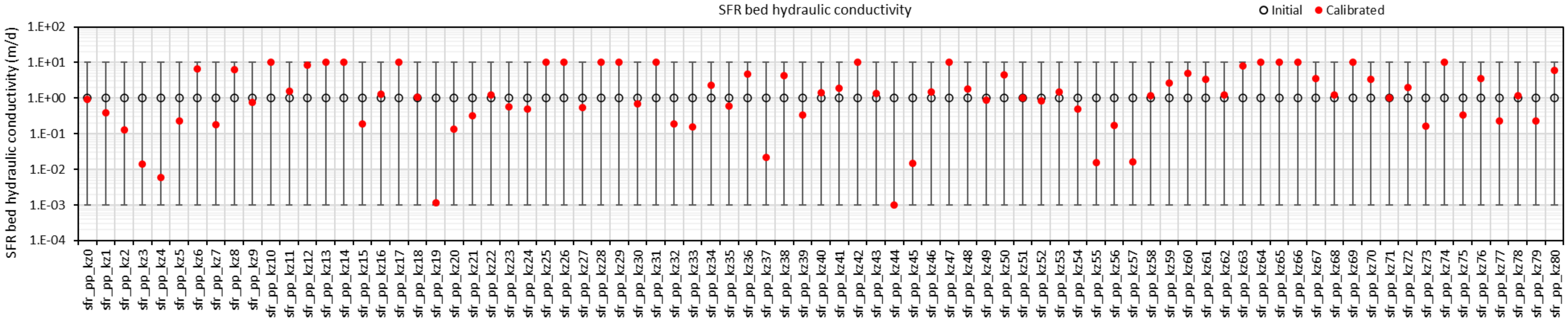
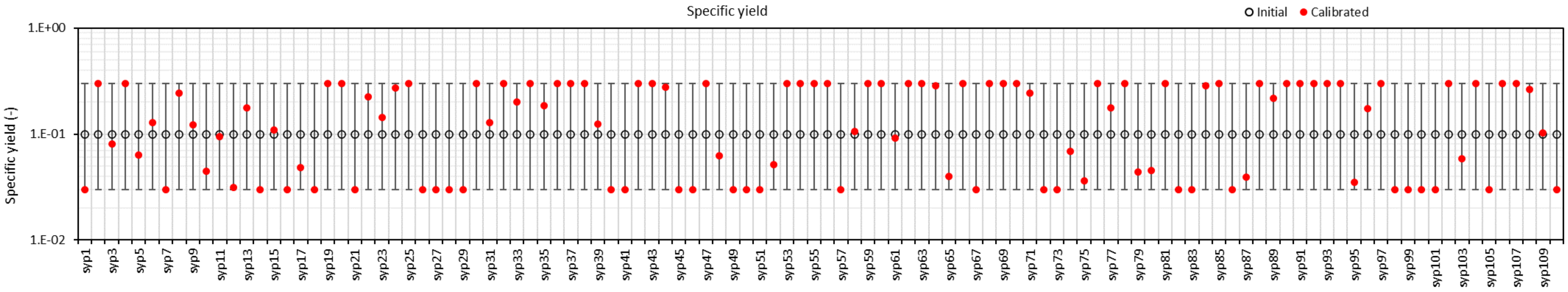


Figure 4-16 Calibrated parameters and their range – specific yield pilot points and SGB reference water depths



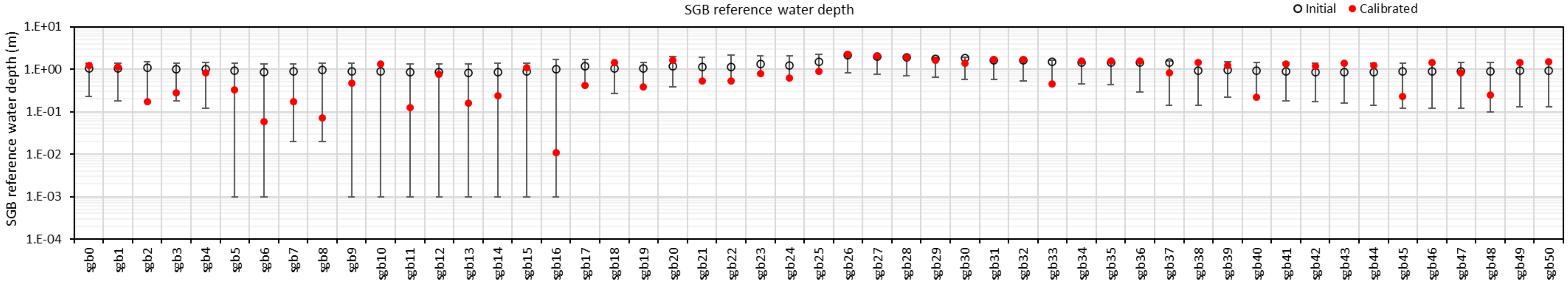


Figure 4-17 Horizontal and vertical hydraulic conductivity distribution

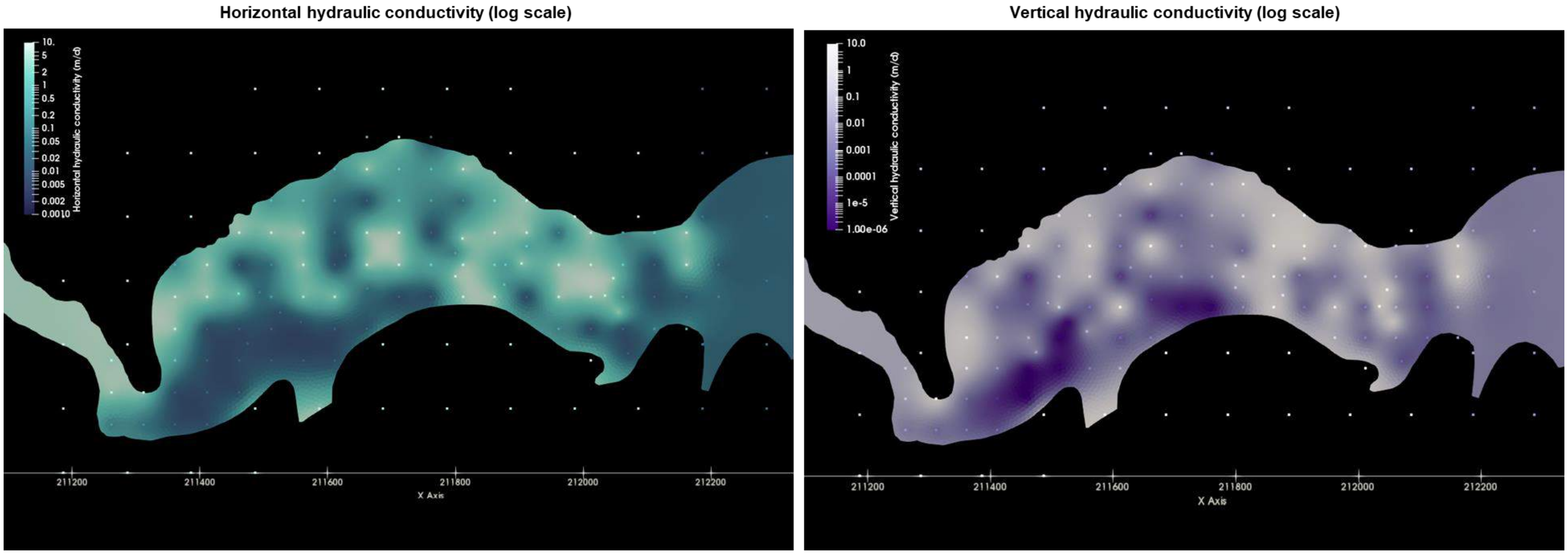


Figure 4-18 RIV and SFR bed hydraulic conductivity distribution

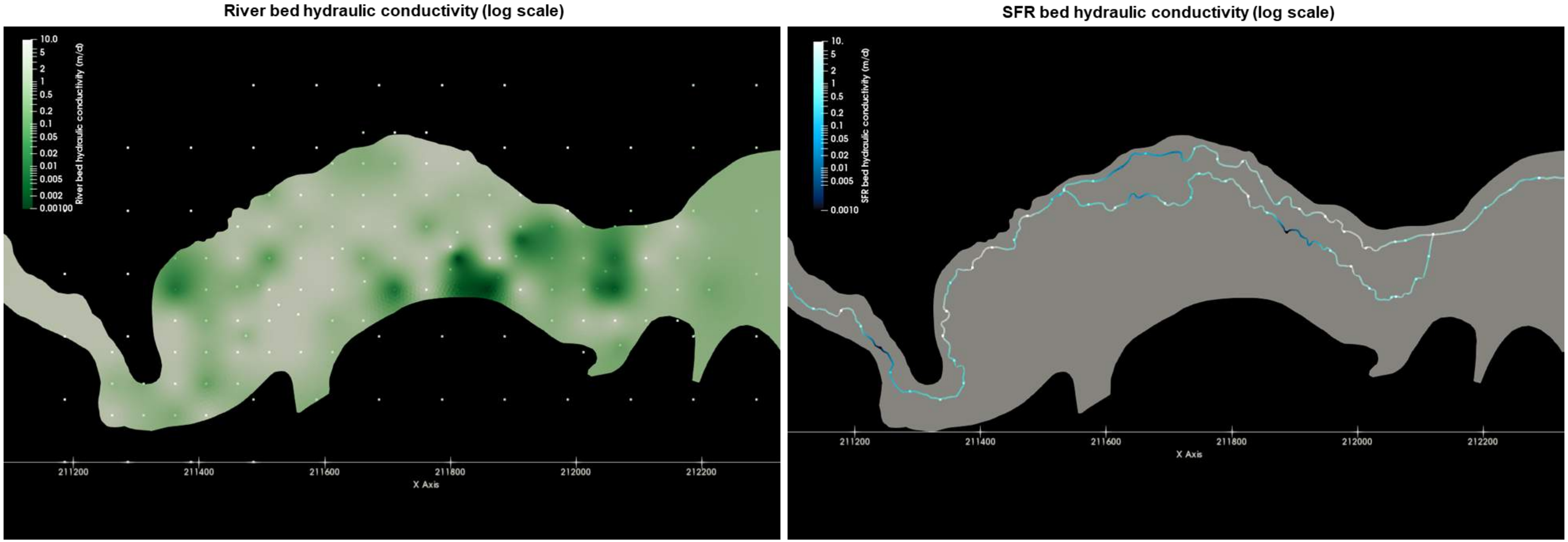
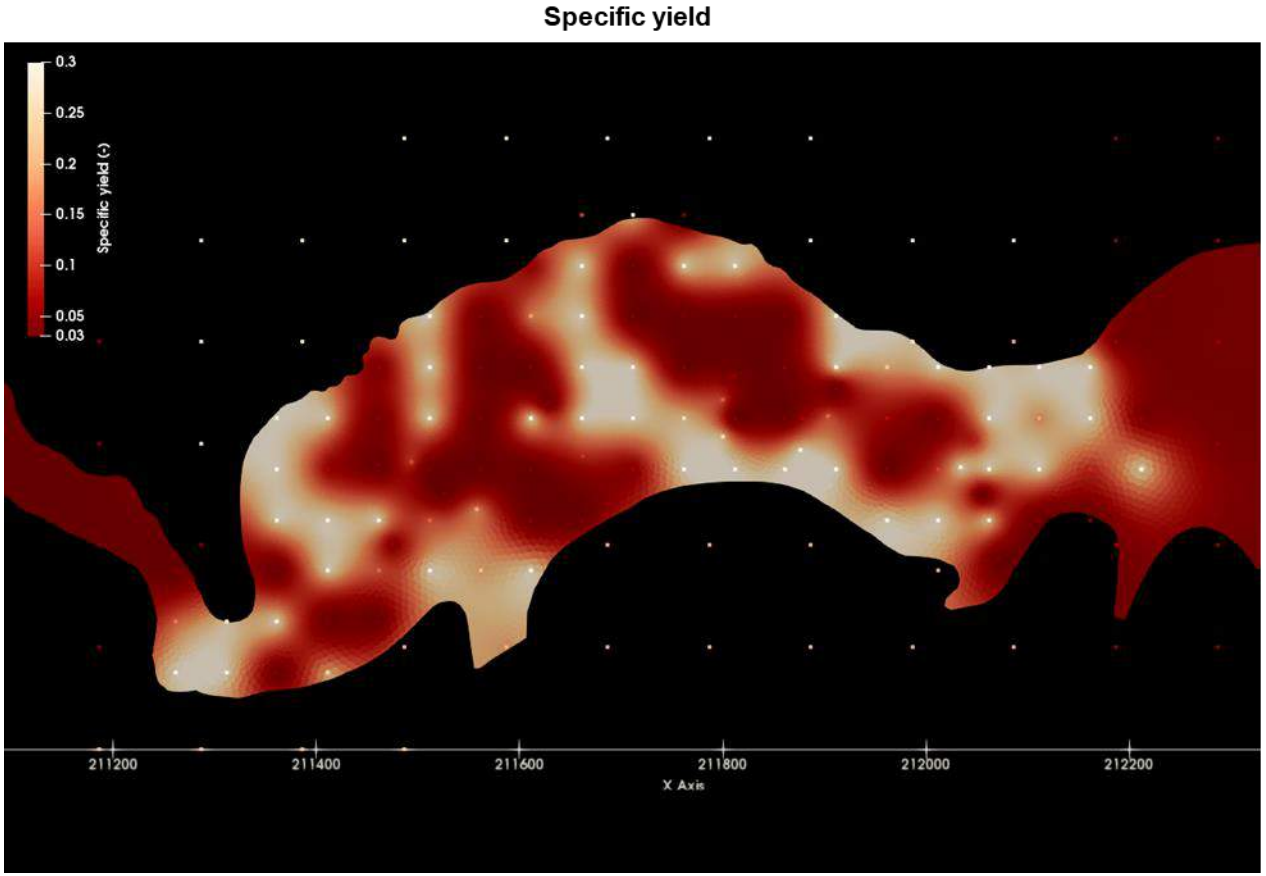


Figure 4-19 Specific yield distribution



Parameter sensitivity

The sensitivity of model outputs (calibration targets) to model parameters is described in this section with reference to parameter sensitivities computed by PEST from the Jacobian sensitivity matrix of the calibrated model. Figure 4-20 shows the sensitivity of each head target group, using the 30 most sensitive parameters. Figure 4-21 shows the sensitivity to the flow target groups.

The parameter sensitivities indicate the following:

- Group 1 head targets show sensitivity to SGB, recharge and EVT parameters of the steady state model (“sgb0”, “rchfac1” and “evtfac1”). This is because Group 1 includes head targets from the wet period of 2019 from upstream bores. The accuracy of heads simulated during the first several months of transient calibration depends on the accuracy of starting heads, which are derived from the steady-state (initial condition) model.
- Group 2 head targets are derived from upstream bores BSBH11 to BSBH18 for the dry period between January and April 2020. High sensitivity to EVT parameters reflects the importance of EVT as a discharge mechanism during the dry period. High sensitivity is also shown for SGB parameters in stress periods 26, 27 and 28, corresponding to a period when the distinctive rising trend is observed in a number of upstream bores. Flow mass balance described in Section 4.4.6 indicates a component of upflow from the SGB during this period, with high parameter sensitivity further supporting the importance of upward flow from the LTA in initiating the recovery of the water table as it falls below a critical level/threshold (when/where the vertical flow direction reverses).
- Group 3 head targets are derived from upstream bores BSBH11 to BSBH18 following the dry period (from April 2020), when the rising trend shifts from upward leakage to rainfall-driven effects (recharge and overland flow). Therefore, high sensitivity is recorded for transient recharge and EVT parameters ("rchfac2" and “evtfac2”) as well as the SGB parameters.
- Group 4 head targets include those from downstream bores BSBH04 to BSBH07. These targets show higher sensitivity to RIV bed hydraulic conductivity pilot points than other groups because bores BSBH06 and BSBH07 are located within the footprint of inundation and are more responsive to leakage from the RIV cells directly above.
- SFR stage and flow observation groups show high sensitivity to SFR parameters, hydraulic conductivity and, to lesser extent, specific yield and RIV bed hydraulic conductivity. The Group 2 flow observations (Flow2) as well as flow difference observations are also sensitive to the SGB parameters during the dry period, which is expected as the recovery of the water table is initiated by the vertical upflow from the LTA and this affects the interaction between groundwater and surface water.

It should be noted that Figure 4-20 and Figure 4-21 compare the sensitivity ranking of model-wide parameters such as recharge, EVT and SGB parameters against pilot point parameters. As each pilot point only affects the model outputs locally, the figures give the impression that model outputs are less sensitive to pilot point parameters than to model-wide parameters. This is not necessarily correct and when considered on an aggregate (parameter group) basis, the majority of the head observation groups show similar or higher sensitivity to hydraulic conductivity and this is supported by the number of hydraulic conductivity pilot point parameters that appear in each figure.

Another important observation is the moderate sensitivity of head targets to RIV bed hydraulic conductivity pilot points. This could partly be due to the key upstream bores located outside of the simulated extent of inundation, which means the modelled response is more sensitive to horizontal hydraulic conductivity that controls the resistance to flow in the horizontal direction as the pressure propagates laterally from the point of leakage to the location of bores. This does not mean the modelled heads are insensitive to RIV bed hydraulic conductivity. The rate of leakage also depends on the RIV stage and location of RIV cells, which are derived from the TUFLOW model and are not incorporated as adjustable parameters in the calibration process. The model calibration performance is highly sensitive to the accuracy of the TUFLOW model outputs, which has been identified during iterative exchange of outputs between the TUFLOW and USG-Transport models.

Figure 4-20 Head observation group parameter sensitivities

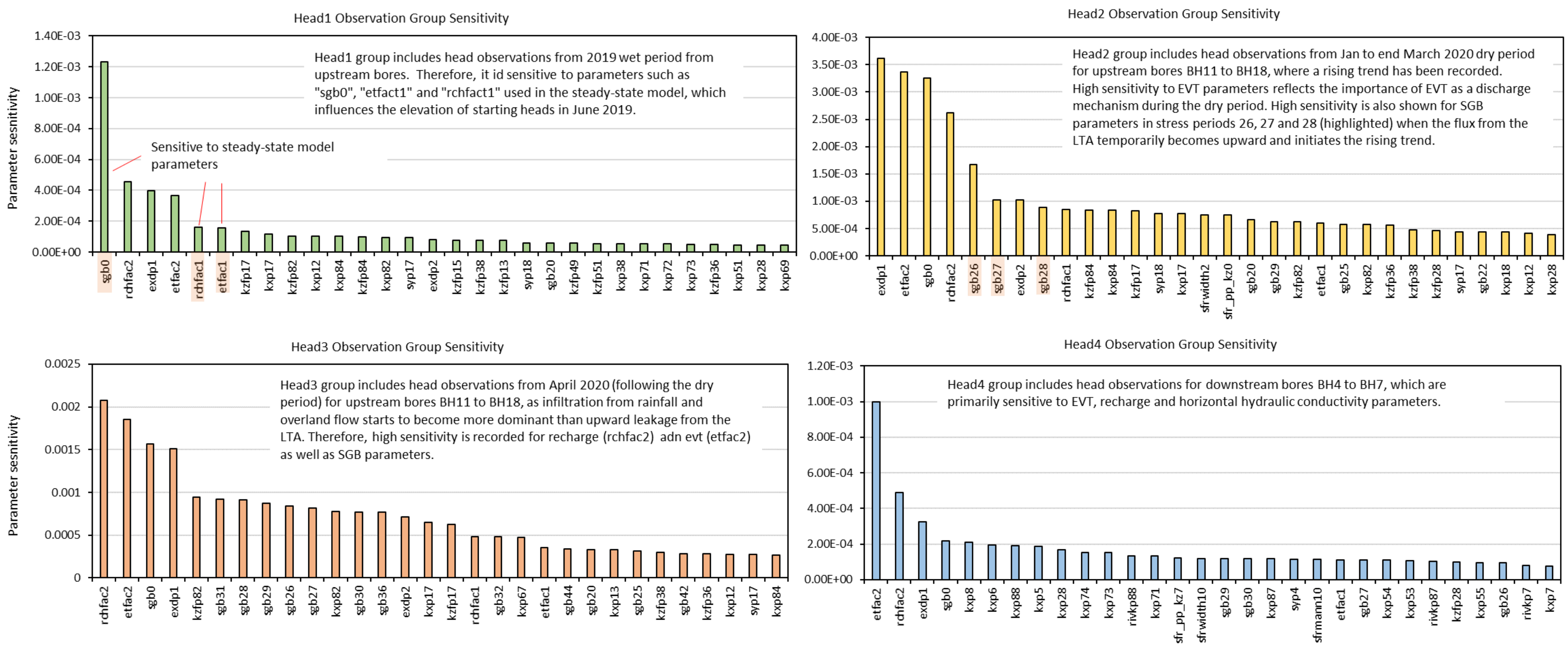
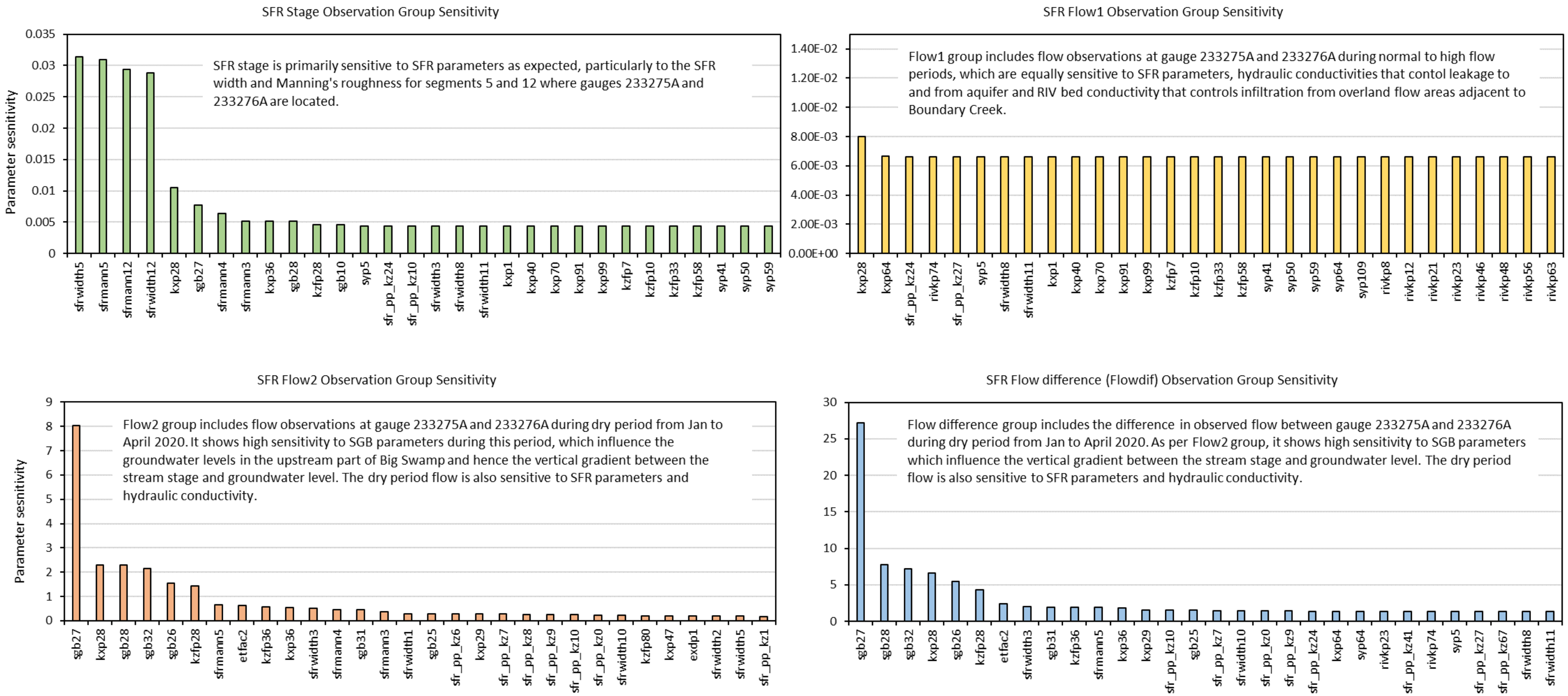


Figure 4-21 Stage and flow observation group parameter sensitivities



4.4.6 Mass balance

The cumulative mass balance error is 0.05 % and the mass balance error for all time steps is less than 0.01 % except for a small number of time steps between stress periods 25 and 28 (14-day long stress periods during the dry period), where the error ranges from 0.3 to 1.5 %. These mass balance errors can be minimised by controlling the time step size in the auto-time stepping function of USG-Transport, although implementing a tighter time step control made no material difference to the model outputs and quality of calibration.

Table 6 provides a breakdown of the model-wide transient water balance, including the average and cumulative inflow and outflow in ML/d. The model-wide water balance is also shown graphically in Figure 4-22. Table 6 indicates that inflow into the QA is currently dominated by leakage from Boundary Creek (stream) and overland flow (flood inundation) and flow out of the QA is predominantly leakage into the underlying LTA (flow out of SGB). However, fluxes into and out of the QA are spatially and temporally variable. In topographically elevated areas in the upstream reaches of Boundary Creek (upstream of Big Swamp), the water table is deeper and there is net leakage from the creek and flooded areas. Across Big Swamp, the water table becomes shallower, and parts of the aquifer becomes fully saturated during wet periods resulting in more variable flow dynamics.

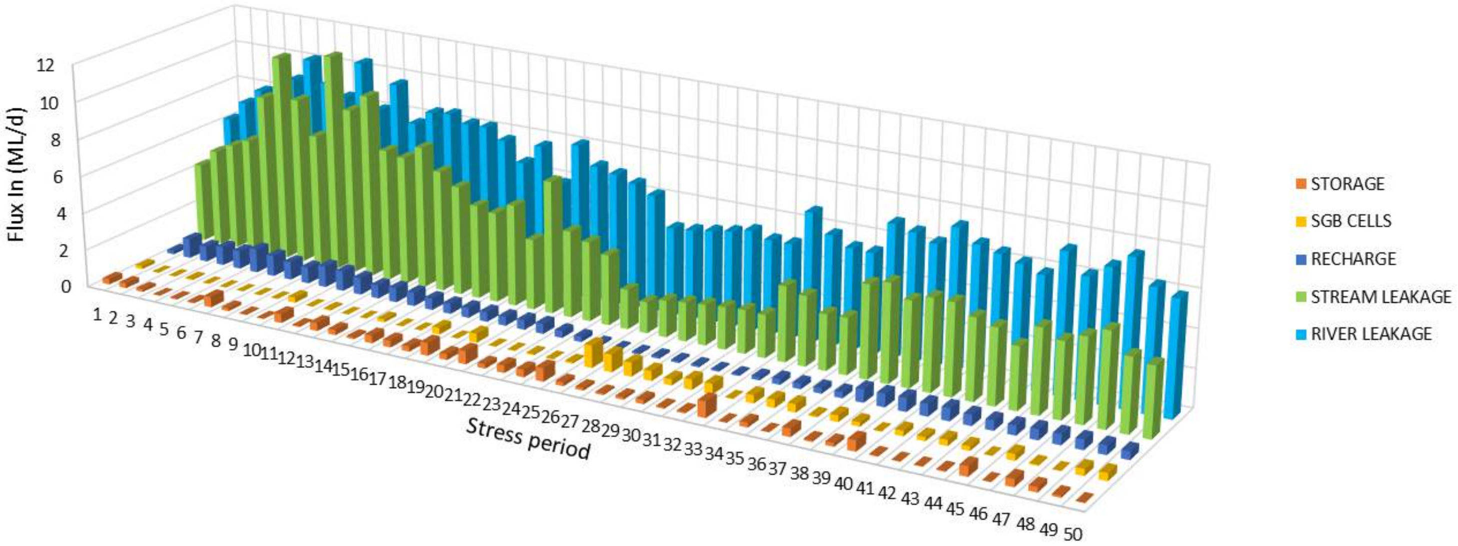
The local water balance of Big Swamp, between gauges 233275A and 233276A, has been extracted using the ZONBUDUSG utility. Figure 4-23 shows the fluxes into and out of Big Swamp from the SGB, recharge and EVT boundaries. During the dry period from stress period 25 to 32, when EVT is greater than recharge, there is net flux into the swamp from SGB. This represents the component of upflow from the LTA, which initiates the rising trend observed in the upstream bores in the middle of the dry period. This is consistent with the model sensitivity to the SGB parameters during this period.

Figure 4-24 shows the fluxes into and out of Big Swamp from the RIV and SFR boundaries. The figure shows almost as much fluxes leaving the RIV boundaries as they are entering from the RIV boundaries; however, the majority of inflow from the RIV boundaries are occurring in the upstream area where the water table is deeper whereas the outflow is occurring in the downstream areas and within the vicinity of Boundary Creek where the water table is shallower and the aquifer becomes fully saturated regularly. This effect can be seen in Figure 4-25, which compares the RIV fluxes from sub-areas within Big Swamp and how they vary spatially. The implication is that net leakage is likely to be limited in the downstream area, which becomes frequently inundated by overland flow as well as through-flow of groundwater accumulated from upstream.

Table 6 Average and cumulative model water balance

Component	Avg. IN (ML/d)	Avg. OUT (ML/d)	Cuml.IN (ML)	Cuml.OUT (ML)
RIV leakage	7.13	3.73	2843.11	1335.29
SFR leakage	5.02	0.16	1886.75	63.49
SGB	0.21	8.39	109.52	3446.84
Recharge	0.55	0	212.2	0
EVT	0	0.39	0	185.76
Drain	0	0	0	1.86
Storage	0.44	0.68	149.49	170.47
Total	13.35	13.36	5201.07	5203.7

Figure 4-22 Model water balance



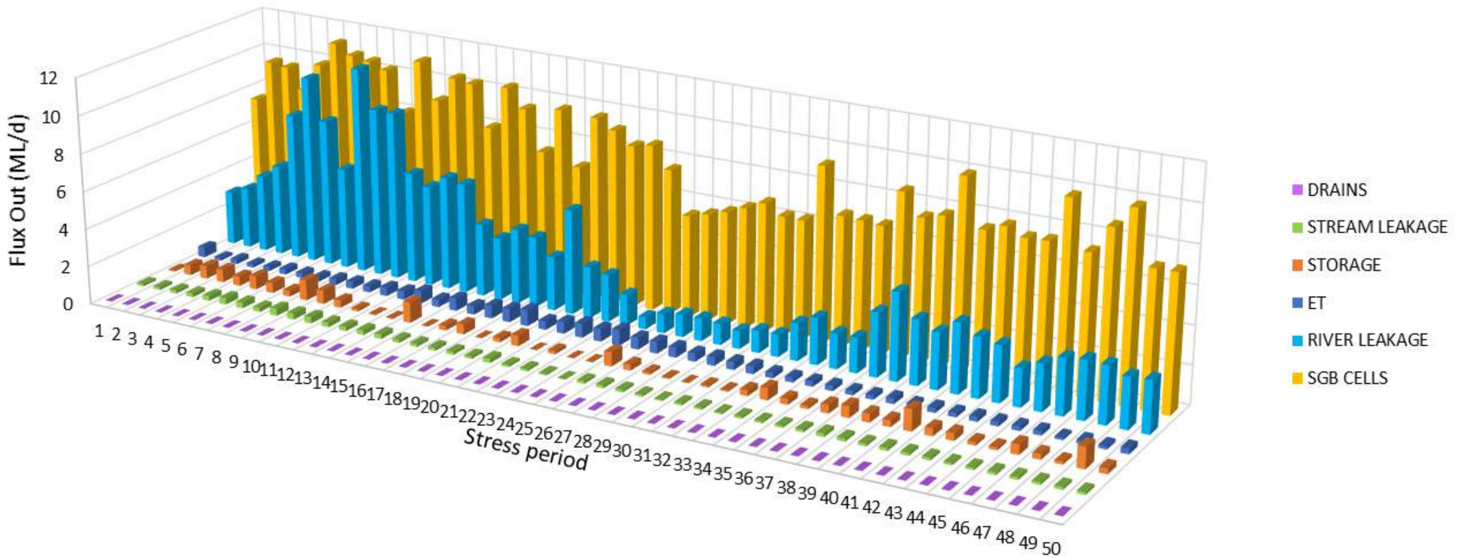


Figure 4-23 Big Swamp local water balance – vertical flux, recharge and evapotranspiration

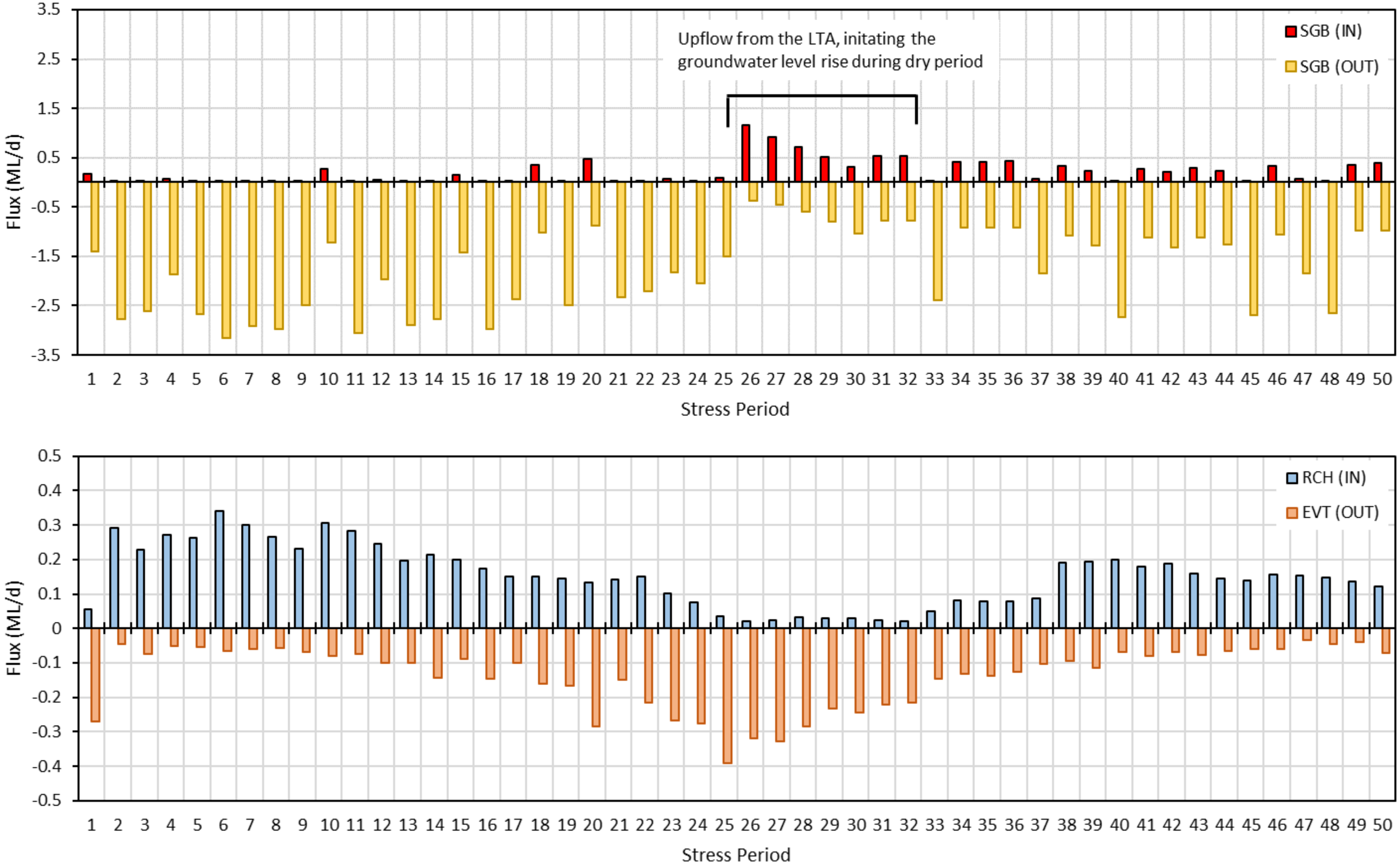


Figure 4-24 Big Swamp local water balance – RIV and SFR fluxes

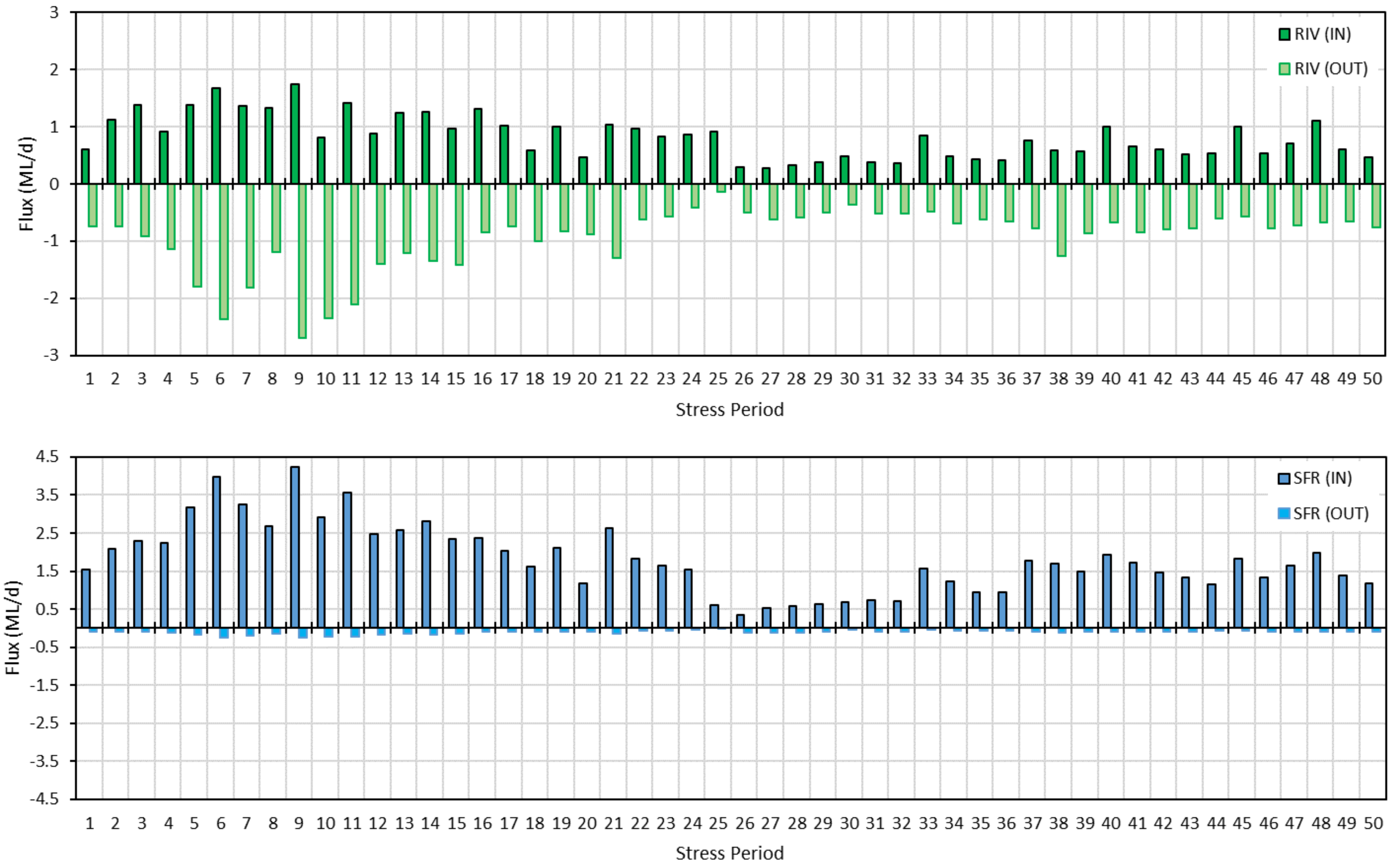
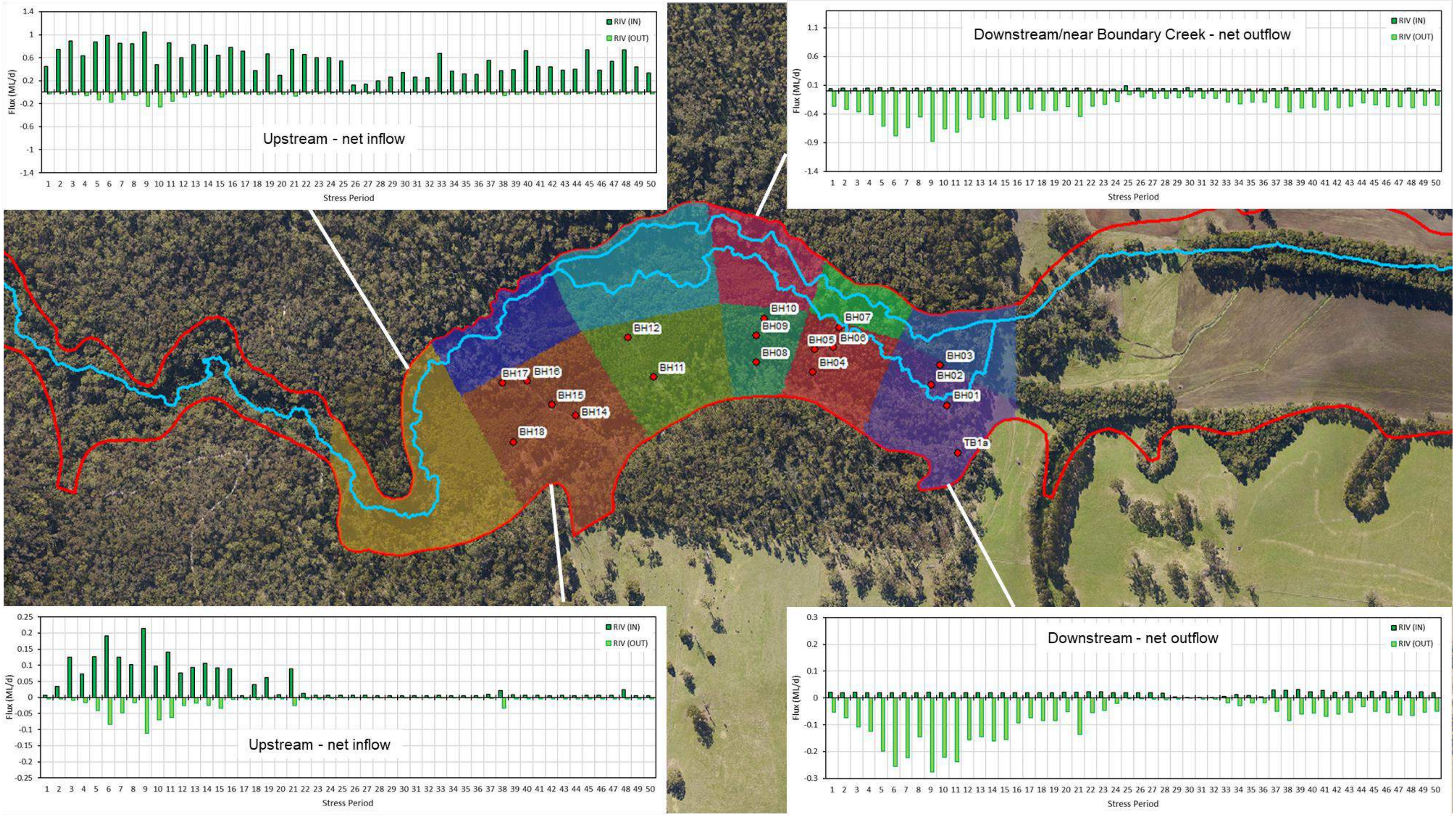


Figure 4-25 Big Swamp local water balance – RIV flux spatial variability



5. Model predictions

5.1 Predictive modelling objectives and approach

The purpose of predictive modelling is to derive hydraulic barrier configurations and supplementary flow regimes that would:

1. Maintain the water table near constant at or above the target groundwater levels defined for key monitoring bores to minimise further activation of acid sulfate soils.
2. Maintain a minimum stream flow of 0.5 ML/d at Yeodene gauge (233228) downstream of Big Swamp.

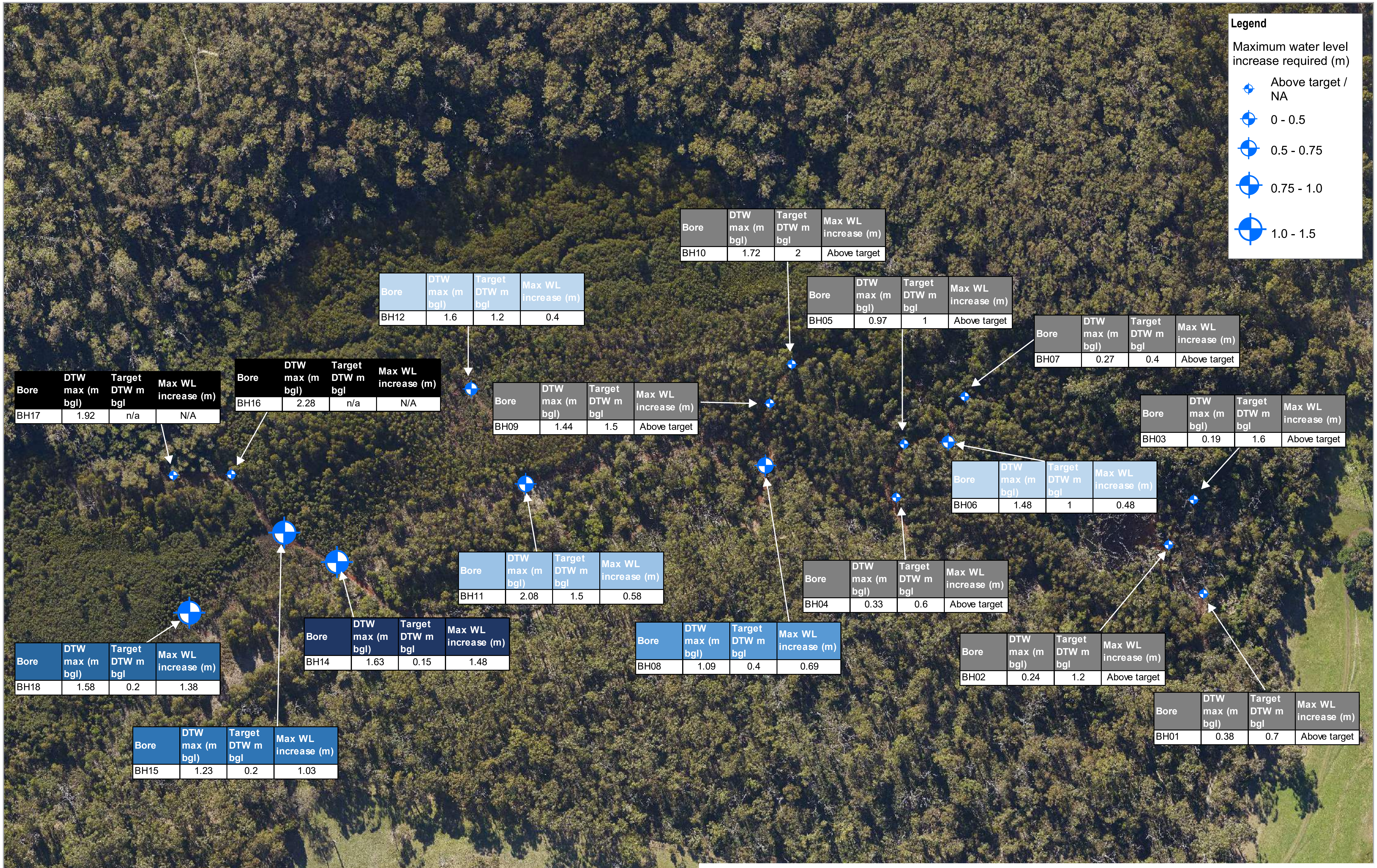
The target water level required for each of the key monitoring bore is summarised in Table 7. It is understood that these target water levels are designed to minimise the amount of sulfate available for oxidation at each bore, based on the concentration of sulfate recorded in soil cores collected during drilling. Also included in the table is the maximum increase in groundwater level required to meet the target level at each bore based on their maximum depth to water (DTW) recorded to date. Figure 5-1 shows how this varies spatially. More than 1 m of increase in groundwater level is required at upstream bores BSBH14, BSBH15 and BSBH18, where the swamp is more elevated and depth to groundwater is deeper. This decreases in the downstream area of the swamp, where the aquifer becomes frequently inundated and groundwater levels in many of the bores currently remain above the target levels.

The process of arriving at the preferred hydraulic barrier configuration has been iterative. Several hydraulic barrier configurations were initially tested in TUFLOW based on the need to redistribute surface water to the areas of critical bores and the level of ponding that may be required to maximise the increase in groundwater level. Once a barrier configuration with the most effective redistribution of surface water was identified, its effectiveness on maintaining the groundwater level was assessed using the USG-Transport model. The outputs from the USG-Transport model were then used to refine the number, location, length and height of the barriers. This was followed by examining the effects of different supplementary flow regimes on maintaining the required flow during the dry period, including the effect of different flow diversions within Boundary Creek.

The following sections provide detailed descriptions of model iterations and key findings. All predictive model outputs are based on the climate data from the 14-month calibration period.

Table 7 Target groundwater levels for managing acidification

Bore ID	Target GWL (mAHD)	Target DTW (mbgl)	Max DTW (mbgl)	Maximum increase (m)
BH01	141.16	0.7	0.38	Above target
BH02	140.55	1.2	0.24	Above target
BH03	140.14	1.6	0.19	Above target
BH04	142.77	0.6	0.33	Above target
BH05	142.08	1	0.97	Above target
BH06	141.9	1	1.48	0.48
BH07	142.1	0.4	0.27	Above target
BH08	144.22	0.4	1.09	0.69
BH09	142.86	1.5	1.44	Above target
BH10	142.31	2	1.72	Above target
BH11	145.6	1.5	2.08	0.58
BH12	146	1.2	1.6	0.4
BH14	147.52	0.15	1.63	1.48
BH15	147.22	0.2	1.23	1.03
BH16	N/A	N/A	2.28	N/A
BH17	N/A	N/A	1.92	N/A
BH18	148.52	0.2	1.58	1.38



Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 54

Barwon Water
Big Swamp Modelling for Detailed Design

Target groundwater levels

Project No. **12536659**
Revision No. **B**
Date **18/11/2020**

FIGURE 5-1

N:\AU\Melbourne\Projects\31\12536659\GIS\Maps\Deliverables\31_12536659_05_BoreDTW_A3L_RevB.mxd
Print date: 08 Apr 2021 - 17:48

Data source: Barwon Water, Imagery, 2019; Jacobs, Bore Locations, 2019; GHD, bore details, 2020; . Created by: bsmyth (tworth)

5.2 Flood (TUFLOW) model results

5.2.1 Predictive TUFLOW model set up

The predictive modelling in TUFLOW involved making several modifications to the calibrated model described in Section 4.3, including:

- placing hydraulic barriers to redistribute surface water and improve surface water connectivity at critical locations within Big Swamp.
- modifying the upstream inflow to simulate the effect of different supplementary flow rates
- filling the fire trench, as currently planned. This results in local tributary runoff from the area south of the swamp flowing out into the middle of the swamp instead of getting diverted along the southern boundary of the swamp and ultimately joining Boundary Creek at the downstream end.

As indicated in Section 5.1, the process of arriving at the preferred hydraulic barrier configuration has been highly iterative. This process is described briefly in the sections to follow, including different barrier configurations tested and how their outputs were used to progressively refined the barrier configurations. All TUFLOW outputs presented in this section assumed the existing supplementary flow of around 2 ML/d during the dry period, although the model has been run with higher supplementary flow rates to inform the USG-Transport model (see Section 5.3.3).

5.2.2 Initial testing of barrier configurations

The initial sets of hydraulic barriers were placed primarily based on topography and the locations of bores. Given the focus of the remedial system on meeting the target level at each bore, the barriers configurations are biased towards maintaining the groundwater levels elevated at these specific locations. This means the barrier configurations may be less optimal for other parts of the swamp, such as along the northern boundary where the presence of potential acid sulfate soils is not well understood.

A total of 18 different barrier configurations have been tested in TUFLOW, although many of these are slight variations of the same basic design. These barriers configurations focused on diverting water from Boundary Creek and then encouraging surface water ponding around the upstream bores where the largest increase in groundwater levels is required to meet the targets. When a direct barrier is placed over the main channel, the blockage of flow results in Boundary Creek going dry during low flow periods. Adding a weir at this location, set as a rectangular cut-out of 0.5 m in width with an invert at 148.4 mAHD, partially alleviates this problem by letting some flow pass down the channel during dry periods while allowing surface water to build up around the barrier during wetter periods, diverting some flows overland through the swamp.

Three initial barrier configurations were found to produce modest results, with reasonable amounts of ponding when run over a short test period. The first two of these (Group 1 and Group 2) used three barriers; one to divert flow, one to encourage ponding around BSBH11, BSBH14 and BSBH15 and one to encourage ponding around BSBH08 to BSBH10. The third option (Group 3) was aimed at creating a series of ponds using seven barriers, each blocking the primary flow path through the low point in the swamp to create small ponds. To improve the extent of ponding achieved, a second version of Group 3 configuration was developed whereby the height of the barriers was increased and the barriers were connected together to prevent the loss of flow around the side or back.

This version of barrier configurations was aimed at generating as much ponding as possible in critical areas, to assess whether or not the target groundwater levels are attainable and then scale back the design as required. The barrier locations and maximum ponded depths reached during the 4 week test period (in July 2019) are shown in Figure 5-2, Figure 5-3 and Figure 5-4 for barrier configuration Groups 1, 2 and 3 (the second version) respectively.

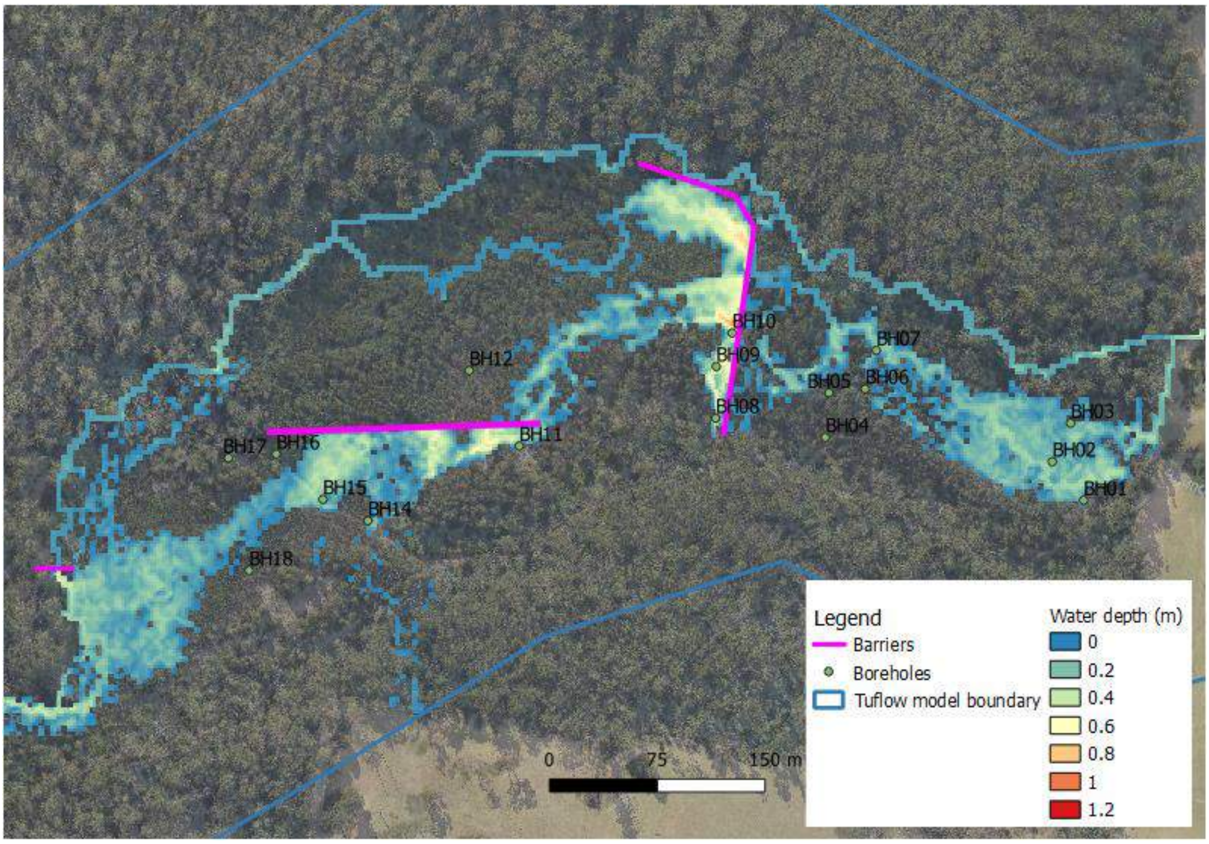


Figure 5-2 Barrier configuration Group 1 and maximum ponding depth

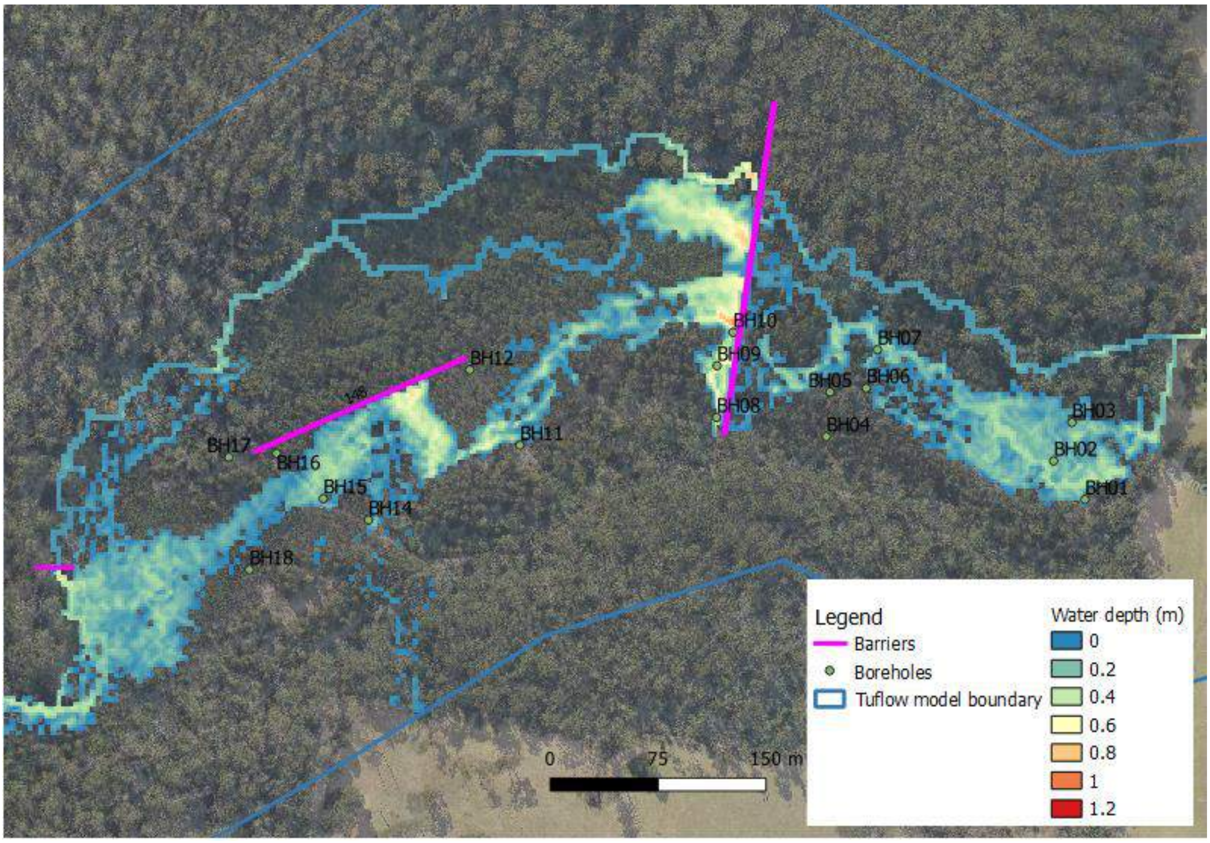


Figure 5-3 Barrier configuration Group 2 and maximum ponding depth

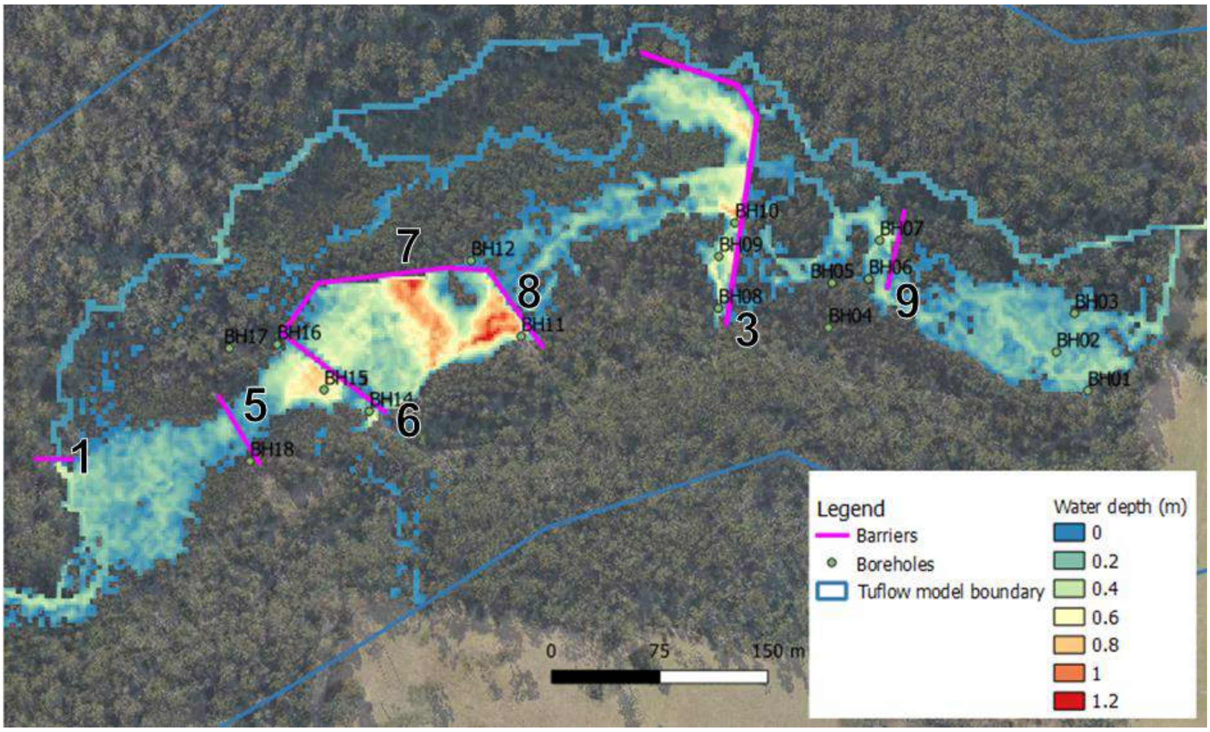


Figure 5-4 Barrier configuration Group 3 (second version) and maximum ponding depth (including barrier numbers)

5.2.3 Further testing of barrier configurations in conjunction with USG-Transport model

Based on the outcomes of short-term test runs, the effect of a slightly improved version of Group 3 barrier configuration was examined in TUFLOW for the entire 14-month calibration period and the results were incorporated into the calibrated USG-Transport model to assess their potential effect on groundwater levels. The outputs from the USG-Transport model indicated that the modified Group 3 barrier configuration is effective albeit far exceeding the required target levels at upstream bores BSBH11 to BSBH15 while inducing a slight lowering of the groundwater level at downstream bores BSBH4 to BSBH6. The USG-Transport model also indicated only a slight increase in the groundwater level at BSBH18, which remained below its target level.

One important finding of the initial testing of the barrier configuration was the maintenance of flow to keep the ponded areas topped up and overflowing. As longs as sufficient flow is maintained to keep the barriers topped up at a rate greater than infiltration and evaporation losses, then the groundwater levels would remain elevated, effectively resulting in near constant groundwater levels.

Based on the insights gained from the preliminary outputs of the USG-Transport model, four new barrier configurations were developed and simulated over the full 14-month calibration period in TUFLOW. These barrier groups are described in Table 8 and were aimed at improving efficiency whilst addressing some of the shortfalls of Group 3 barrier configuration (such as not meeting the target levels at bores BSBH04 to BSBH06 and BSBH18). These are variations of Group 3 (Version 2) barriers, utilising more realistic lengths and heights of barriers where changes to these attributes were considered unlikely to detrimentally influence their performance (refer to Figure 5-4 for barrier numbers).

The Group 5 barriers and their variants were generally found to be effective when incorporated into the USG-Transport model. The exception was for Group 8 barriers, where the 0.2 m increase in the height of Barrier 5 to encourage more ponding at BSBH18 resulted in insufficient flow passed down to other barriers further downstream i.e. the increased barrier height prevented overtopping during the dry period. This resulted in the ponded areas going dry when the flow in Boundary Creek was reduced (see Figure 5-5), resulting in the lowering of groundwater levels back towards their existing levels. This indicated that sufficient flow should be maintained at all times to keep the ponded areas topped up due to the tendency for the groundwater levels to decline to their natural levels relatively quickly as soon as the ground surface becomes dry. It also highlighted that even with a taller barrier, the simulated incremental increase in the groundwater level at BSBH18 remained below its target level. Therefore, the small incremental benefit gained from placing a taller barrier at BSBH18 is unlikely outweigh the risks of detrimentally impacting the performance of the barriers further downstream.

Table 8 Additional barrier configurations

Barrier group	Description
5	Realistic version of Group 3 (Version 2), with a reduced length for barriers 7 and 8 and increased length for barrier 9.
6	Based on Group 5 with barrier heights reduced by 0.3 m
7	Based on Group 6 with barriers 5,6, and 9 removed
8	Based on Group 5 but barrier 5 is 0.2 m taller

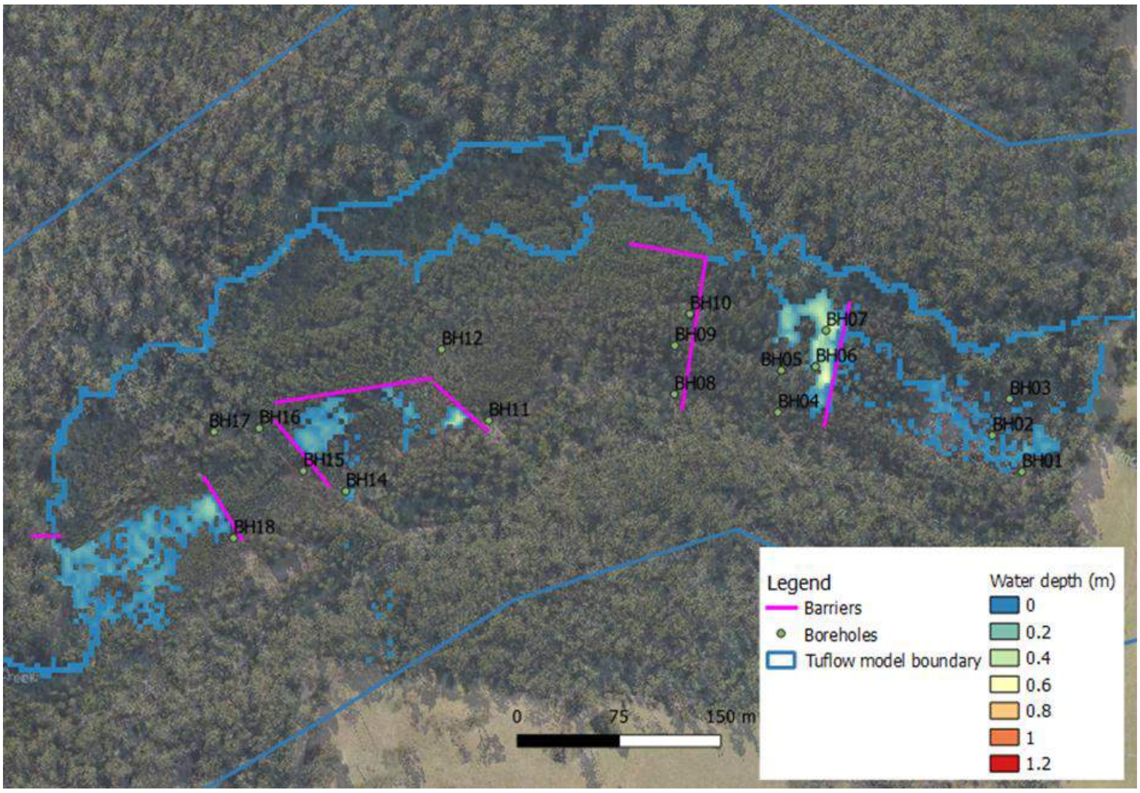


Figure 5-5 Barrier configuration Group 8 and dry period ponding depth

5.2.4 Flow split and supplementary flow

The barrier configurations presented up to this point have focused on maximising the ponded areas to meet the target groundwater levels at the bores. However, maintaining as much flow as possible in Boundary Creek is also an important design consideration for meeting the minimum flow target as well as minimising the lowering of groundwater levels along the northern boundary of Big Swamp. The modelling of barrier configurations up to this point indicates that between 70 and 90% of the stream flow is diverted from Boundary Creek in wet periods and around 30 to 50% is diverted in the dry period. This occurs because the weir to allow flow down the main channel is assumed to be 0.5 m wide, so only a small flow rate can pass through. Encouraging more flow down Boundary Creek during wet periods is likely to have some beneficial effects, potentially reducing the stress during the early stages of dry periods. From a practical point of view, it is unlikely to be necessary for up to 70 and 90% of water to be diverted during the wet period to maintain the ponded areas.

To provide a more even flow split at Barrier 1, the weir level can be increased to encourage more ponding upstream of the diversion such that surface water could flow freely out of the ponded area and down the main channel as well as along the diversion. Figure 5-6 shows the relationship between the barrier heights and topography. By setting the weir at 148.4 mAHD (area of blue contours), the flow rate needed to be constricted to ensure that the water level rose up to a level (148.5 mAHD) required to flow down the diverted path. Setting the weir level at 148.5 mAHD removes this constriction, allowing ponding between Barriers 1 and 5. This means the size of weirs put on these barriers can be used to determine the flow split.

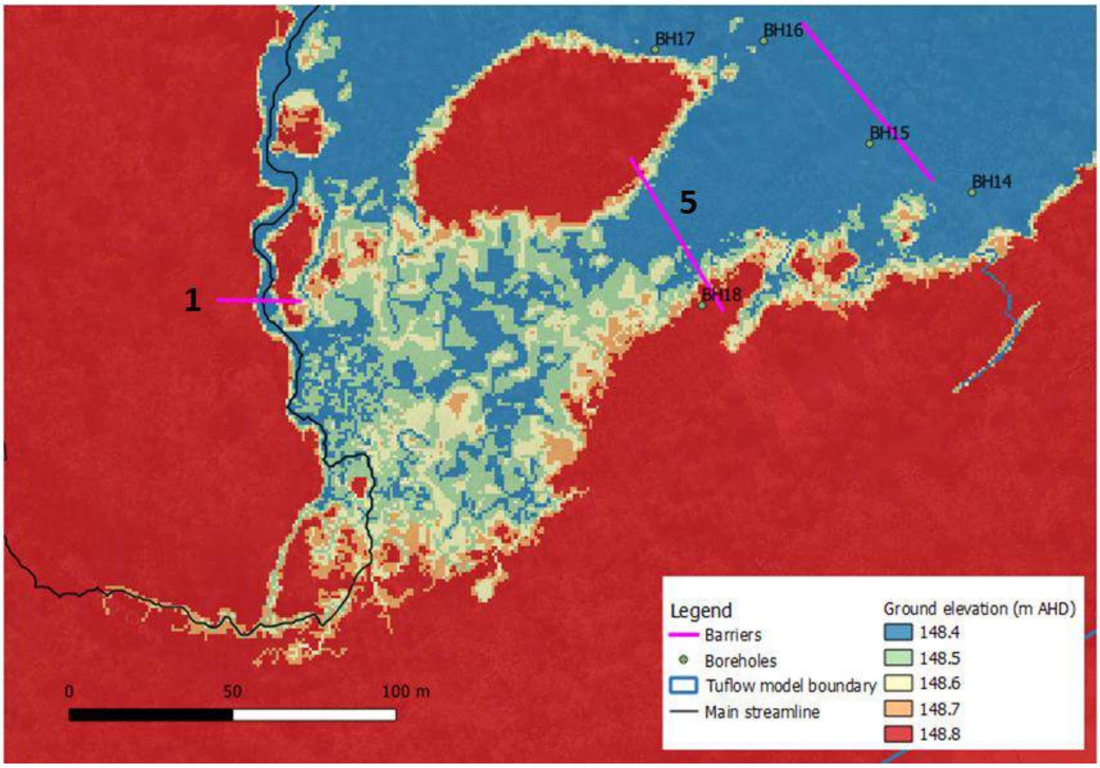


Figure 5-6 Topography around Barriers 1 and 5

5.2.5 Preferred hydraulic barrier configurations

The preferred hydraulic barrier configuration has been developed from Group 5 barriers, with modifications to encourage more ponding at BSBH18 (without incurring drying at the downstream barriers) and to improve the flow split at Boundary Creek (to pass more flow downstream). This has been achieved by increasing the height of the weir at the main channel flow diversion (Barrier 1) to 148.5 mAHD (increasing it by 0.1 m) and placing an identical weir at Barrier 5 downstream of BSBH18 (Figure 5-7). Both weirs are set to 2 m wide and the height of both barriers are set to 148.7 mAHD. This configuration causes surface water to pond up to 148.5 mAHD, which would then flow out from the two identical weirs, thereby ensuring the same flow rate down the main channel and the diversion. This setup has the added benefit of introducing direct control over the flow split, as the weir widths can be easily altered to produce any desired flow splits. These weirs could also be constructed as a series of stop logs, such that the flow split can be adjusted by simply adding and removing stop logs. This is considered important in the context of optimising the usage of supplementary flow for maintaining both the ponded areas and flow downstream of the swamp.

Because the land above BSBH18 is relatively flat, this configuration creates a relatively large ponded area upstream of the bore as well as increasing the depths in the area immediately adjacent to the bore. In this sense, the ponding generated under this configuration is considered as high as practically feasible.

The TUFLOW model results of the preferred barrier configuration are shown in Figure 5-7, including the modelled ponded depths at the driest and wettest points in the 14-month calibration period. The estimated barrier lengths, levels and maximum heights are presented in Table 9. Note that there are 7 barries in total, albeit the numbering is not currently sequential due to the iterative process involved in developing the preferred barrier configuration, whereby some barriers were removed or added.

It is important to note that the preferred barrier configuration is derived using outputs from the modelling that relies on the available DEM data. If the actual topography differs, then the barrier lengths and locations may need to be adjusted to ensure that the ponded areas are not bypassed by surface water flowing around them. This is examined further as part of sensitivity analysis (see Section 6.1.2).

Table 9 Barrier specification for preferred configuration

Barrier	Level (m AHD)	Max Height (m)	Length (m)
Barrier 1	148.7	0.9	75
Barrier 5	148.7	0.6	54
Barrier 6	147.9	0.7	62
Barrier 7	147.7	1	115
Barrier 8	147.6	1.1	51
Barrier 3	144.9	1	169
Barrier 9	142.7	0.7	92

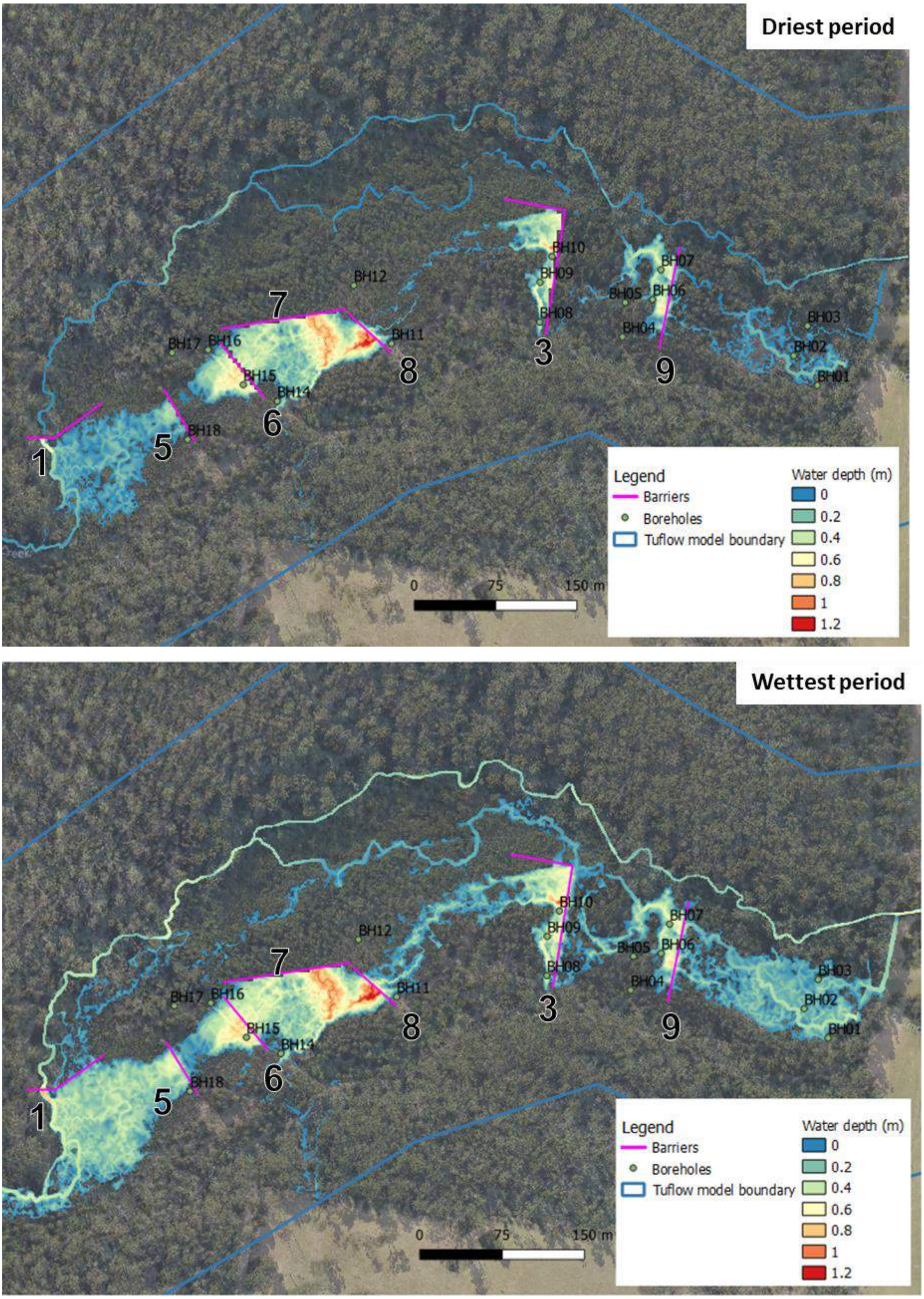


Figure 5-7 Preferred barrier configurations and predicted water depths

5.3 Groundwater (USG-Transport) model results

5.3.1 Predictive USG-Transport model set up

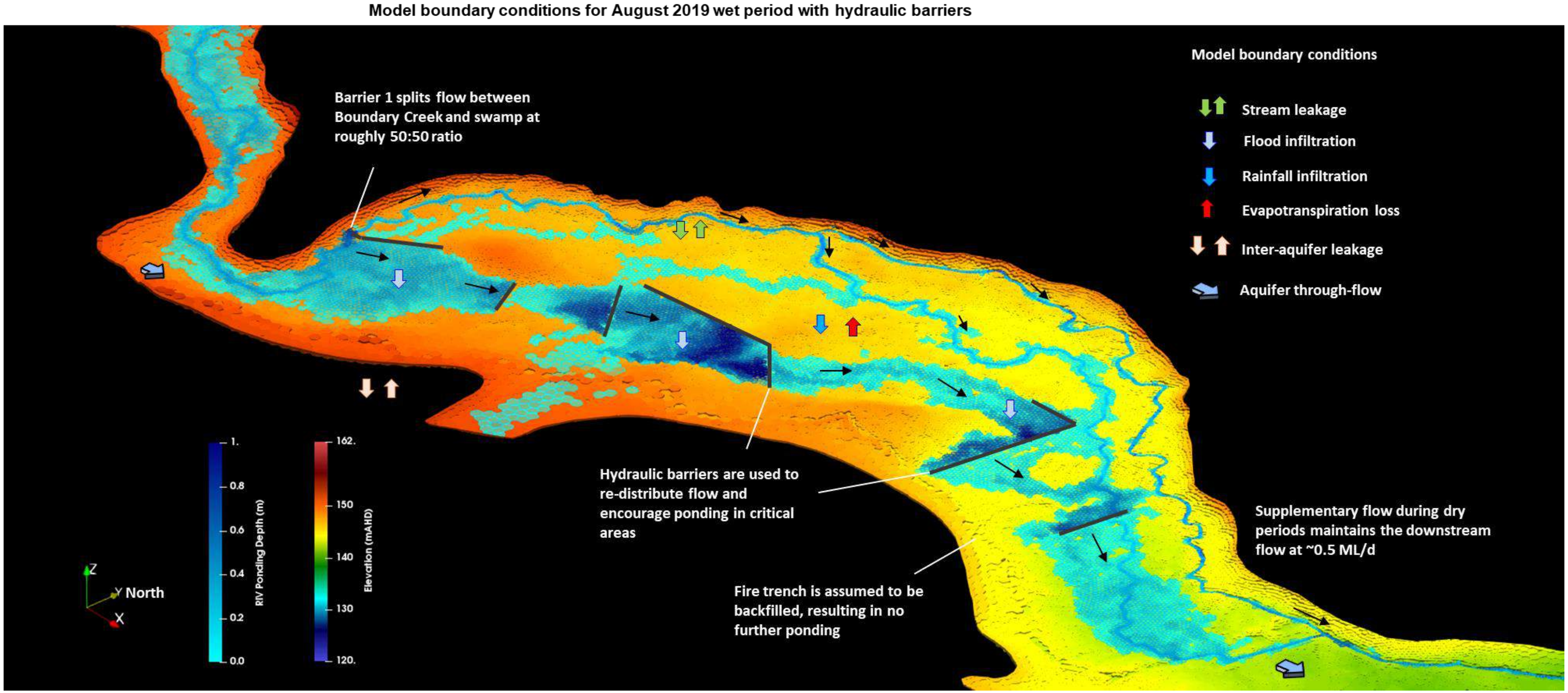
Although the USG-Transport model has been used in conjunction with the TUFLOW model to test the effectiveness of different barrier configurations, the predictive modelling outputs are presented only for the preferred barrier configuration described in Section 0 due to the very large amount of model outputs generated.

The USG-Transport model for predictive modelling uses the same simulation period and boundary conditions applied to the calibration model except for the following modifications:

- The RIV boundary condition has been updated based on the flood extents and ponding depths modified by the hydraulic barriers, as computed using the TUFLOW model.
- The RCH and EVT boundary conditions are updated with zero rates assigned to the revised location of RIV cells.
- The SFR boundary condition has been updated to include a new segment at the location of Barrier 1, to simulate the diversion of water from Boundary Creek. In this case, water diverted to the swamp is assumed to be no longer part of the flow in the creek. This is achieved by diverting water to a new segment specified at the last reach of the SFR boundary, such that diverted flow is lost from the steam flow. The diversion is specified as time-varying ratios, based on the flow splits computed by the TUFLOW model. This currently equates to around 50:50 split, although different flow splits have been explored using the TUFLOW model.
- The inflow into the most upstream segment of the SFR boundary, representing flow downstream of McDonald’s Dam, has also been modified to explore the effect of different supplementary flow regimes.
- The DRN boundary condition is not used in the predictive model, as the fire trench is assumed to be backfilled.

Figure 5-8 shows the model boundary conditions and processes for the predictive conditions, including the changed extent and depth of flood inundation and the final location of hydraulic barriers used for predictive modelling.

Figure 5-8 Model boundary conditions and processes – predictive condition



5.3.2 Effect of hydraulic barriers on groundwater levels

The effect of hydraulic barriers on maintaining the groundwater levels at each monitoring bore is demonstrated using hydrographs of existing and changed heads, and how they compare against the target groundwater level. These hydrographs shown in Figure 5-9 and Figure 5-10 are based on the model run with the full supplementary flow (4.4 ML/d during the dry period) and 50:50 flow split, as discussed further in Section 5.3.3. It should be noted that the extent and depth of flooding are not particularly sensitive to different supplementary flow regimes (for 50:50 flow split). This means the hydraulic barriers generally have similar effects on the groundwater levels at lower supplementary flows.

The hydrographs indicate that the hydraulic barriers are effective in raising the groundwater levels at the location of monitoring bores. At the majority of bores, the computed heads are at or above the target groundwater levels for the entire 14-month period. The exception is at BSBH18 where the computed heads are consistently lower than the target level by around 0.3 m. The hydraulic barriers have been adjusted to maximise the amount of ponding at BSBH18 without limiting the flow to other bores further downstream. This means there is likely to be a practical limit to forcing flow upgradient to BSBH18 without unduly influencing the performance of the barrier system further downstream.

Where flooding/ponding is maintained near constant, the QA becomes fully saturated and the groundwater level becomes equilibrated with the pond level. This explains why the model simulates little to no variability in the computed heads at a number of bores such as BSBH10 and BSBH15.

Figure 5-11 and Figure 5-12 are head frequency duration curves, showing the fraction of time within the 14-month simulation period when the computed heads are above the values indicated on the Y-axis. Also shown on the Figures are the duration curve of computed head differences with and without the barriers and the target groundwater level. At BSBH08, the head duration curves indicate that the hydraulic barriers have the potential to maintain the groundwater levels at or above the target level 60 to 70% of the time, and there is the potential for the groundwater level to fall below the target level about third of the time albeit by a very small amount.

The spatial differences in the effect of hydraulic barriers are also demonstrated with reference to several depth to groundwater contour maps. Figure 5-13 compares the depth to water contours for the historical case (calibrated model) and remedial case (predictive model) in the presence of hydraulic barriers and supplementary flow. These are statistical maps derived from water table depth frequency during the 14-month simulation period, and include the wet (upper 5th percentile), dry (lower 95th percentile) and typical (50th percentile) climatic conditions.

The effectiveness of the remedial system can be quantified for each climatic condition by calculating the difference between the historical case and predictive case. This is shown in Figure 5-14, where the negative change represents areas where the water table is shallower and the positive change represents areas where the water table is deeper. The largest negative change is simulated in the flooded areas under the dry climatic condition, where the remedial system has been specifically designed to meet the target levels at critical upstream bores.

The modelling indicates that hydraulic barriers and associated redistribution of flow has the potential to cause slight lowering (<0.5 m) of the water table along Boundary Creek under the wet and typical climatic conditions due to less flow passed down the creek. However, during the critical dry period the modelling indicates no further lowering of the water table in areas along Boundary Creek, with the potential for a slight increase in the downstream area. This is partly due to the flow maintained by 4.4 ML/d supplementary flow, which results in a net increase in leakage into the underlying QA.

The modelling indicates a possible lowering of the water table along the southern boundary of Big Swamp, due to the filling of the fire trench. The fire trench currently forms a local low point where surface water ponds during wet periods, resulting in localised infiltration. The filling of the fire trench means this source of recharge is no longer present, resulting in the lowering of the water table by 0.5 to 1 m.

Figure 5-15 shows the range of seasonal variability in the groundwater levels across Big Swamp for the historical and remedial cases. Also shown in the Figure is the difference between the two contours, which represents the effect of the remediation system on the seasonal variability in the groundwater levels. The areas of negative change represent areas where the seasonal variability has been reduced by the remediation system and vice versa. For example, in the flooded area near bores BSBH14 to BSBH16, the historical case indicates a natural seasonal variability of around 2 m whereas the variability is <0.1 m in the remedial case, as the groundwater level equilibrates with the near constant pond level. This means the modelling indicates a reduction in seasonal variability by up to around 2 m in this area.

Figure 5-9 Predicted bore hydrographs – BSBH01 to BSBH09

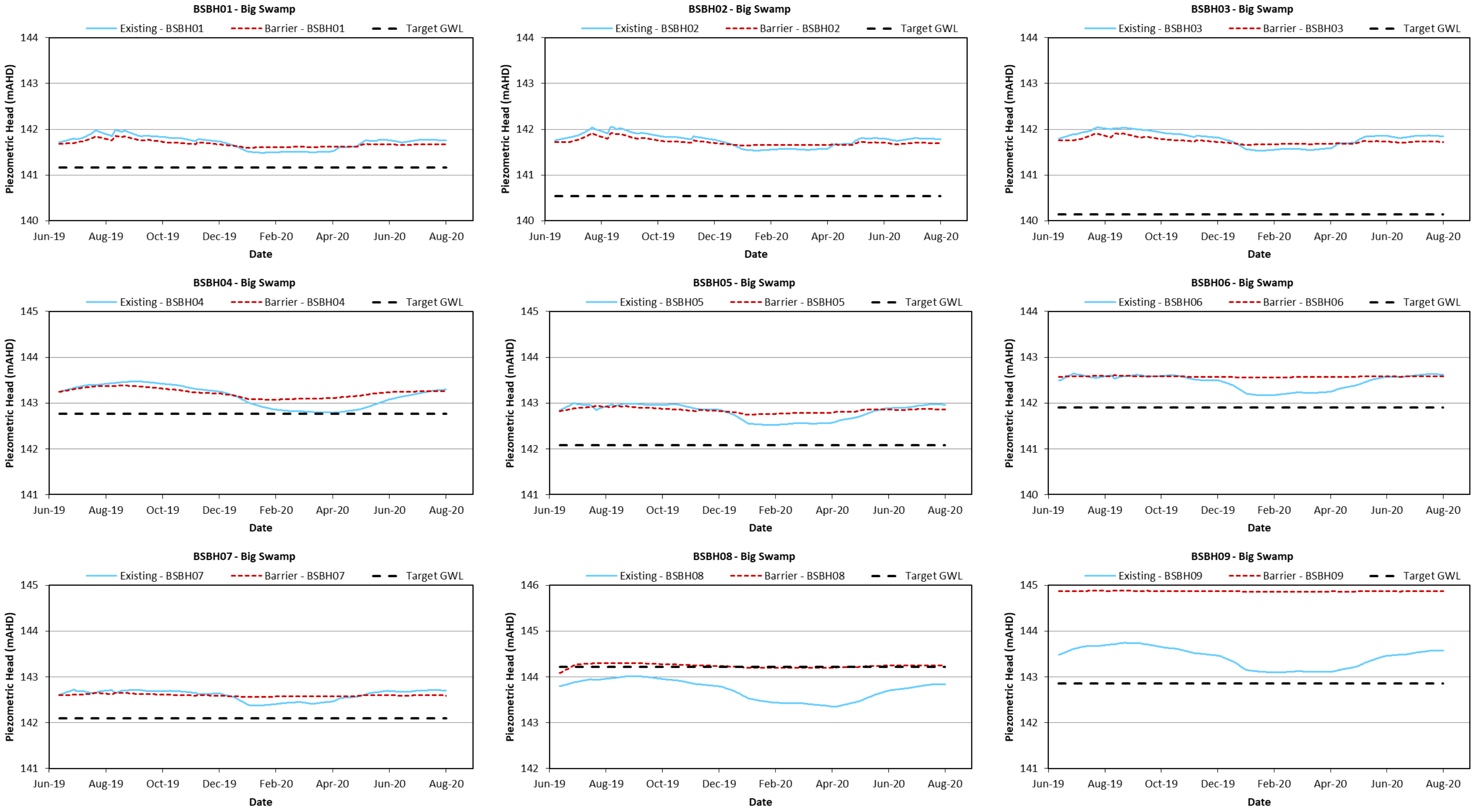


Figure 5-10 Predicted bore hydrographs – BSBH10 to TB1A

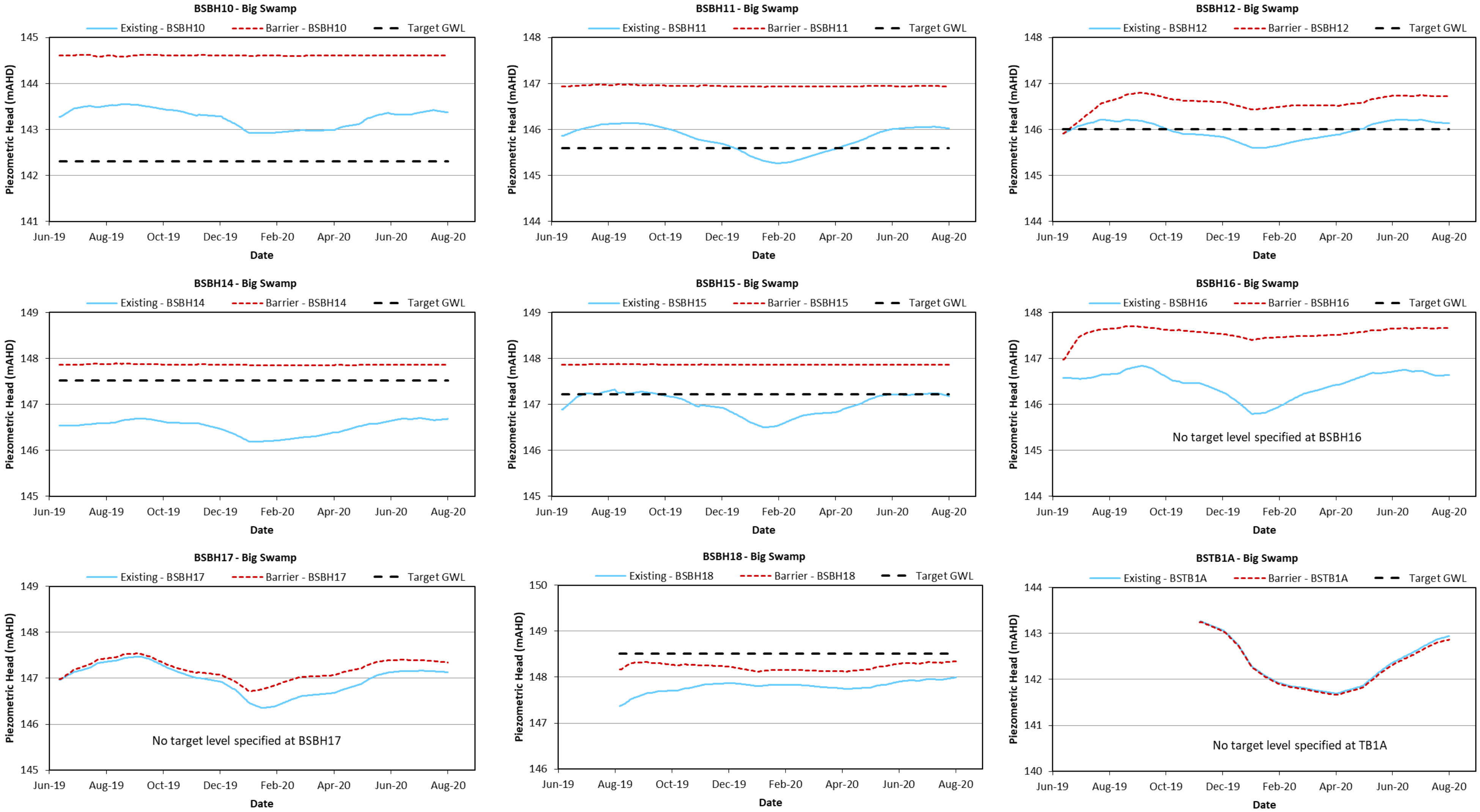


Figure 5-11 Head frequency duration curves – BSBH01 to BSBH09

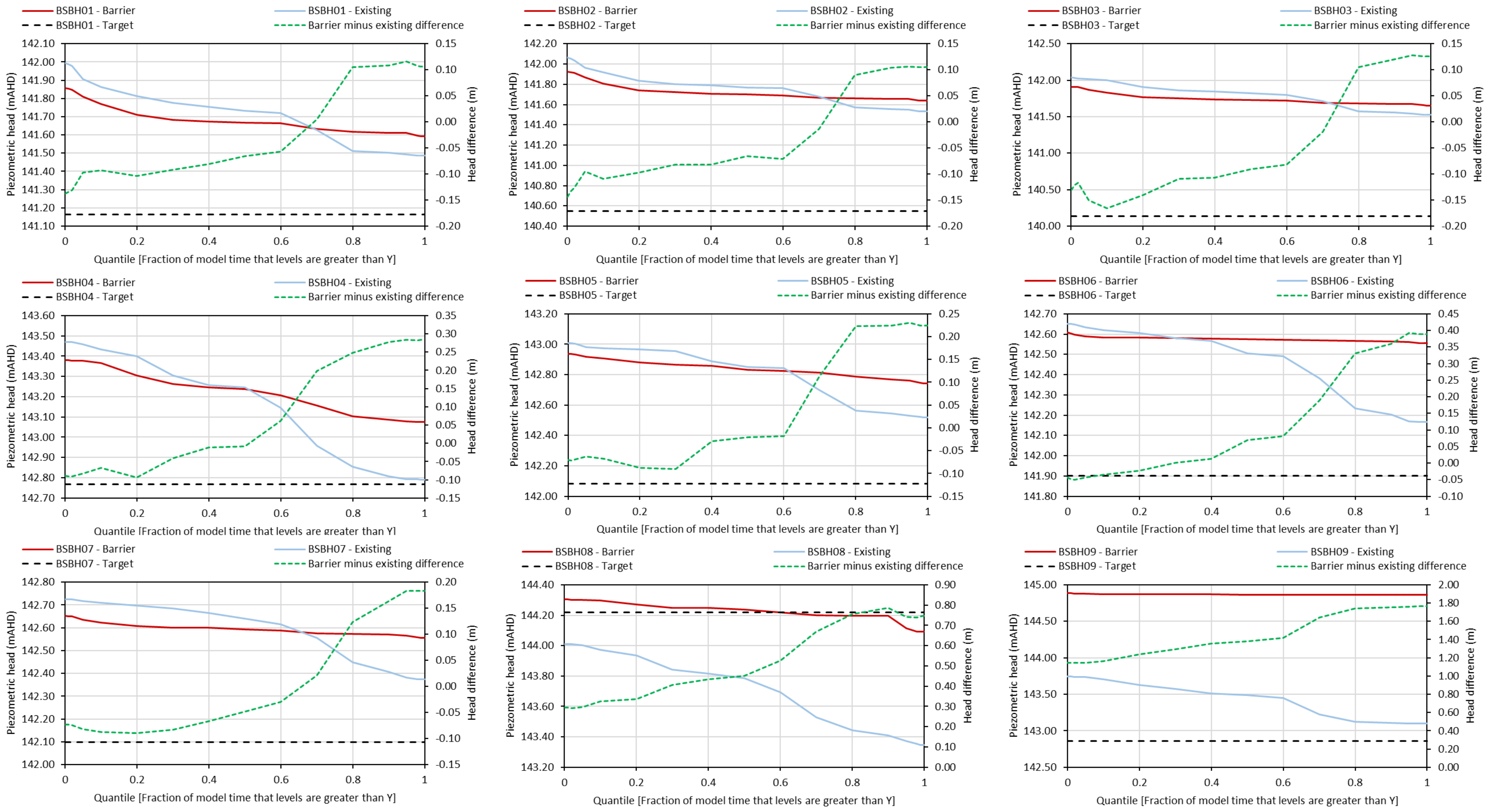


Figure 5-12 Head frequency duration curves – BSBH10 to TB1A

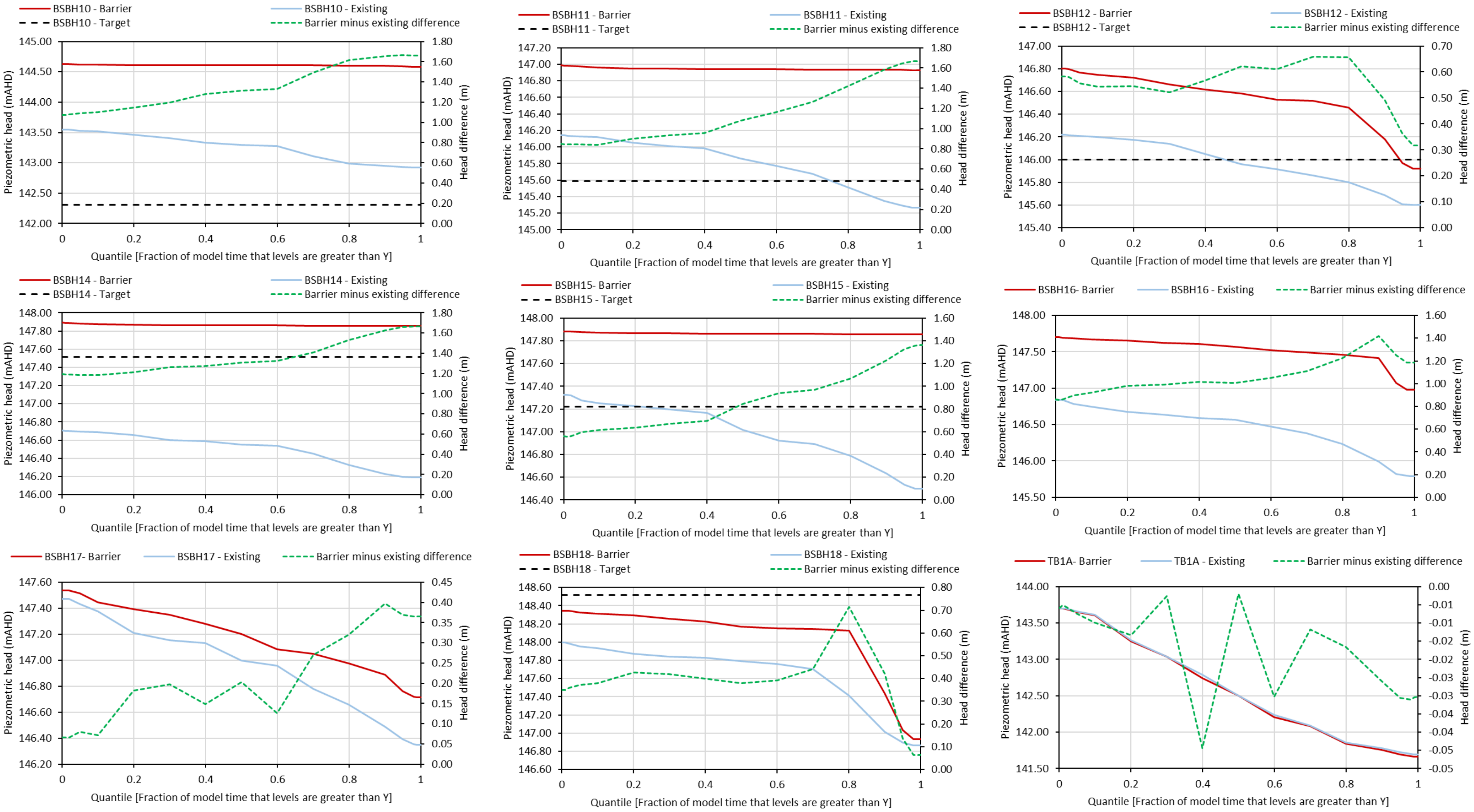


Figure 5-13 Modelled seasonal depth to water variability

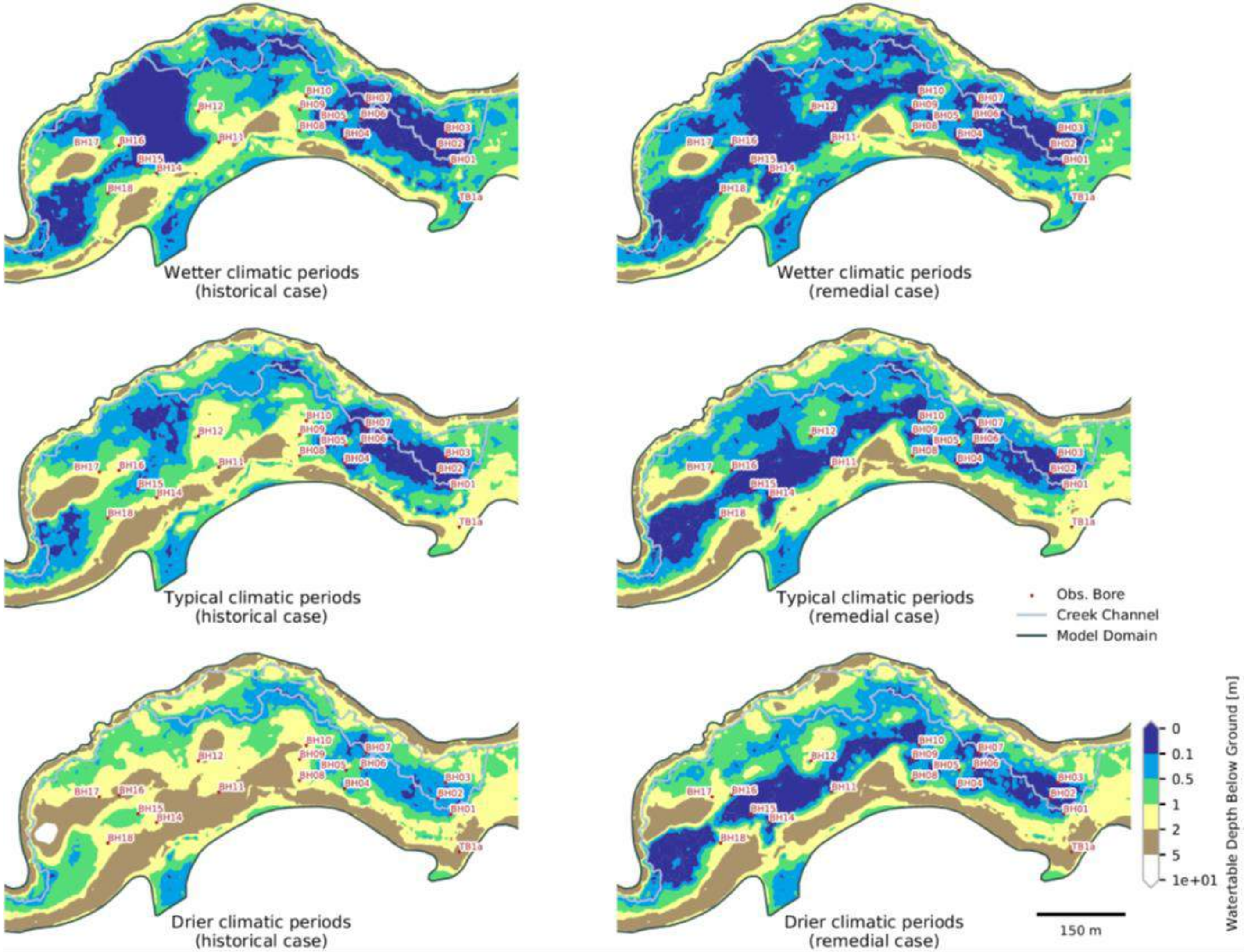


Figure 5-14 Effect of remedial system on depth to water variability

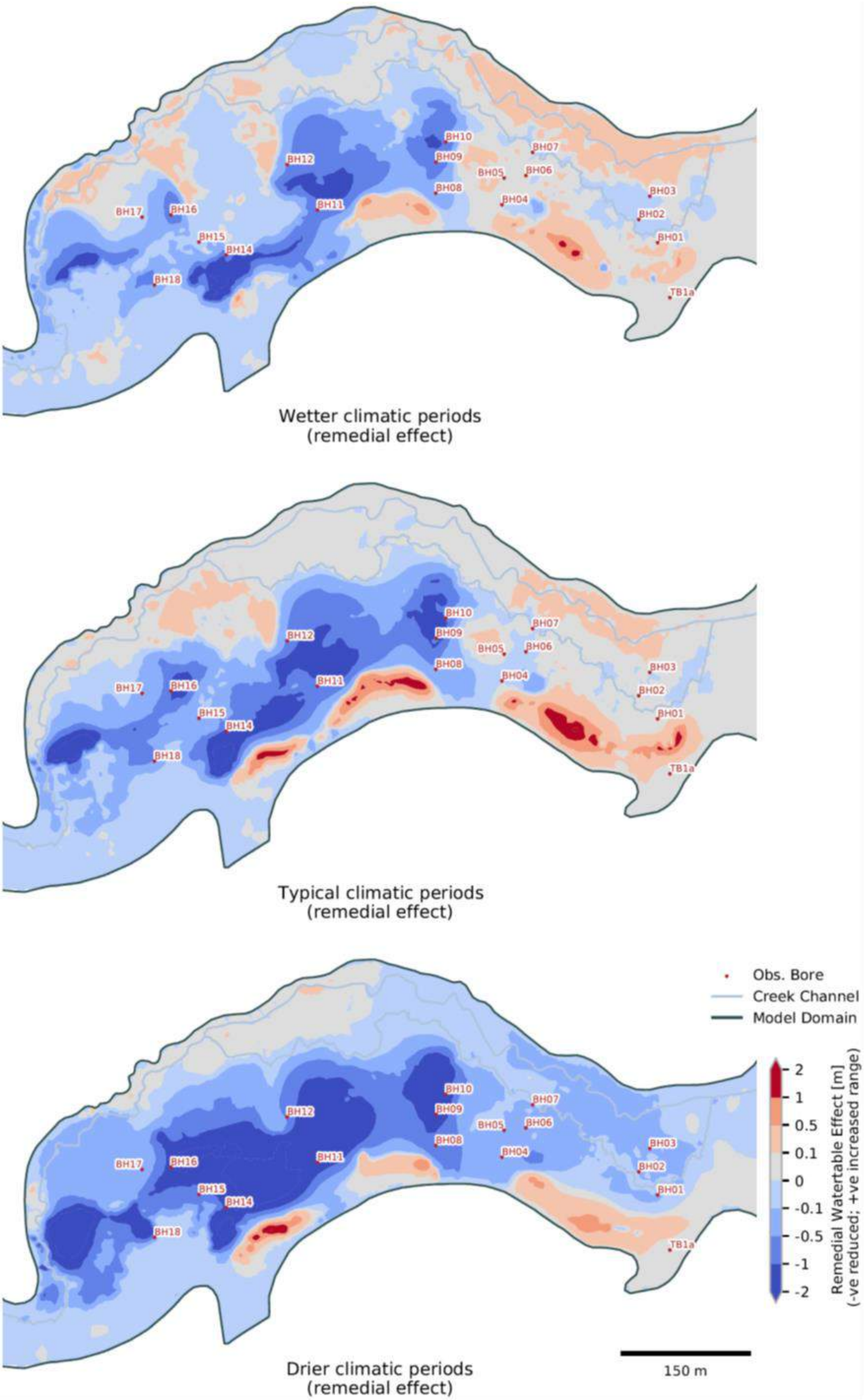
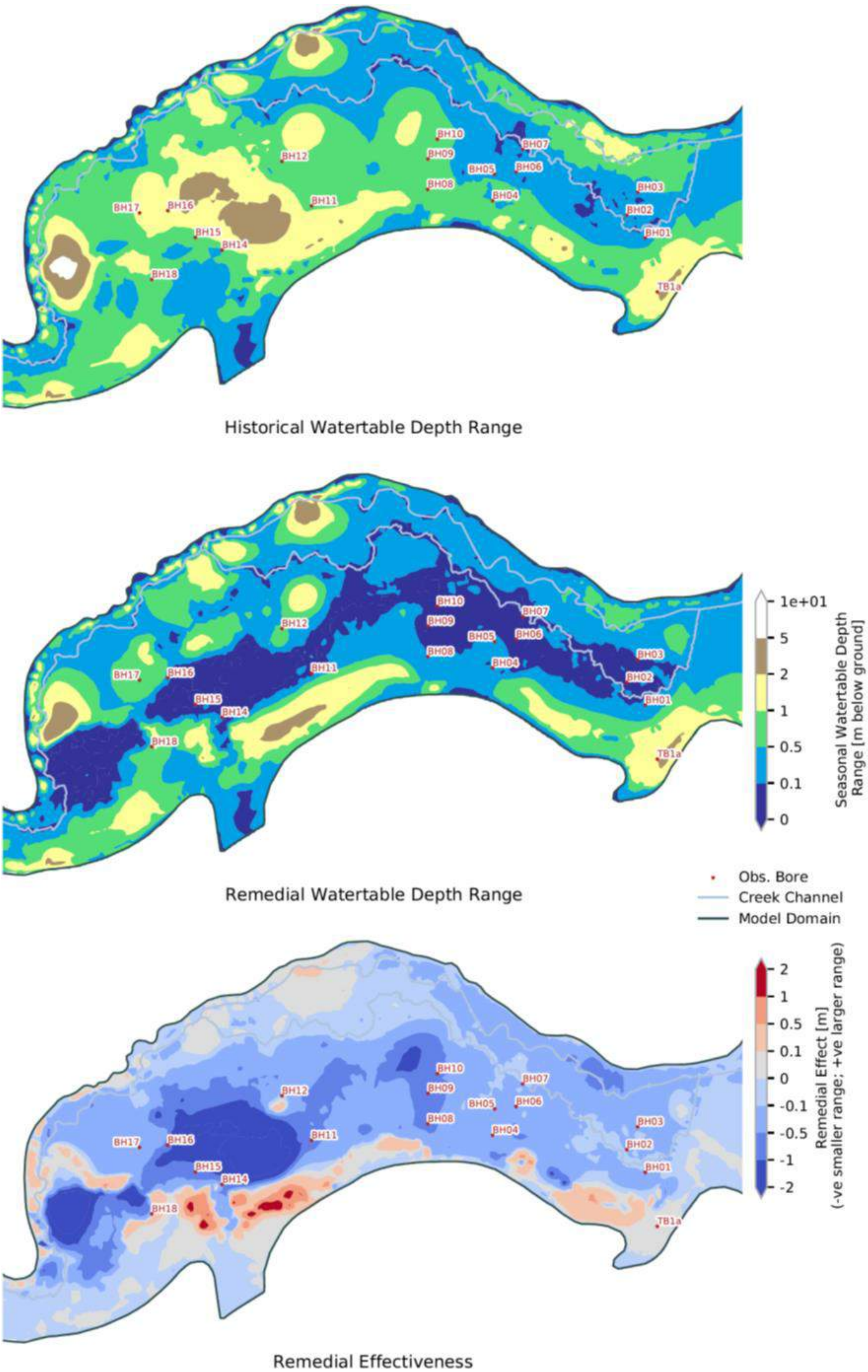


Figure 5-15 Modelled seasonal water table range and remedial effect



5.3.3 Effect of supplementary flow on downstream flow

During the dry period of 2019 to 2020, supplementary flow was used to maintain flow downstream of McDonald's Dam at around 2 ML/d. Even with the extra flow, a complete loss of stream flow was recorded at gauge 233267A, indicating that 2 ML/d is insufficient to maintain 0.5 ML/d at 233267A and further downstream at 233228, particularly after the flow is re-directed to the swamp to maintain the groundwater levels.

It is understood that up to 500 ML of supplementary flow can be made available in a given year. The analysis of flow data indicates that there were around 114 days when the flow downstream of McDonald's Dam was either at or less than 2 ML/d. Assuming that 2 ML/d of supplementary flow was already utilised, it would be possible to use the remaining flow volume over 114 days to increase the supplementary flow to up to 4.4 ML/d. To explore the effect of further increasing the supplementary flow, the flow into the upstream segment of the SFR boundary was increased to 3, 4 and 4.4 ML/d. For each supplementary flow rate, the calibrated TUFLOW model has been re-run to provide revised flood extents and depths, as well as the flow splits, which are used to update the RIV and SFR boundary conditions of the USG-Transport model.

Figure 5-16 shows the hydrographs of stream flow computed at gauge 233267A and 233228. The critical dry period is highlighted in green. The hydrographs compare the flow computed under the existing condition with the flow computed in the presence of hydraulic barriers, with supplementary flow of 2, 3, 4 and 4.4 ML/d. The flow under the existing condition is greater during the wet period because roughly 50% of the flow is diverted to the swamp by Barrier 1.

The hydrographs indicate that almost all of supplementary flow would be required to meet the flow target of 0.5 ML/d during the dry period (generally met when the supplementary flow is between 4 and 4.4 ML/d). The flow duration curves presented in Figure 5-17 indicate that flow would be greater than 0.5 ML/d for 90% of the 14-month simulation period, assuming the maximum supplementary flow rate of 4.4 ML/d during the dry period.

It should be noted that the results presented in this section assume a 50:50 flow split at Barrier 1, which may be considered conservative. Further testing in TUFLOW indicates that when the maximum supplementary flow is used, it may be possible to relax the flow split to as much as 80:20 (only 20% diverted to the swamp) to maintain near constant ponding at the location of bores. The implication is that it may be possible to divert more flow to Boundary Creek or achieve the 0.5 ML/d flow target with less supplementary flow by adjusting the flow split at Barrier 1.

Figure 5-16 Predicted flow hydrographs at downstream gauges

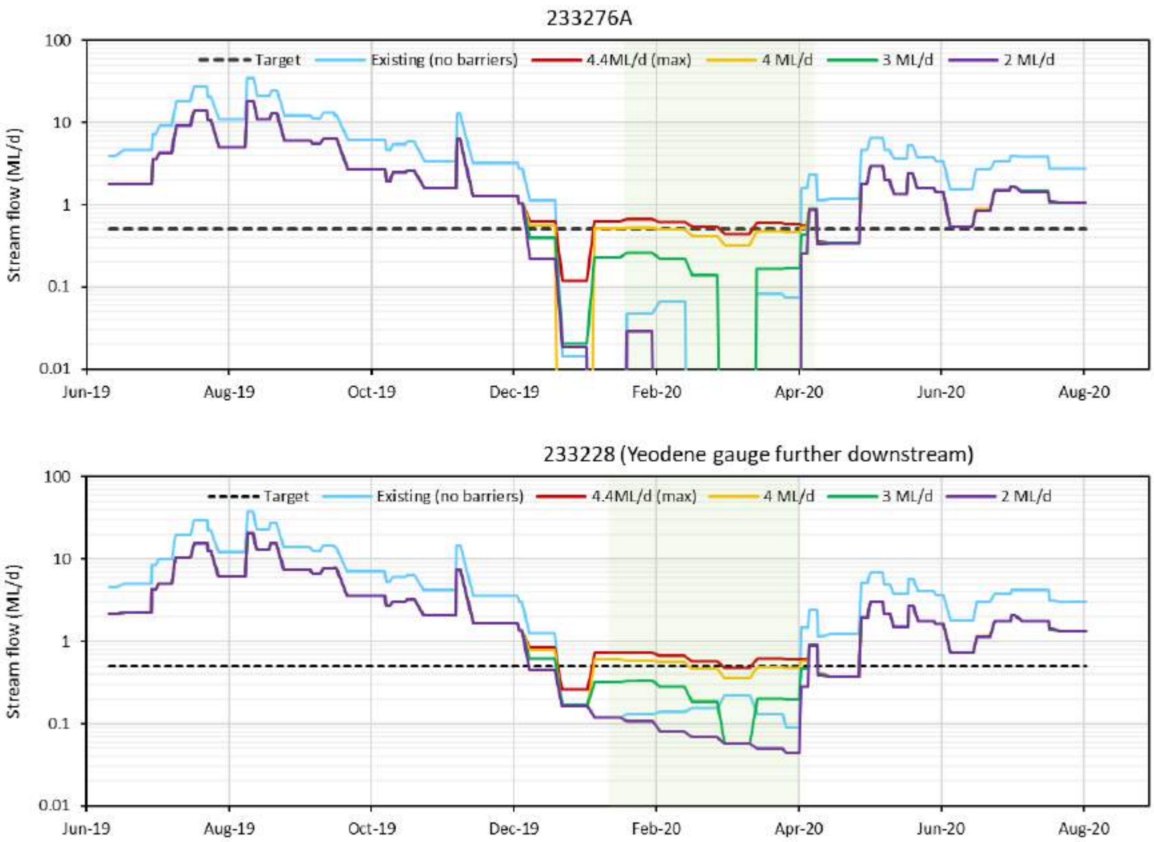
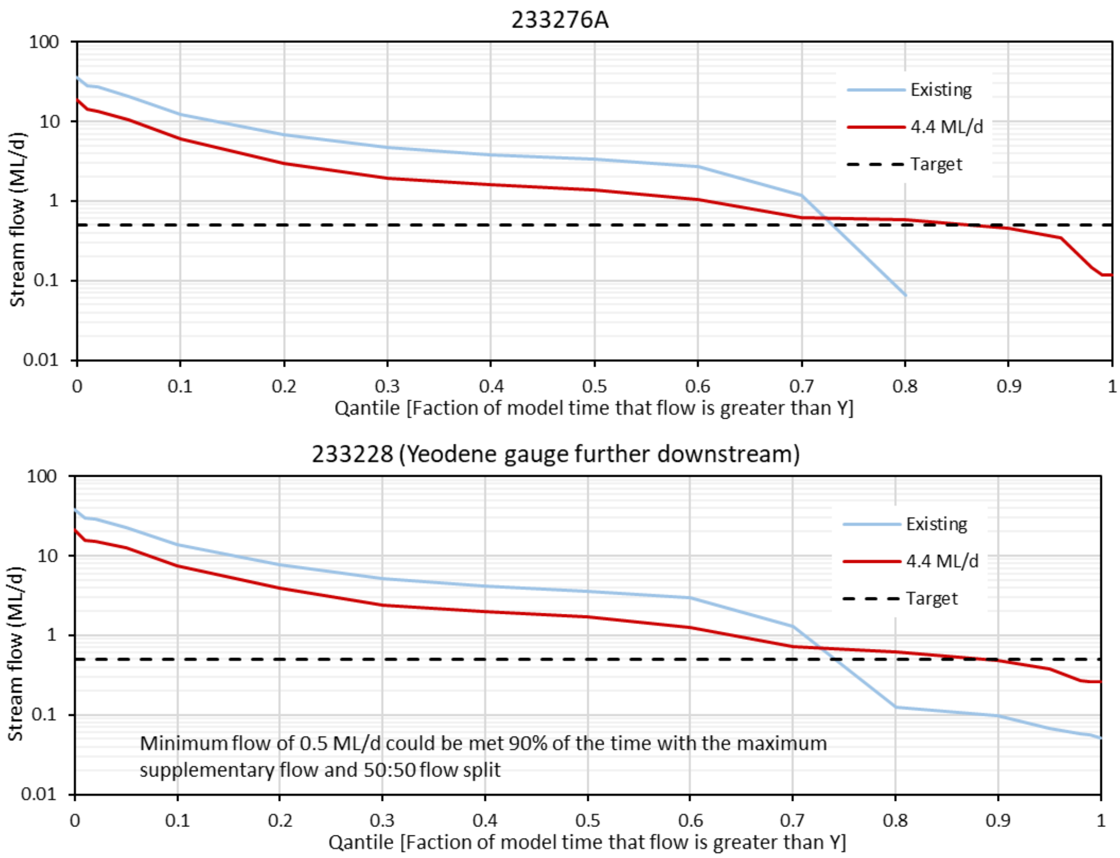


Figure 5-17 Predicted flow duration curves at downstream gauges



6. Sensitivity and uncertainty analysis

6.1 Flood (TUFLOW) model sensitivity analysis

6.1.1 Sensitivity to soil infiltration losses

A sensitivity analysis of soil infiltration losses is considered important due to uncertainties associated with this parameter and the differences in the way infiltration is treated in the TUFLOW and USG-Transport models. The effect of different infiltration losses can be demonstrated using afflux plots that show the differences in the simulated flood levels (ponding depths) when the infiltration loss is varied from 25 to 40 mm/d i.e. the difference between the calibrated and the upper bound estimate.

Figure 6-1 shows the afflux plots of ponded depths at the wettest and driest points in time within the 14-month calibration period. These afflux plots show that both the extents and depths of water are not significantly different, varying by less than 0.01 m in depth with minimal changes to the flood extents. The afflux plots comparing the 10 and 25 mm/d showed similar results, with less than 0.01 m higher ponding depths at the lower infiltration rate. The implication is that the TUFLOW water depths are not particularly sensitive to the variations in infiltration losses within the plausible range of 10 to 40 mm/d, as the ponded areas are generated by surface water flows that are much greater than the rate of loss via infiltration.

The results of the barrier configurations also show low sensitivity to the assumed infiltration losses, as the size of the ponds created is governed primarily by the level of the barriers and the topography. The modelling shows that the ponds fill up rapidly in the wet season, and as long as the inflows to the ponds match or exceed the losses to evaporation and infiltration, the ponds would remain full and retain their size.

To further understand the risk of the ponds drying out due to higher than expected soil infiltration rates, the TUFLOW model has been run with the preferred barrier configuration using the following infiltration losses: (1) 32 mm/d over the ponded areas, (2) 40 mm/d over the ponded areas, and (3) 40 mm/d over the ponded areas and 80 mm/d along Boundary Creek (as opposed to 35 mm/d used for all other runs). All three sensitivity runs assume the existing supplementary flow of 2 ML/d with a flow split of approximately 50:50. The results from Sensitivity Run (1) shows little difference to the based case with infiltration set at 25 mm/d (the version used to inform the USG-Transport model). However, at the infiltration rate of 40 mm/d the flow ceases at the last barrier (Barrier 9) during the driest point in the simulation period, resulting in the drying of the pond furthest downstream. For Sensitivity Run (3), with 80 mm/d infiltration along Boundary Creek, the last two ponds at Barrier 3 and Barrier 9 become dry.

Figure 6-2 shows the ponding depths at the driest time for Sensitivity Run (2), showing the drying of the pond adjacent Barrier 9. The last pond along the diverted flow path is the furthest downstream and is the first pond to start drying when the losses upstream prevent the flow from reaching this point. Figure 6-3 shows the relationship between the rate of flow diverted (in this case, after Barrier 5) and the pond water levels simulated adjacent to Barrier 9 for the base case (25 mm/d) and each of the three sensitivity runs. At 25 and 32 mm/d infiltration rates, the pond water level remains just above 142.7 mAHD for the entire simulation period and the flow downstream of Barrier 9 is maintained. At 40 mm/d infiltration, the pond water level starts dropping for a few weeks through January 2020 as the diverted flow drops below 0.45 ML/d. When the infiltration rate along Boundary Creek is increased to 80 mm/d, the pond becomes dry for around 3 months as the diverted flow drops below 0.49 ML/d.

The sensitivity analysis indicates that if the infiltration rates are higher than expected (up to around 40 mm/d), then a relatively small additional flow of around 0.2 ML/d would be required to maintain all of the ponds wet. This could be achieved by adjusting the flow split or increasing the supplementary flow, which is likely to be required for meeting the downstream flow target of 0.5 ML/d according to the findings of groundwater modelling. Even at the infiltration rate of up to 80 mm/d along Boundary Creek, only around 0.8 ML/d of additional flow would be required to keep the last pond topped up, which is well within the range of supplementary flow.

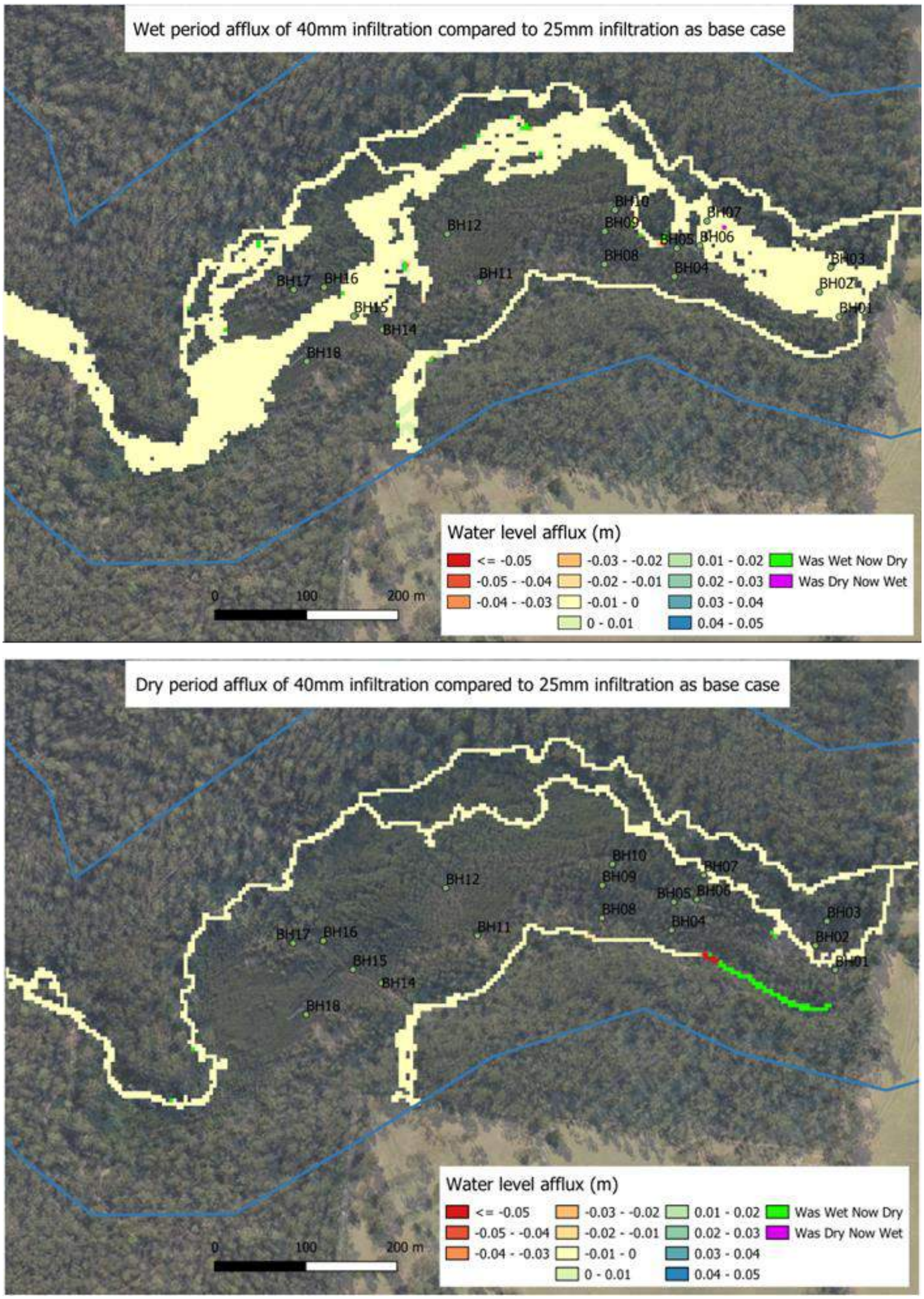


Figure 6-1 Sensitivity analysis – afflux plots

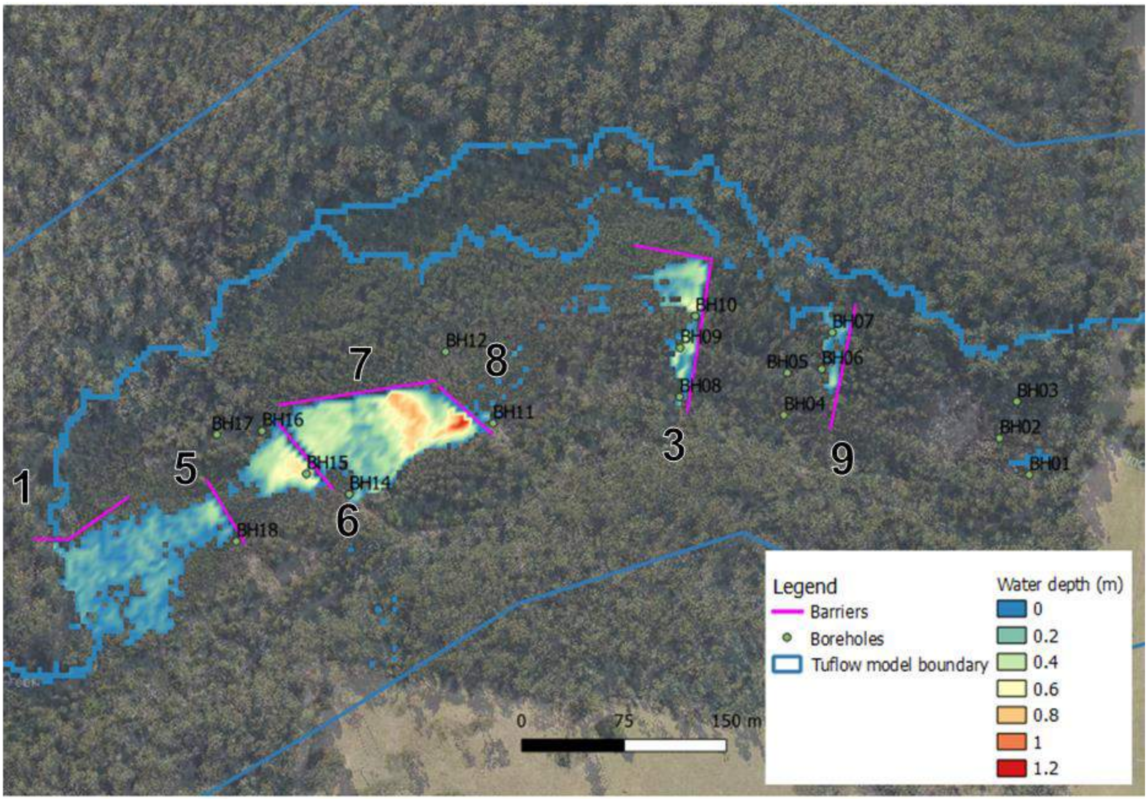


Figure 6-2 Sensitivity Run 2 dry period ponding depth at 40 mm/d infiltration

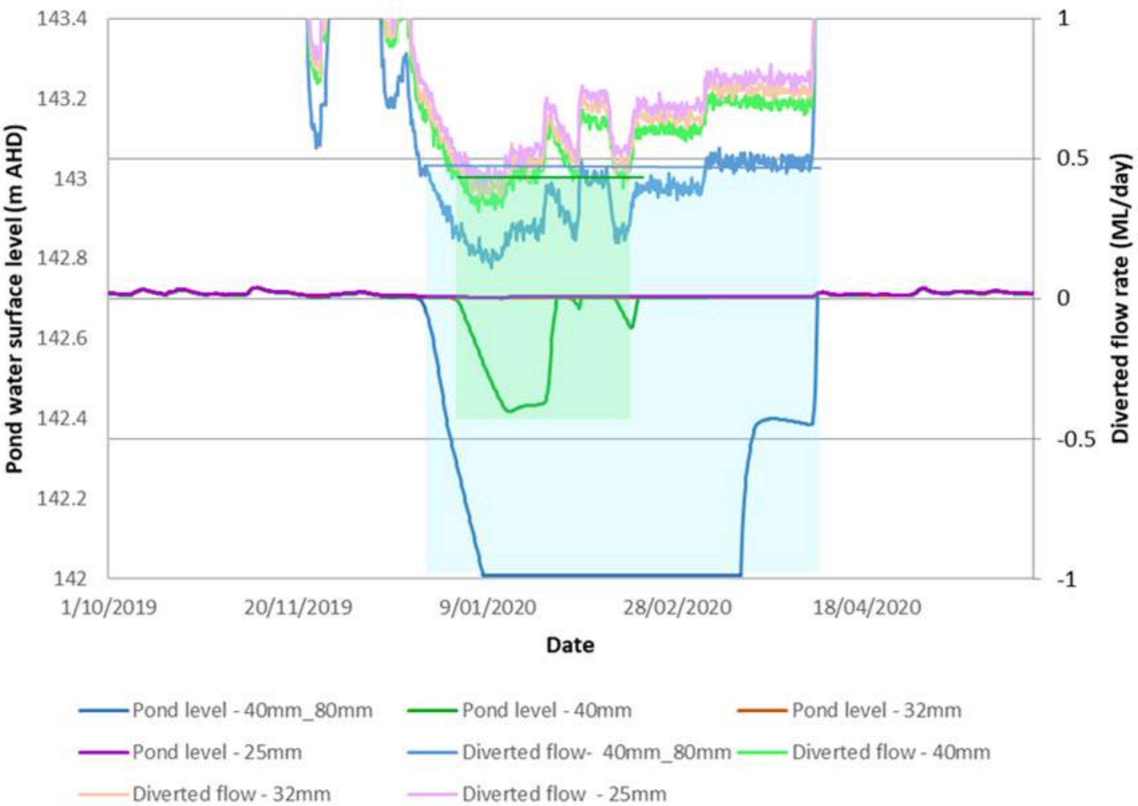


Figure 6-3 Sensitivity of pond adjacent to Barrier 9

6.1.2 Sensitivity to other parameters

Several additional sensitivity runs have been undertaken to examine the effect of altering the model configuration and input parameters where these changes are considered to have potential effects on model outcomes. These sensitivity runs include:

- Reducing the TUFLOW grid cell size from 4 to 1 m.
- Reducing the timestep of upstream inflow data from daily to 15 minutes.
- Using outputs from the GR4J model as the upstream inflow (rather than gauge data)
- Using TUFLOW's double precision computation (rather than single)
- Removing the gully shaping along the main channel to examine the effect of changes to the terrain.

The additional sensitivity analyses indicate the following:

- 1 m grid appears to produce outputs that are largely similar to those from the 4 m grid. Boundary Creek appears to be slightly thinner with the finer spatial grid, as expected, otherwise using a coarser grid of 4 m to improve run time efficiency has not materially affected the accuracy of TUFLOW model outputs.
- The 15-minute timesteps for the upstream inflow result in only minor differences, primarily slightly larger flooded extents during the wettest period. This is unlikely to change the effectiveness of the hydraulic barrier configuration, given the likelihood of failure (ponds drying) is most sensitive to the flow maintained during dry periods.
- Similarly, using a slightly different upstream inflow data derived from the GR4J model has only minor effect on increasing the flood extent during both the wet and dry periods.
- Using double precision has a negligible impact on the results, with a few additional wet cells with very small ponding depths that are generally below the threshold applied in the USG-Transport model.
- Removing gully (z-line) shaping has the largest effect. Without this, Boundary Creek becomes dry in many places and different flow paths occur. The afflux plot between the calibrated model with and without gully shaping is shown for the wet period in Figure 6-4. These differences highlight the importance of accurate terrain data, with errors in the existing terrain data significant enough to change the modelled flow paths within Big Swamp. This is important because if the actual topography differs from that represented in the existing terrain data, then the shape and location of hydraulic barriers may need to be modified to achieve the required pond sizes and depths to maintain the groundwater levels.

A comparison of the calibrated TUFLOW model (base case) against the various sensitivity runs at the gauge locations is shown in Figure 6-5 and Figure 6-6 for flows and water levels respectively. The flow results show that both the 15-minute timestep run and the GR4J inflow run result in higher peak flows in the wet period. For the GR4J inflow run, significantly higher flows are also simulated during dry periods which is due to difficulties in correctly calibrating the GR4J model to simulate low flows. The 1 m grid has shifted the simulated stage at 233276A, although the magnitude of changes is larger, with deeper peaks and troughs that appear to better replicate the observed data. Removing gully-shaping has the largest effect on the simulate stage at downstream gauge 233228.

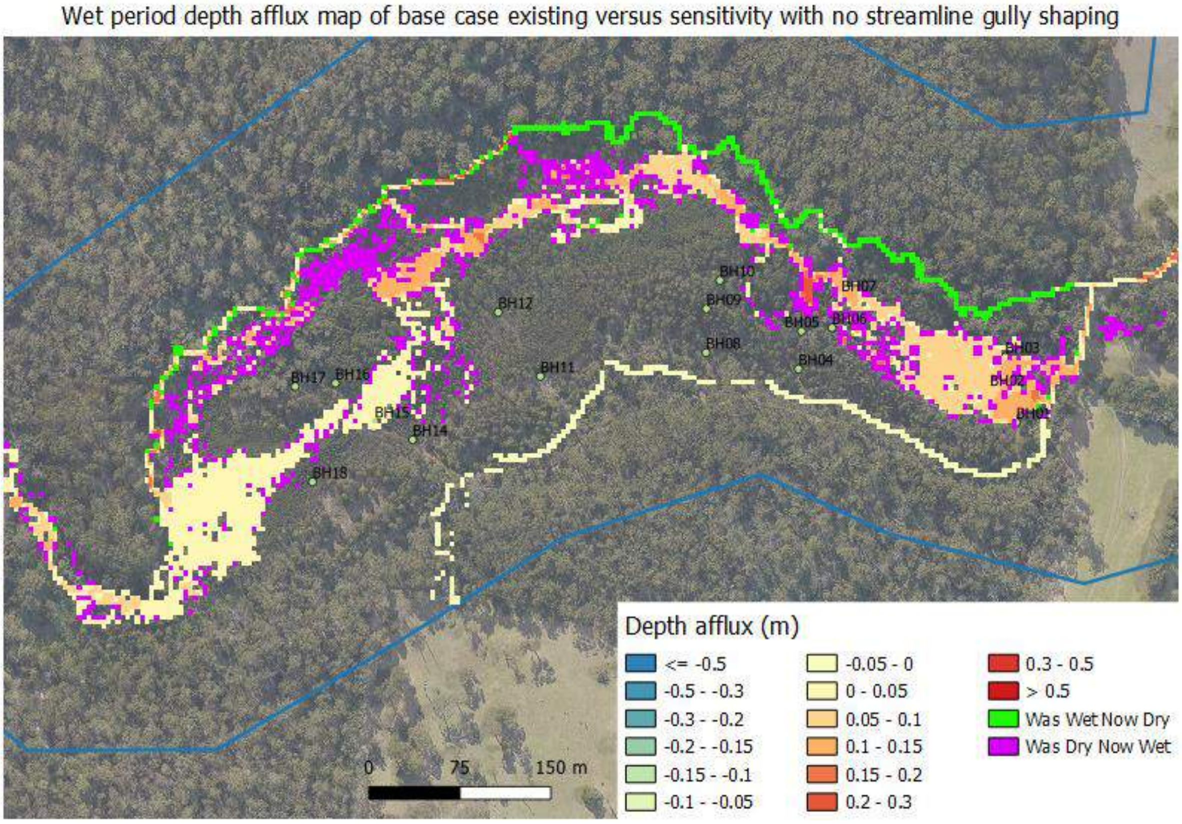


Figure 6-4 Sensitivity analysis – afflux plot with and without gully shaping

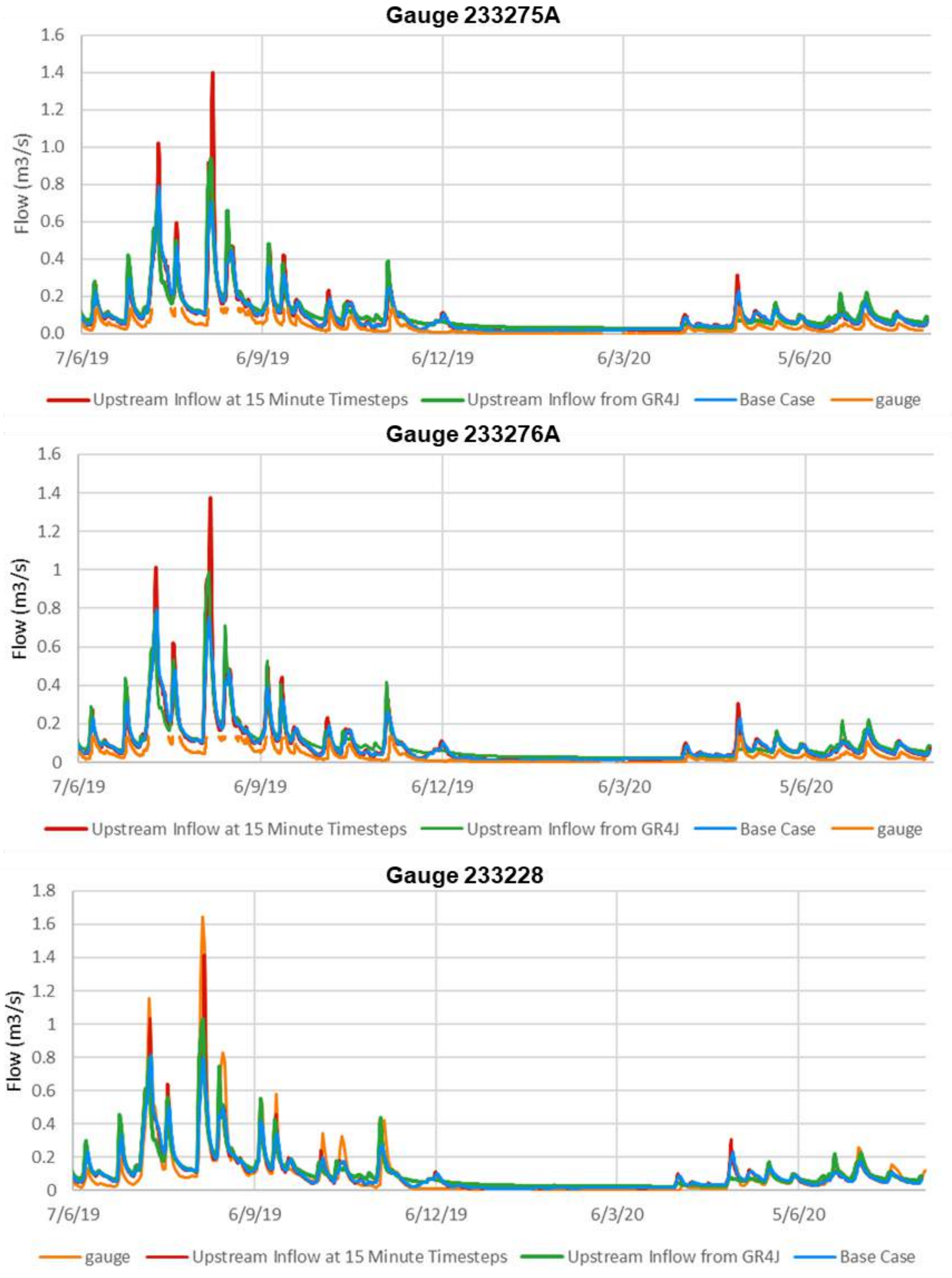


Figure 6-5 Sensitivity analysis – simulated flow at key gauges

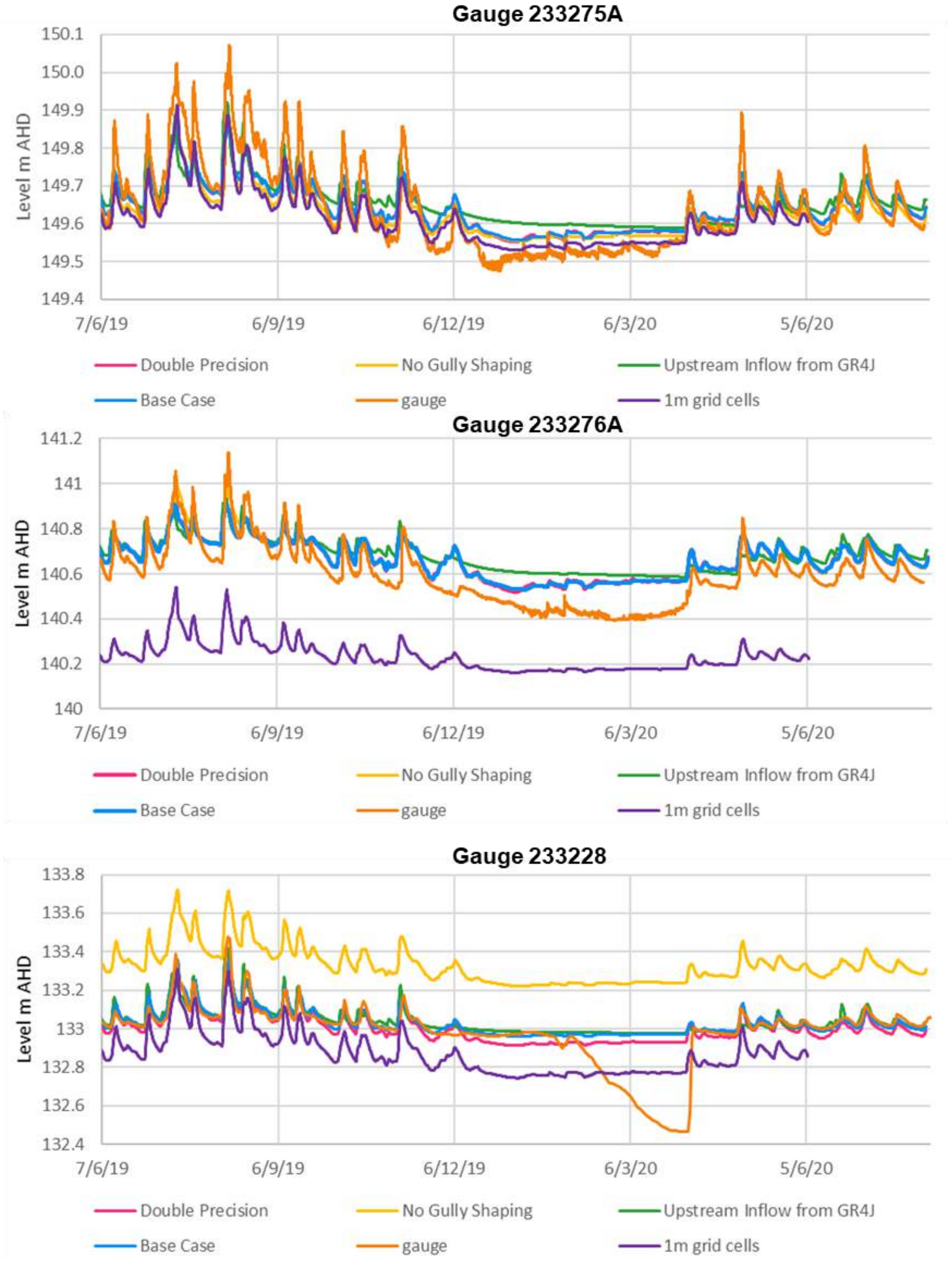


Figure 6-6 Sensitivity analysis – simulated stage/level at key gauges

6.2 Groundwater (USG-Transport) model uncertainty analysis

6.2.1 Overview

The USG-Transport model used for forecasting potential swamp remediation effectiveness, as outlined in prior sections of this report, has been subjected to a process of rigorous model parameter and predictive uncertainty analysis.

This involved the development of many model parameter sets that each provides an acceptable level of agreement between historical observations of creek flow and groundwater levels, and their modelled counterparts. Those parameter sets are then used to batch run and post-process many different versions of the historical and forecast (remedial) models. This approach is referred to as non-linear uncertainty analysis, which is the most comprehensive form of uncertainty analysis (Group 3 uncertainty quantification technique, according to Middlemis and Peeters, 2018).

Results from these models have been aggregated to present measures of the level of confidence that can be expected in the primary conclusions, made using the optimally history-matched model in Section 5.3, given the available observation data with which to constrain the models, and other limitations as outlined in Section 7.3.2.

6.2.2 Uncertainty analysis method

The iterative ensemble smoother code PESTPP-IES (White et al., 2018; PEST++ Development Team, 2020) has been used to sample the allowable parameter ranges outlined in Section 4.4.5, and to develop an ensemble of calibration-constrained model parameter sets. This process has been initiated from the optimally calibrated (minimum error variance) parameters developed through the application of PEST_HP, which is outlined in Section 4.4. In this way, the parameter ensemble optimised by PESTPP-IES is centred on the minimum error variance parameter set.

In this case, no observation error ("noise") has been added to the model calibration targets for the following reasons:

- The requirement for an abnormally low level of absolute head history-matching error, given the absolute nature of the groundwater level (head) remediation targets that are sought to be met and assessed. Introduction of greater error margins to the models would have unnecessarily complicated the assessment of remedial effectiveness.
- The expected centimetre-scale measurement error for most groundwater level observations is smaller than the expected level of structural model error, and hence, its removal from the process is not expected to have significant practical implications.
- To keep the uncertainty analysis workflow relatively simple and rapid.

Parameter variances have been defined as one quarter of each parameter's allowable range (Section 4.4.5), thereby implying a 95% confidence interval. For spatially correlated (pilot point) parameters, such as those defining aquifer hydraulic properties, RIV and SFR conductance (Section 3.4.3), covariances are defined using distance-based factors developed using PEST tools MKPPSTAT and PPCOV_SVA; these distance-based settings have been applied for interpolation of those same parameters to the model mesh (Section 3.4.3). The same 95% confidence limit per-parameter variance assumptions are applied to these covariance matrices (along the diagonal).

PESTPP-IES was first used to develop an ensemble of acceptably well history-matched models. This process was initiated with an ensemble of 300 models. Of this, by the end of the optimisation process (eleven iterations; 3845 runs), only seven of the 300 had failed, indicating a very numerically stable model. The remaining 293 history-matched models were subject to a manual filtering process, in which all groundwater level and flow-related observation sub-groups were assessed for quality; this resulted in a final history-matched model ensemble of 135 members. In this way, all groups in the final ensemble are well-history matched to each of the flows, flow losses and gains, creek stage, groundwater levels (at target bores, and at non-target bores), and hydraulic gradients observation groups. No one observation group is poorly history-matched in any of the 135 ensemble members.

In this filtering process, care was taken to ensure parameter ranges across the ensemble are not unexpectedly narrow. In fact, the final parameter ranges did not differ significantly from the initial ranges, which is a preferable outcome for examining uncertainty across the full parameter ranges. Ensemble parameter means and ranges are presented in Appendix B.

6.2.3 Stochastic history-matching quality

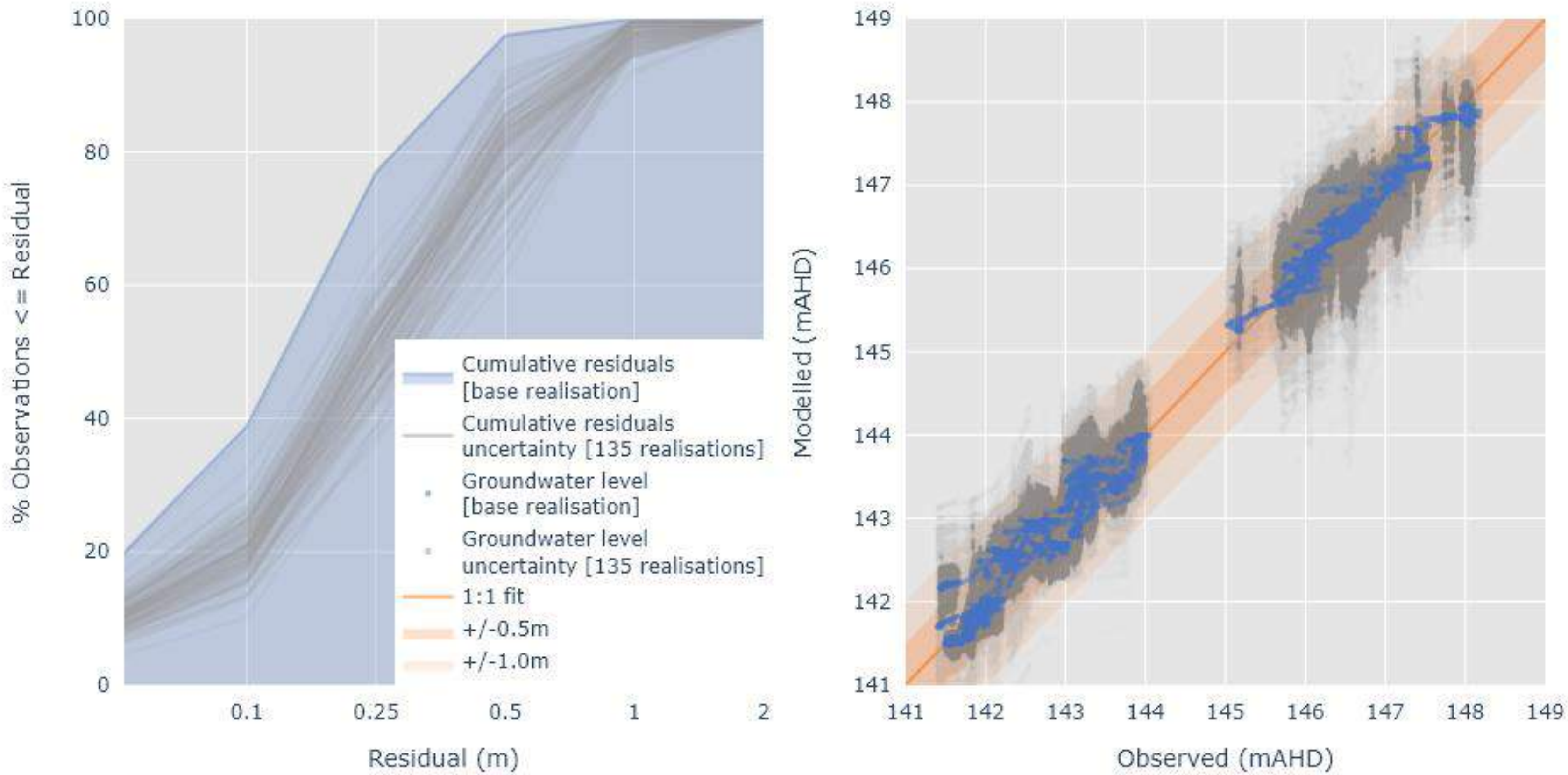
Figure 6-7 summarises the stochastic history-matching outcomes of the PESTPP-IES process. It shows that all 135 model realisations exhibit a generally good match to the groundwater level observation data, and that the history-match quality statistics are very good:

- Mean absolute residual errors range from 0.16- to 0.42 m, with a mean 0.31 m.
- Normalised root mean square error ranges from 3.1 % to 7.7 %, with a mean of 5.9 %.
- 90 % of the cumulative residual errors are within 1 m or the observation data across all 135 models.

Figure 6-8 shows a selection of history-matched hydrographs, for the base model, and the other realisations. These are plotted along with the remedial target levels (shown as the pale red band) for practical context. The hydrographs for all bores are presented in Appendix C.

Figure 6-9 compares the modelled flow from the 135 stochastic realisations against the observed flow data for gauges 233275A (upstream of the swamp) and 233276A (downstream). These are generally of similar quality to those of the minimum error variance ("base") model reported in Section 4.4.4. However, for the downstream gauge 233276A, the period of low to no flow between January and April 2020 is slightly overestimated by many of the stochastic models, with more persistent flows than those observed. Although it may be tempting to eliminate these realisations from the ensemble, this could be detrimental to the comprehensiveness of the uncertainty analysis. A better approach, but one requiring more project time than is available, would be to investigate structural model issues that may be contributing to this effect, particularly in the GR4J model that generally overestimates flows, including at the upstream gauge, in the preceding period. It may be beneficial to conduct such assessment once a longer period of flow and swamp groundwater level data become available to make it a worthwhile exercise.

Figure 6-7 Calibration statistics of uncertainty realisations



Model / Statistic of 135 realisations:	Number of Observations:	Sum of Squared Residuals:	Root Mean Square (RMS) Residual (m):	Normalised RMS (nRMS) residual:	Mean Absolute Residual (m):
Base realisation:	7339	322	0.21	3.1%	0.16
Minimum:	7339	327	0.21	3.1%	0.17
Mean:	7339	1220	0.40	5.9%	0.31
Maximum:	7339	2022	0.52	7.7%	0.42

Figure 6-8 Example calibration hydrographs from 135 model realisations

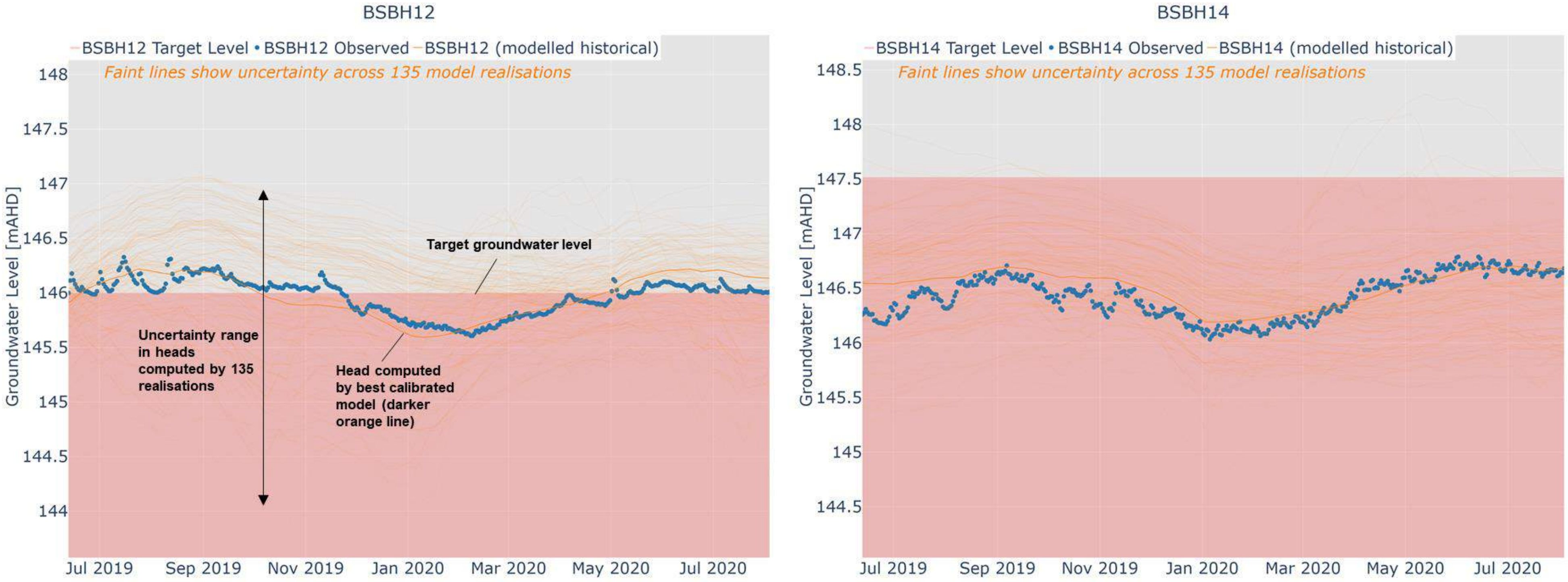
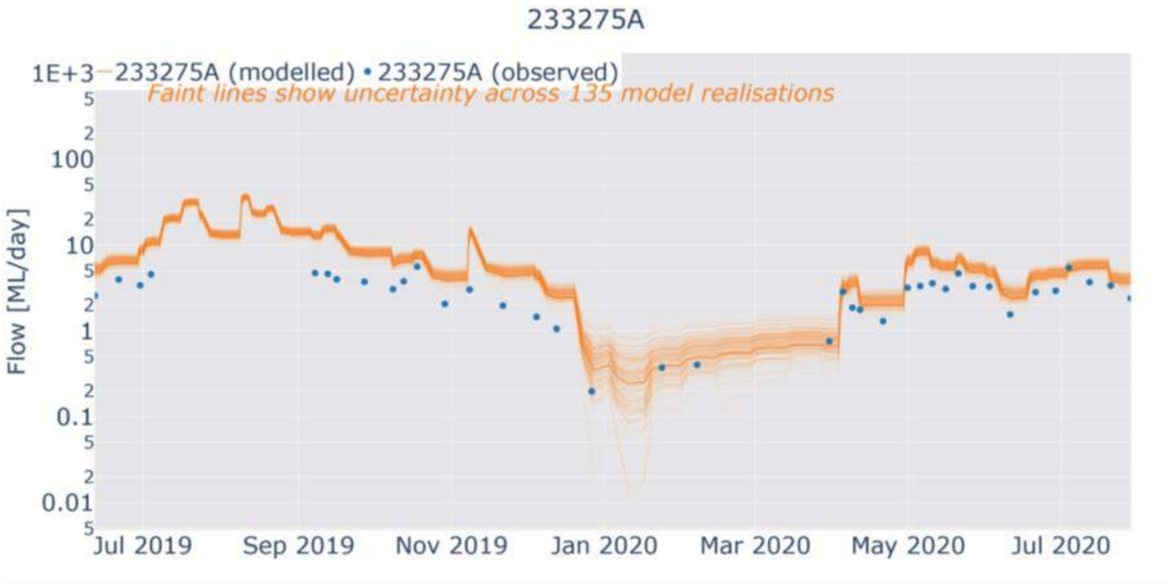
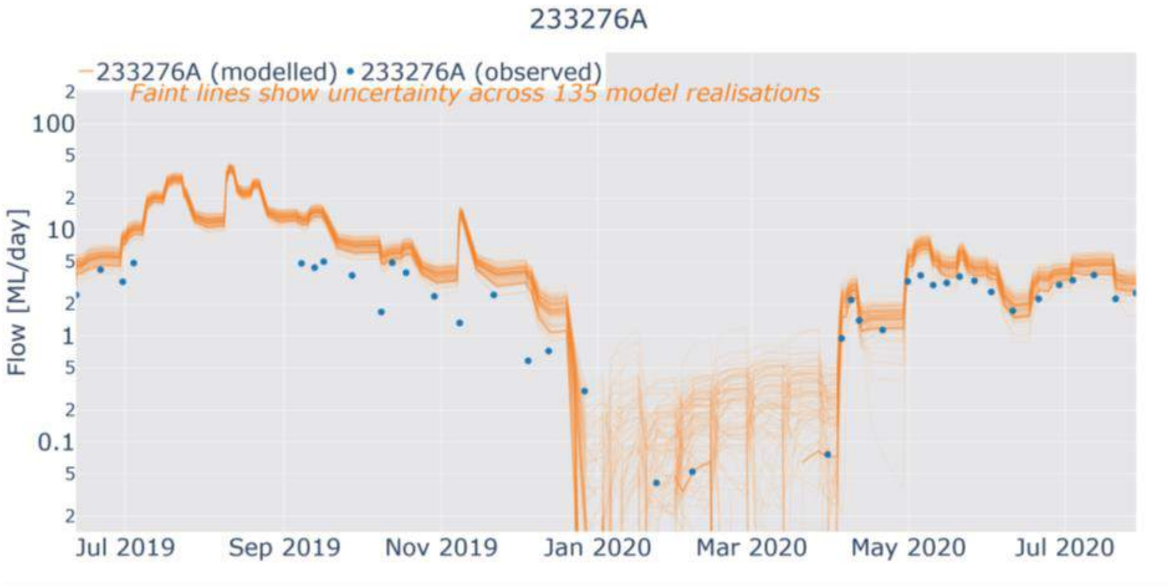


Figure 6-9 Stochastic history match for flow observations





6.2.4 Model uncertainty analysis outcomes

The 135 history-matched model parameter set realisations were used to batch run the historical and forecast models, and to process key outcomes relating to potential swamp remedial effectiveness, relative to historical conditions. This has been undertaken using the code PESTPP-sweep (PEST++ Development Team, 2020).

Uncertainty of groundwater levels at bores

Figure 6-10 and Figure 6-11 present example water table hydrographs, including model uncertainty, at selected observation (and remedial target level) bores. Each chart shows the modelled historical groundwater level (in blue), and the modelled forecast water level under the modelled remedial scenario (in orange, with the thick line representing the "base" model realisation, and faint lines representing uncertainty across the 135 history-matched model realisations). These modelled hydrographs are compared with each bore's remedial target level (as a pale red band).

Figure 6-10 shows that at bores BSBH14 and BSBH15 there is very little model uncertainty; this is the result of local inundation (by the remedial design) controlling the water table as it equilibrates with the pond level. In both cases, the remedial target level is met across all 135 model realisations. This means where the bores (or adjacent areas) are fully inundated, there is low model uncertainty since the water table is controlled by the ponding (inundation) level irrespective of parameter uncertainty. This also means that understanding the nature of interaction with the underlying LTA may not be as critical in some places as long as ponding can be maintained to control the water table.

In contrast, Figure 6-11 shows the same information but for bores BSBH08 and BSBH12, which exhibit a more visible uncertainty range. In both cases, the target level is met for most of the time across most model realisations but not all, with the modelled level falling below the target level for some periods in some realisations. In general, these are by relatively small amounts and for limited time, indicating a low likelihood of occurrence.

Similar results are presented for all observation bores in Appendix D. These plots indicate that the target level can be met with the simulated remedial system for most bores, for most of the time, over most of the 135 model realisations. Exceptions are:

- BSBH04: some model realisations suggest the target level may be slightly exceeded during dry periods, although the model tends to underestimate the observed dry period groundwater levels at this bore (see Appendix D).
- BSBH08: some model realisations suggest that the target level may be slightly exceeded most of the time, although the vast majority of the realisations show a significant persistent increase in the simulated groundwater levels at this bore under the remedial scenario.
- BSBH12: some model realisations suggest the target level may be slightly exceed, although during the critical dry period all realisations simulate groundwater levels above the target level.
- BSBH18: most model realisations suggest that the simulated remedial measures are insufficient to persistently meet the desired target level. However, the uncertainty analysis does show that the uncertainty range of groundwater levels at this bore is much reduced compared with the historical conditions (compare BSBH18 charts between Appendix C and Appendix D). The same charts also indicate that the simulated remedial measures are likely to achieve a persistent rise in groundwater levels at this bore in the order of 0.3 to 0.5 m.

For bore BSBH06, whilst the model indicates that the remedial target level is likely to be met, it should be noted that the calibrated model overestimates groundwater levels generally, but particularly during dry periods at this bore. This also appears to be the case across the majority of 135 model realisations, although there are a few realisations that better simulate the dry period groundwater levels. Despite this, given that the model error during the dry period is in the order of 0.5 m at this bore, and the remedial systems across 135 realisations consistently achieves an increase of greater than this amount, the remedial target is still likely to be met (but possibly not by as large a margin as that shown in Figure 5-9). In practice, the effectiveness of the remedial system would need to be verified at bore BSBH06, which may identify the need for some adjustments.

Uncertainty of groundwater levels across Big Swamp

Figure 6-12 and Figure 6-13 present maps showing the lower and upper bound uncertainty estimates of depth to groundwater, both for the historical conditions (left side) and remedial conditions (right side). These lower and upper uncertainty estimates are taken as the lower 5th and upper 95th percentile (on a cell-by-cell basis) across the 135 model realisations.

The upper end estimate in Figure 6-13 represents a more conservative view of the potential remedial effectiveness, with lesser area affected by the remedial inundation shown on the right-hand side. However, even under this conservative case, the depth to water is maintained at significantly shallower levels over much broader areas of the swamp compared to the historical conditions (left hand side), irrespective of the prevailing (dry, typical, or wet) climatic conditions. This is particularly the case in the upstream (western) end of the swamp (around BH11 through BH18), where the remediation system has been designed to encourage ponding.

Under the more optimistic (lower uncertainty estimate) case presented in Figure 6-12, the remediation system is shown to result in a more widespread shallow water table, as shown in the plots on the right-hand side of this figure.

Figure 6-14 presents maps of model uncertainty in the simulated effect on depth to water variability, which can be used as a proxy measure of acid generating potential, and for illustrating the general effectiveness of the remediation system on maintaining moist conditions across the swamp. The figure better illustrates the incremental effect of the remediation system than Figure 6-12 and Figure 6-13. This is most clearly demonstrated by the broad areas of blue colour that are persistent in all six plots (across different climatic conditions and parameter uncertainty range), which correspond to areas where the water table has been increased by the remediation system. This means there is high confidence that the remediation system would be effective across much of the critical areas of the swamp, where the system has been designed to achieve as much ponding as possible, as long as the ponds can be maintained (as currently simulated by the TUFLOW model). It also shows that the upper uncertainty (conservative) estimate of the potential incremental lowering of the water table during the critical dry period is generally <0.5 m, with only localised areas where larger declines may be possible.

Uncertainty in stream flow

Figure 6-15 presents the simulated flow hydrographs under historical and remedial cases, including uncertainty, for the two downstream gauges (233276A and 233228). The vast majority of the 135 stochastic model realisations meet or exceed the minimum flow target of 0.5 ML/d at gauge 233228, with more persistent flow during the dry period maintained by the supplementary flow of 4.4 ML/d.

It should be noted that some realisations of the model do not meet the 0.5 ML/d flow target at all times, highlighting a small but nonetheless identifiable risk. This level of uncertainty should be considered in conjunction with the flow splits that could be optimised to allow more flow down Boundary Creek as required to maintain the flow.

Figure 6-10 Example of predicted hydrographs – low uncertainty range in constant ponded areas

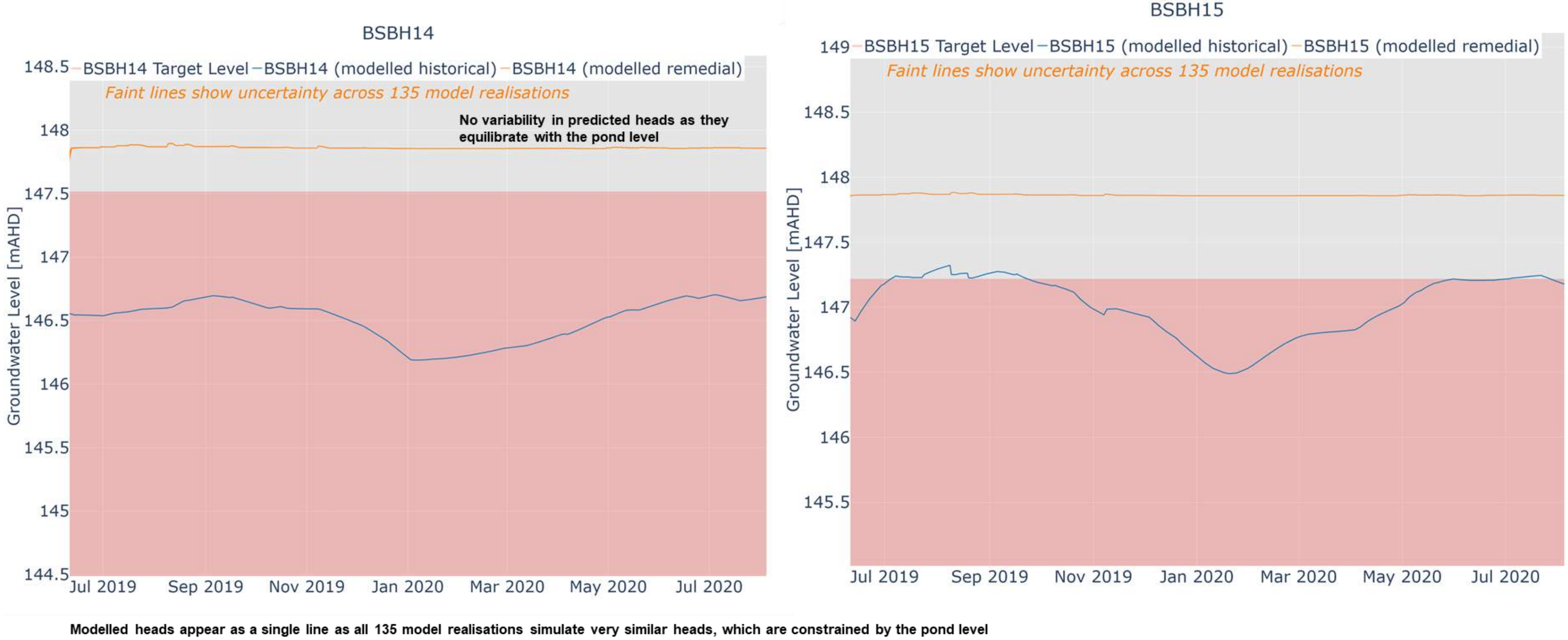


Figure 6-11 Example of predicted hydrographs – higher uncertainty range in variably ponded areas

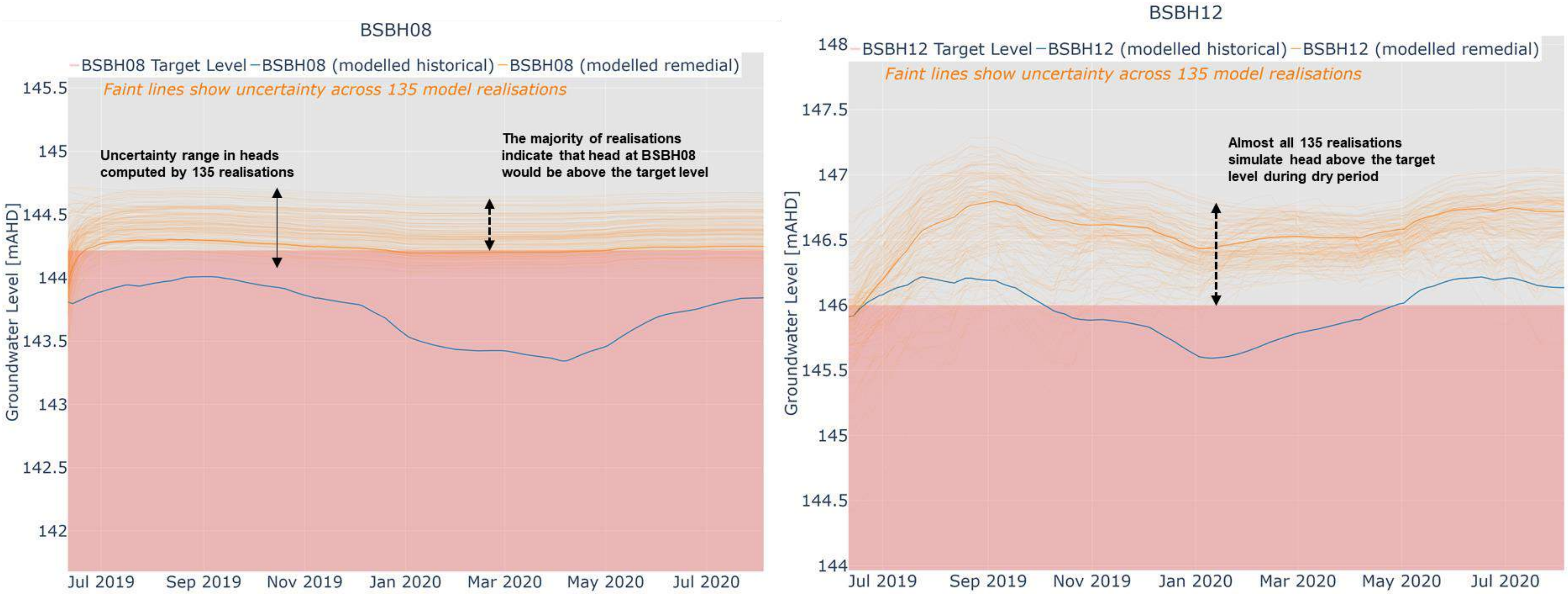


Figure 6-12 Lower uncertainty estimate of modelled seasonal depth to groundwater variability and remedial effect

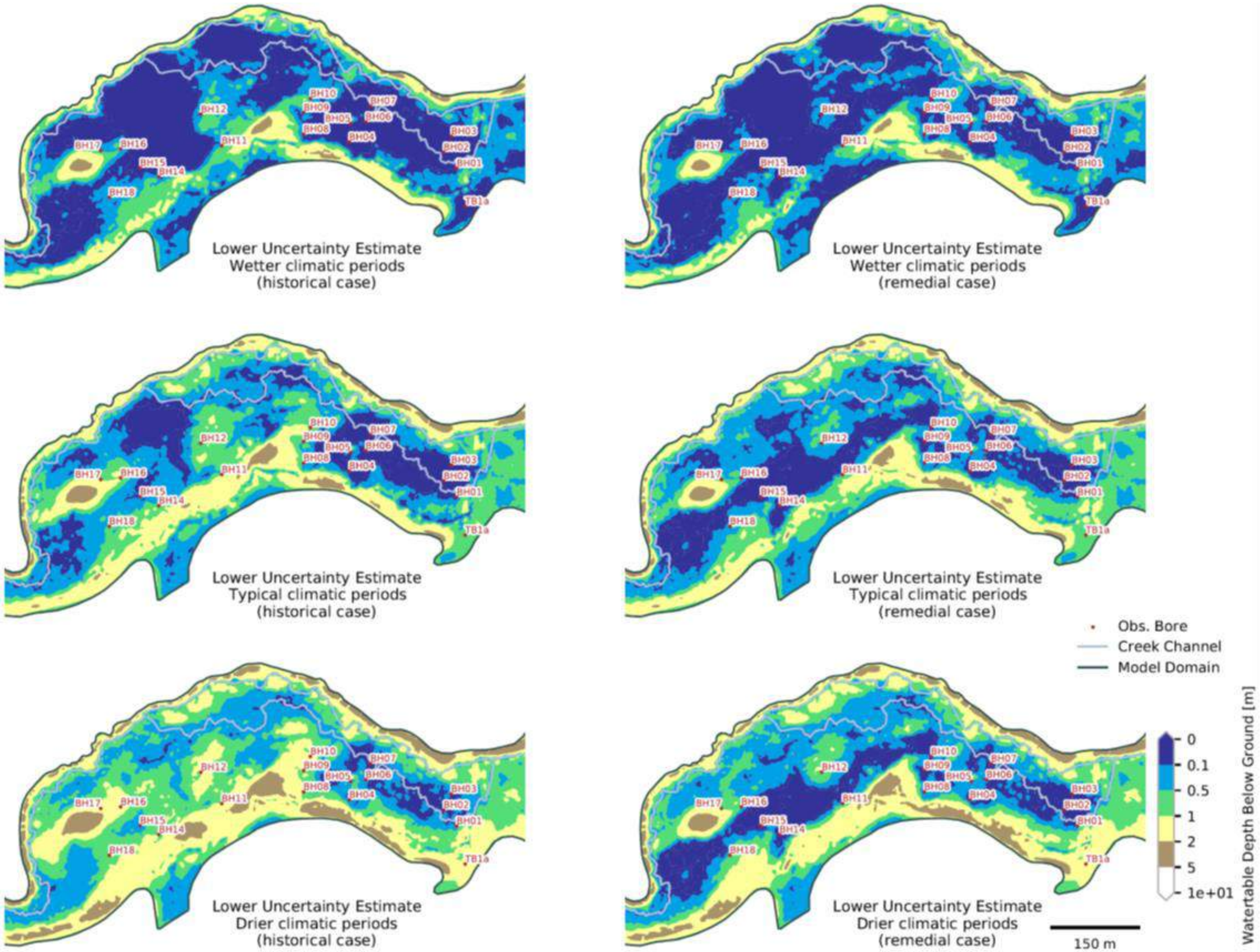


Figure 6-13 Upper uncertainty estimate of modelled seasonal depth to groundwater variability and remedial effect

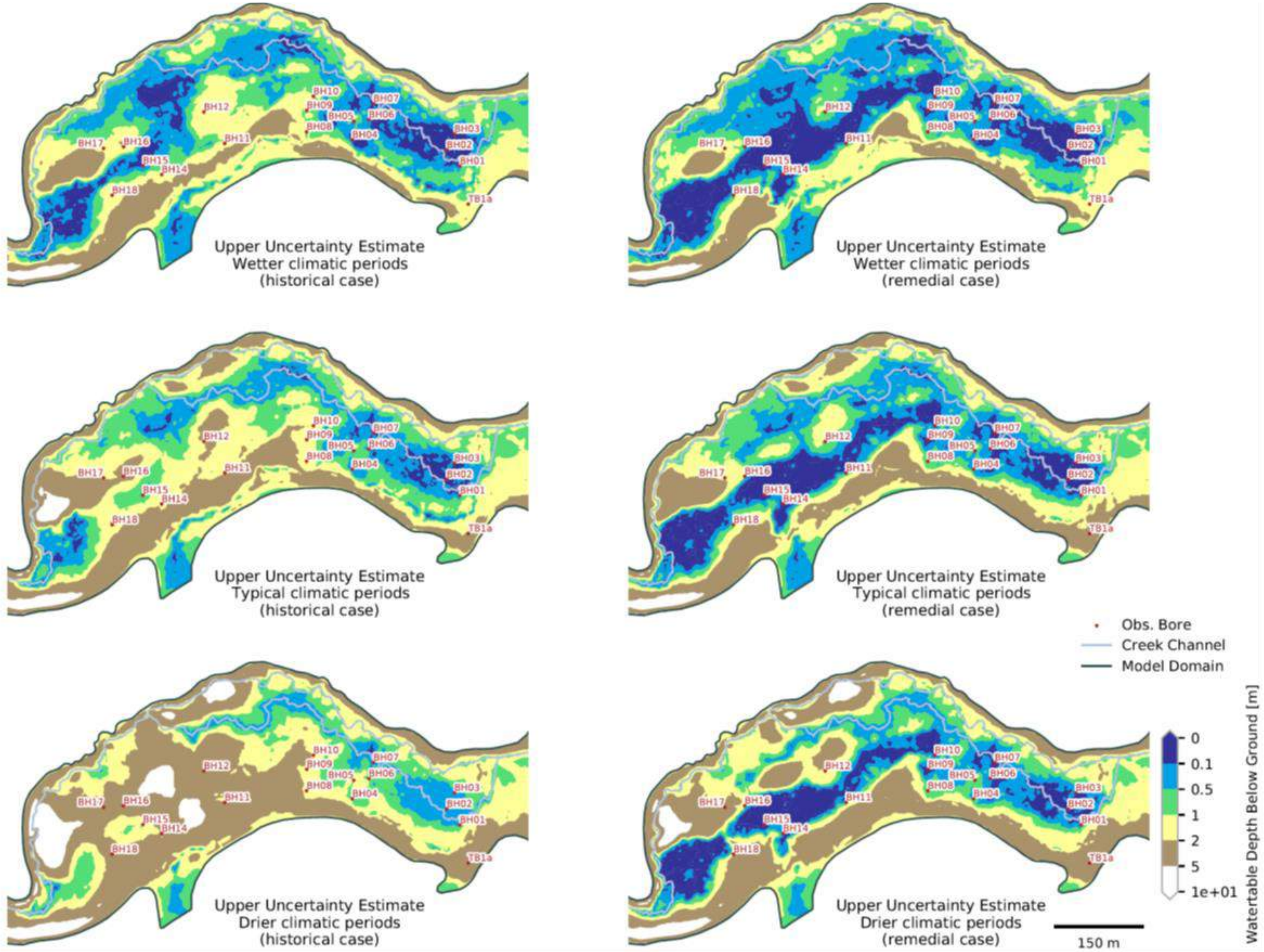


Figure 6-14 Uncertainty in remedial effectiveness on depth to groundwater variability

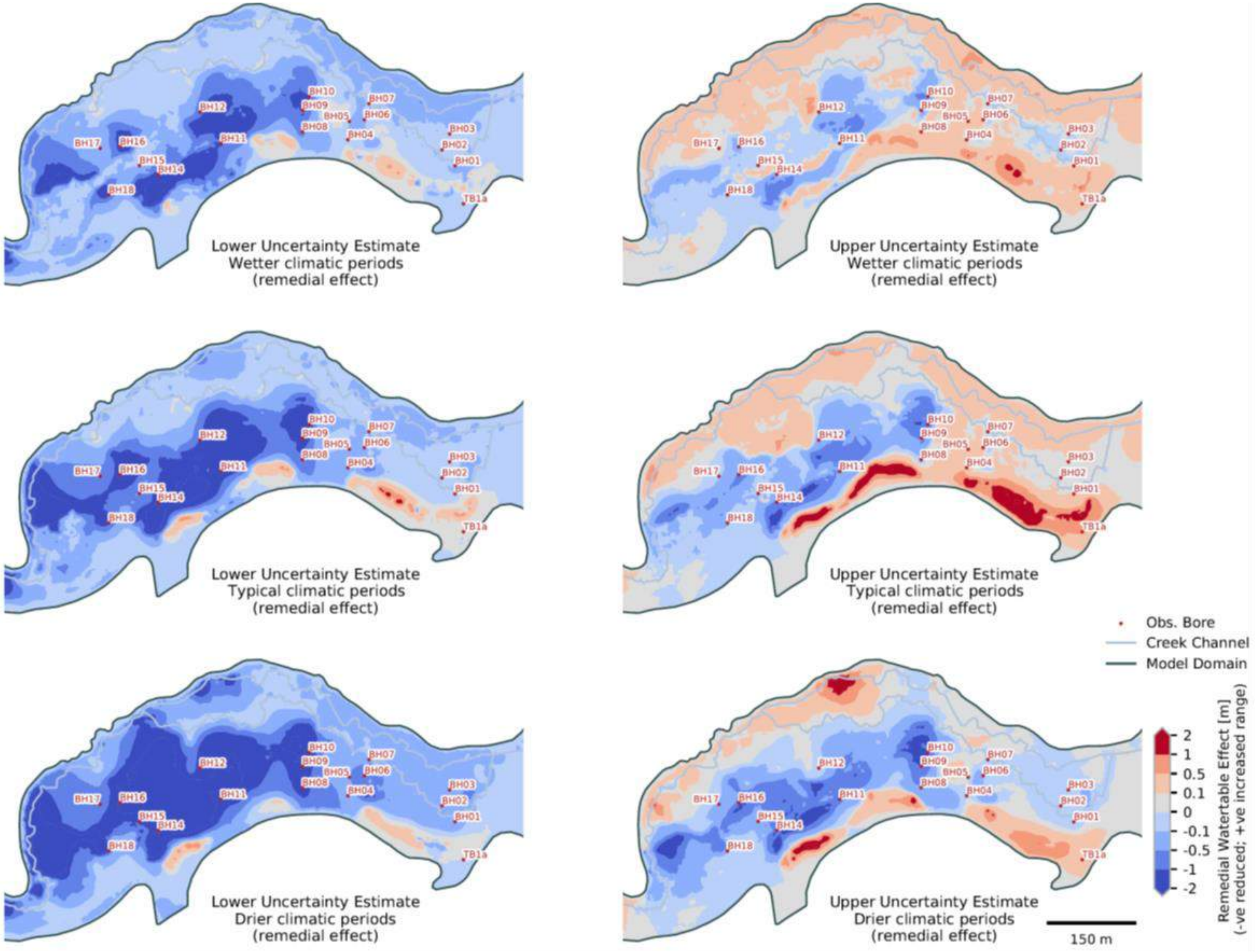
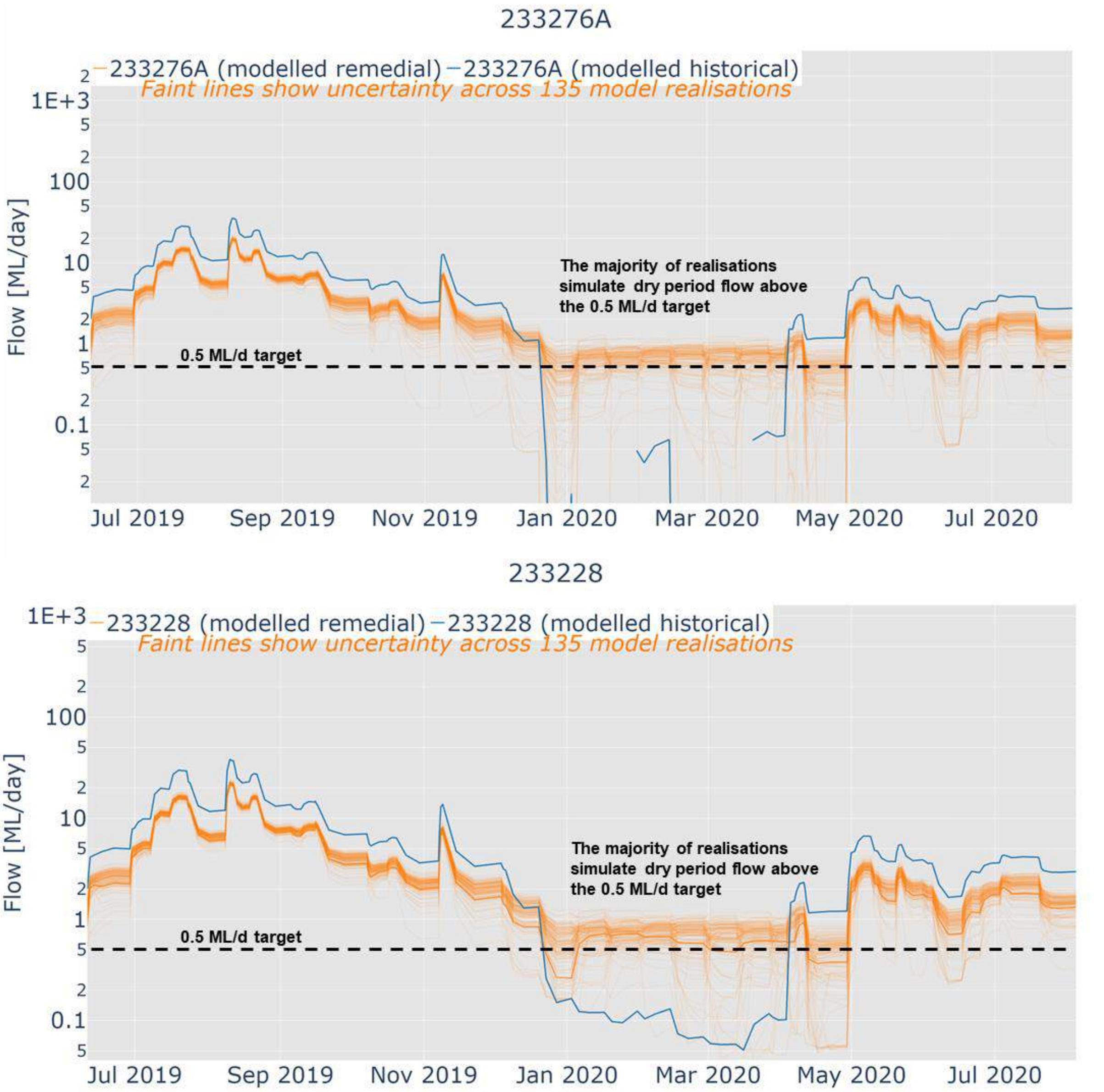


Figure 6-15 Predicted flow hydrograph uncertainty



7. Conclusions

7.1 Summary of key findings

Integrated modelling of surface water and groundwater systems of Boundary Creek and Big Swamp has been undertaken by loosely coupling GR4J, TUFLOW and USG-Transport models. The models have been rigorously calibrated to monitoring data collected over a period of 14 months, which included measurements of groundwater levels in 18 monitoring bores and stage and flow data at key stream gauges. The calibrated models have been used to examine the effectiveness of different hydraulic barrier configurations and supplementary flow regimes in maintaining the groundwater levels in Big Swamp and flow in Boundary Creek downstream. The uncertainty in the effectiveness of the remedial strategy has been quantified through sensitivity analysis and non-linear uncertainty analysis.

The integrated modelling indicates the following:

- The water balance of the Big Swamp aquifer system is dominated by inflow from overland flow (flood inundation) as well as stream flow along Boundary Creek and outflow (downward leakage) into the underlying regional aquifer. This means the accuracy of ponded areas and depths derived from the TUFLOW model is important for simulating the water table response during wet periods. The inflow (infiltration) from ponded areas is largest in the upstream area of the swamp, where the water table is deeper. In the downstream area, the water table is shallower and the aquifer becomes fully saturated frequently, acting as the point of discharge for groundwater from further upstream.
- During dry periods, evapotranspiration becomes an important groundwater discharge mechanism. In upstream bores, a distinctive rising groundwater level trend is observed in the middle of the dry period when there is negligible overland flow and recharge. The model calibration indicates that this is due to upflow from the underlying regional aquifer, which occurs when the water table falls to a critical level and results in a temporary reversal in vertical hydraulic gradient that initiates upward leakage.
- The preferred hydraulic barrier configuration comprises of 7 barriers and these are likely to be very effective in maintaining inundation in critical areas within Big Swamp, which results in near-constant groundwater levels at or above the target levels at the majority of bores. The exception is at BSBH18, where the groundwater level may remain around 0.3 m lower than the target level. As this bore is located on higher ground, there are likely to be practical limitations on how much flow can be forced upgradient without compromising the performance of the barrier system at bores further downstream.
- Sufficient inundation and ponding could be maintained under the existing flow regime with a supplementary flow of 2 ML/d during dry periods. However, this is unlikely to meet the minimum flow of 0.5 ML/d required downstream of Big Swamp due to stream loss/leakage to the underlying aquifer. The amount of supplementary flow needed to maintain the required minimum flow depends on the proportion of stream flow diverted towards the swamp to maintain inundation. At 50:50 flow split/diversion, the modelling indicates that almost all of the 500 ML supplementary flow would be required to maintain flow at 0.5 ML/d or more downstream of the swamp most of the time (around 90% of the 14-month simulation period). However, at the maximum supplementary flow rate, the modelling suggests that inundation could be maintained with a flow split as low as 80:20. The implication is that there is an opportunity to optimise the flow split to enable more flow to be passed down Boundary Creek, potentially achieving the 0.5 ML/d minimum flow with lower supplementary flow rates.

- Barriers 1 and 5, located in the upstream end of Big Swamp, should be constructed as weirs that allow some level of control over their width, for example by using stop logs that can be added or removed. This will allow some flexibility in the future for optimising the usage of supplementary flow to maintain both the ponded areas and flow downstream of the swamp. For example, in the event that the future climate is drier than that experienced over the past 14 months or that the infiltration losses are greater than those modelled, then the flow split can be adjusted to keep the ponds topped up.
- The supplementary flow is also likely to be important in preventing the water table in the northern part of the swamp from declining during drier periods. The modelling indicates that under a typical climatic condition, the diversion of flow from Boundary Creek has the potential to slightly lower the water table by <0.5 m along and in the vicinity of Boundary Creek. During drier periods, however, supplementary flow and associated leakage into the underlying aquifer has the potential to prevent further lowering of the water table (i.e. not make the condition any worse than it currently is), possibly resulting in some increase in the downstream area. This may be important for managing acidification in the northern area of the swamp, where there is currently limited information on its acid generating potential.
- The fire trench currently forms a local low point, where surface water ponds and acts as a localised source of recharge. When the fire trench is filled in the future, this localised source of recharge would no longer be present, resulting in a possible lowering of the water table by 0.5 to 1 m. This may be important, depending on the acid generating potential of swamp sediments in this area.
- Although the method of handling infiltration in the TUFLOW and USG-Transport model is different, this is unlikely to have a material effect on the key findings of the modelling. The sensitivity analysis indicates that if infiltration rates were higher than that assumed in the calibrated TUFLOW model, then there is a risk that the pond generated adjacent to the barrier furthest downstream would go dry under dry climatic conditions. However, this could be mitigated by allowing small volumes of additional flow diverted to the swamp to keep the ponds topped up, which can be achieved by adjusting the flow split or increasing the supplementary flow (which would be required for maintaining the 0.5 ML/d flow anyway).
- The sensitivity analysis indicates that the accuracy of the terrain data is very important in simulating the flooded areas and extents and, by extension, the hydraulic barrier configurations required to maintain desired ponding. If the actual topography differs from that represented in the existing terrain data, then the shape and location of hydraulic barriers may need to be modified to achieve the required pond size and depth to maintain the groundwater levels.

7.2 Confidence level classification

When a groundwater model is used to inform the outcome of a particular future scenario, the level of confidence in model’s outputs depends fundamentally on the data used to calibrate the model and their relevance to the hydrological processes of future scenarios. It follows that a model that is required to predict response to hydrological stresses that are similar to those of the past and for a period of time similar to the period of historical observations would have high confidence in its predictions, provided that the model has been adequately calibrated and the results of the model are mathematically sound. This forms the basis of the confidence level classification in the Australian Groundwater Modelling Guidelines (Barnett et al, 2012).

In the context of the Big Swamp integrated modelling, the future stresses associated with the construction of hydraulic barriers are primarily related to the changed extents, duration and depths of inundation. This means the future stresses are similar to those of the past (associated with the same hydrological processes), albeit slightly larger due to the greater ponding depths introduced in certain areas over a longer duration. The period of predictive modelling chosen for this project is also the same as the period of calibration. In this sense, the USG-Transport model developed for the purpose of informing the proposed remediation strategy can be said to satisfy, at least partially, some of the key criteria for the highest (Class 3) confidence level classification of the Australian Groundwater Modelling Guidelines (see Figure 7-1).

While the magnitude of stress and period of predictive simulation are not excessive compared to those of the past, recognised data gaps and model limitations outlined in Section 7.3.2 mean the USG-Transport model would be considered generally a Class 2 model with some attributes of Class 3.

It is important to note that moderate to high confidence in the USG-Transport model outputs relates specifically to their intended use, which is to assess the effectiveness of different hydraulic barrier configurations and supplementary flow regimes on meeting the groundwater level and flow targets. If the future use of the USG-Transport model is extended to include longer simulation periods or climatic conditions that are very different to those of the period of historical observations, then the level of confidence associated with the model outputs would need to be revised accordingly. This would also be the case if the USG-Transport model is used for purposes other than its intended primary use (for example, to examine the effects of changes in the LTA heads).

7.3 Model limitations

7.3.1 Surface water model limitations

The GR4J model has not been calibrated and validated against flow data from different time periods, which means it is currently not suitable for examining the effects of different or synthetic climate conditions. Further work would be required if the integrated modelling in this report is to be extended to examine different climatic conditions. The model also overestimates flow, with higher peaks and longer declining trends, although part of this is due to the absence of infiltration and evaporative losses which are subsequently accounted for by the TUFLOW model. Inaccuracies in the GR4J model outputs that could not be sufficiently reduced through calibration to existing data are passed onto the TUFLOW and USG-Transport models, although processes within these two models are able to compensate for such inaccuracies to some extent.

Hydraulic models such as TUFLOW are typically used on an even-basis, to examine flood extents and depths over relatively short periods of time. Running TUFLOW for the 14-month period has presented practical challenges, necessitating some simplifications in the model design to provide the outputs required for the USG-Transport model in a timely manner. These include coarser grid resolution and simple time-constant soil infiltration losses, with a sensible number of iterations with the USG-Transport model. Most of these design limitations have been assessed through sensitivity analysis and found to result in minimal effects on model outcomes. One critical limitation relates to the quality of terrain data, to which the TUFLOW model outputs is highly dependent. Due to the presence of dense vegetation in Big Swamp, obtaining reliable topography has been a challenge and this could affect the accuracy of the outputs generated by the TUFLOW model and the effectiveness of the recommended barrier configuration. This limitation should be taken into consideration as part of the detailed design of the remediation system.

7.3.2 Groundwater model limitations

Numerical groundwater models are a mathematical representation of complex real-world systems. The physical domain of interest, comprising layers of rocks and sediments, is discretised into a number of cells and the parameters that control the movement of groundwater through these layers is prescribed to each cell. The governing groundwater flow equations are solved by the code to compute hydraulic head and fluxes into and out of each cell. This mathematical representation of a natural physical system, using a finite number of cells, is a necessary simplification that is inherent in all numerical modelling, the degree of which is influenced by factors including the availability of data, scale of the model, intended model use and computational demand of modelling techniques.

The groundwater model described in this report is designed to simulate the key hydrogeological characteristics of a swamp that has a dimension of approximately 250 m by 800 m. Although it is not feasible to simulate individual discrete sand or clay lenses without adequate supporting information, the model has been designed to account for potential local scale variability in material properties through a rigorous calibration exercise utilising a large number of model parameters. The modelling also considered the effect of parameter uncertainty through a thorough non-linear uncertainty analysis, providing probabilistic indications of the effectiveness of the proposed remediation strategy in meeting the water level and flow targets. In order to provide this level of detail at a fine spatial scale, some simplifications of regional processes have been necessary. The quality of model calibration achieved and the results of predictive modelling indicate that this level of simplification has not limited the intended use of the model, which is to inform the detailed design of the remediation strategy and its effectiveness in meeting the water level and flow targets.

As with all models, the level of uncertainty is larger in parts of the model where observations are not available to constrain the model parameters or benchmark the performance of the model. In this study, a wide range of parameter values have been used in the non-linear uncertainty analysis to addresses this data gap. However, uncertainty remains in areas where data is currently absent or limited, such as the thickness of the QA, distribution of hydraulic heads in the LTA, the location of the MTD boundary and the natures of groundwater interaction between the QA and LTA. As additional data become available over time, the model can be periodically updated and the level of confidence in model’s outputs would increase accordingly.

An important limitation of the modelling and associated conclusions of this report is that the remedial scenario, and model history matching, are both based on observation data from a very limited period of time. As such, the data are only representative of limited climatic conditions, and the system may behave differently beyond those conditions experienced in the limited observation data set. This may have important implications for the effectiveness of the remedial system as modelled in this study. It is recommended that the models are further developed to simulate longer, more variable climate sequences than those modelled to date.

Figure 7-1 Confidence level classification assessment for USG-Transport model

Confidence level classification	Data	Comment	Calibration	Comment	Prediction	Comment
Class 3	• Spatial and temporal distribution of groundwater head observations adequately define groundwater behaviour, especially in areas of greatest interest and where outcomes are to be reported.	*Yes for shallow groundwater, which is the focus of this modelling (head data from 18 bores across Big Swamp used in calibration). There is limited data from the LTA to fully characterise the deeper system*	• Adequate validation* is demonstrated.	*No, as all data is fully utilised in calibration*	• Length of predictive model is not excessive compared to length of calibration period.	*Yes, as the predictive model uses the same 14-month calibration period to inform the barrier configuration and supplementary flow regime*
	• Spatial distribution of bore logs and associated stratigraphic interpretations clearly define aquifer geometry.	*Partially, bore logs from 18 bores but maximum QA thickness only verified at one location and lateral extents have not been confirmed*	• Scaled RMS error (refer Chapter 5) or other calibration statistics are acceptable.	*Yes, but limited to shallow groundwater (3.08% SRMS for all head observations)*	• Temporal discretisation used in the predictive model is consistent with the transient calibration.	*Yes, the same stress periods used*
	• Reliable metered groundwater extraction and injection data is available.	*No known groundwater extraction or injection in the model domain*	• Long-term trends are adequately replicated where these are important.	*Partially, as observations are only available for 14 months*	• Level and type of stresses included in the predictive model are within the range of those used in the transient calibration.	*Partially, while the magnitude of change in groundwater levels are similar, the level of ponding is greater and over longer duration in the predictive model*
	• Rainfall and evaporation data is available.	*Yes, rainfall from WMIS gauge*	• Seasonal fluctuations are adequately replicated where these are important.	*Yes, but only for the period of observations (14 months)*	• Model validation* suggests calibration is appropriate for locations and/or times outside the calibration model.	*No, all available observations have been fully utilised in calibration due to the limited length of monitoring. Post-calibration validation would need to be undertaken when additional data become available*
	• Aquifer-testing data to define key parameters.	*Partially, as data is limited to slug tests of low confidence*	• Transient calibration is current, i.e. uses recent data.	*Yes, up to August 2020*	• Steady-state predictions used when the model is calibrated in steady-state only.	
	• Streamflow and stage measurements are available with reliable baseflow estimates at a number of points.	*Yes, gauged stream flow and stage used in calibration*	• Model is calibrated to heads and fluxes.	*Yes, heads, stage and stream flow*		
	• Reliable land-use and soil-mapping data available.	*Partially, eco-hydrological zones*	• Observations of the key modelling outcomes dataset is used in calibration.	*All observation data used in calibration inform barrier configurations and supplementary flow*		
	• Reliable irrigation application data (where relevant) is available.	*No known irrigation in the model domain*				
	• Good quality and adequate spatial coverage of digital elevation model to define ground surface elevation.	*Yes, DEM processed from LIDAR, surveyed bore and flow gauge elevations*				

This table assesses the USG-Transport model against the key indicators of Class 3 confidence level in the context of its intended use, which is to assess whether the hydraulic barriers and supplementary flow could be effective in meeting the groundwater level and stream flow targets. For this purpose, the predictive model utilises the same length and climatic conditions of those of the calibrated model. While the model is considered fit for this purpose, satisfying some of the key indicators of Class 3 confidence level, there are recognised limitations with the model due to gaps in data which are also identified in the table above. This means the model may be classified as Class 2, with some attributes of Class 3. If the USG-Transport model is used to predict potential outcomes of the future, using longer simulation periods and different climatic conditions, or for purposes other than its intended primary use, then the confidence level classification would be revised accordingly.

8. Recommendations

This section provides a number of recommendations that may assist in further improving the performance of the integrated models and the effectiveness of the proposed remediation strategy:

- There is currently limited lithological data to inform the geometry of the QA, with only one nested drilling site in the downstream area of Big Swamp. In particular, the boundary of the MTD and the top of the underlying LTA are currently not well understood. Given the influence of LTA fluxes on the dry period water levels in the upstream area of the swamp, further drilling works to improve the knowledge of the QA thickness and its contact with the underlying geology is considered beneficial.
- Similarly, installing nested monitoring bores in the QA and the underlying LTA at several locations within Big Swamp would assist in improving the understanding of vertical interactions between these two aquifers and how they very spatially and over time. For example, deeper monitoring bores could be constructed in the LTA near some of the existing bores in the QA to form nested sites. Depending on the thickness of the QA, it may also be beneficial to place additional bores near the base of the QA to understand the vertical gradient within the QA and how the hydraulic heads vary across the interface between the QA and LTA.
- There are currently no monitoring bores in the northern area of Big Swamp, near Boundary Creek, and along the southern boundary near the fire trench where the modelling has identified potential lowering of the water table due to redistribution of flow. Additional shallow bores in these areas, if accessible, would assist in model calibration and any risks associated with activation of acid sulfate soils.
- The potential rate of infiltration of surface water could be further constrained, for example, by undertaking infiltration tests using a double ring infiltrometer.
- The modelling presented in this report has been limited to the climatic condition of the 14-month monitoring period. Further testing of the proposed remediation strategy under different climatic conditions (for example, successive dry years) would assist in understanding its sensitivity to future climate. Similarly, the modelling has assumed time-constant LTA heads. Over much longer timeframe, the LTA heads are expected to change slowly depending on the rate of recovery from pumping and the influence of future climate. Further sensitivity analysis of different LTA heads is recommended, for example by incrementally shifting the LTA heads in the SGB cells.
- Additional hydraulic assessments should be completed if the actual topography is found to be significantly different from what is currently indicated in the terrain data, to ensure that the preferred barrier configuration is able to achieve its intended purpose. For example, if there are any low points that are currently not known, then water could bypass the barriers and let flow through before desired levels of ponding could be achieved.
- The findings of integrated modelling detailed in this report should be reviewed in conjunction with the available hydrogeochemical data of Big Swamp to assess potential groundwater and surface water quality changes that may result from the proposed remediation strategy.

9. References

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