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Tuckean Swamp Hydrologic Options Study

WRL TR 2019/21 | October 2020

By D S Rayner, A J Harrison and W C Glamore

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Project details

Report title	Tuckean Swamp Hydrologic Options Study
Authors(s)	D S Rayner, A J Harrison and W C Glamore
Report no.	2019/21
Report status	Final
Date of issue	October 2020
WRL project no.	2014129
Project manager	D S Rayner
Client	OzFish Unlimited
Client address	
Client contact	Cassie Price cassieprice@ozfish.org.au
Client reference	

Document status

Version	Reviewed by	Approved by	Date issued
Draft	W C Glamore	D S Rayner	5 September 2019
Final Draft	G P Smith	G P Smith	15 January 2020
Final	G P Smith	G P Smith	26 October 2020

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Executive summary

ES.1 Background

Tuckean Swamp is a 6,000 hectare low-lying floodplain located on the Richmond River, approximately 25 km upstream of Ballina, shown in Figure ES-1. Since the 1880's extensive drainage works have occurred at Tuckean Swamp to allow the rapid discharge of floodwaters from the naturally low-lying floodplain. In 1971, the major drainage works as it exists today was completed with the installation of the Bagotville Barrage. The barrage comprises eight large culverts with one-way floodgate flaps to enable drainage from the Tuckean floodplain, whilst excluding downstream tidal waters and backwater flooding from the Richmond River. These floodgates also act to promote the lowering of groundwater levels across the connected upstream floodplain. The artificial drainage system, including the Bagotville Barrage, have facilitated agricultural development of this land, which is mostly used for grazing and sugar cane. Approximately 550 ha of the lowest lying area on the floodplain is owned and managed by National Parks and Wildlife Services (NPWS), referred to as the Tuckean Nature Reserve (TNR), indicated on Figure ES-1.

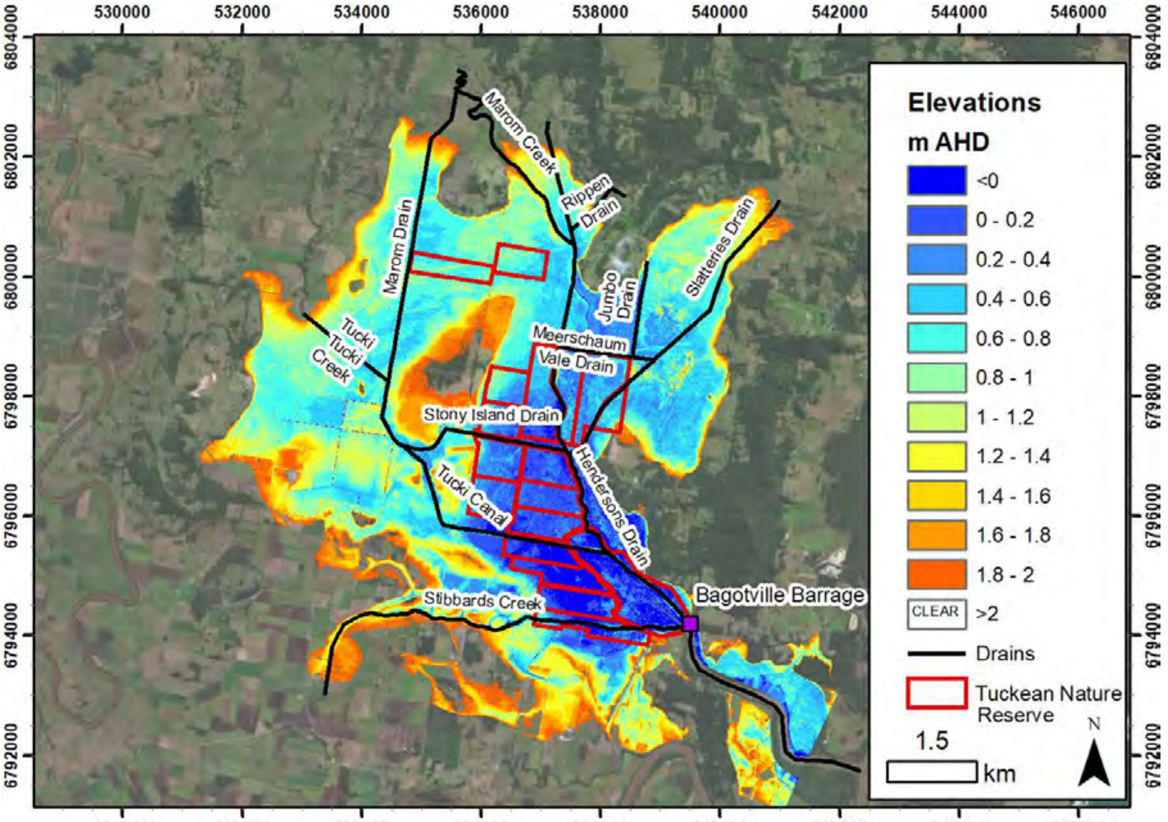

Figure ES-1: The Tuckean floodplain

The extensive man-made drainage network has also had unintended environmental impacts, including the production of acidic discharge from the drainage of acid sulfate soils (ASS), as well as 'blackwater' (low-oxygen water) runoff into the broader estuary. The Tuckean floodplain has been identified as one of the worst acid sulfate soil affected areas in NSW. While some limited tidal flushing was introduced into the system in 2002 to improve surface water quality (through three (3) sluice gates in the barrage), few other strategies have been implemented that have resulted in long-term improvements in floodplain water quality. Subsequently, poor water quality from the Tuckean region continues to be an ongoing issue.

This study identifies the areas of the Tuckean floodplain that are having the greatest impact on water quality in the region, using extensive field data and a conceptual understanding of the site. Using this information, six (6) alternative drainage management options have been developed to address and mitigate some of the issues associated with ASS. The aim of this study is to investigate the feasibility and quantify the impact of each of these alternatives, not only in terms of water quality, but also the potential impact on floodplain inundation, drainage and saltwater intrusion.

An aim of this study is to improve the overall understanding of the hydrology of Tuckean Swamp and floodplain through extensive field data collection and numerical modelling. With a better understanding of how the site currently functions, different management options can be investigated targeted at decreasing acidic discharges from the site and improving overall water quality. While the environmental benefits are important, it is vital that any hydrologic impacts to the wider floodplain and adjacent landholders are equally considered.

The options investigated in this study were developed with input from the Tuckean Steering Committee, consisting of representation from OzFish, Rous County Council, Ballina Shire Council, Lismore City Council, Richmond Valley Council, National Parks and Wildlife Services, Department of Planning, Industry and Environment (formerly OEH), Local Land Services, Jali LALC, Department of Primary Industry – Fisheries and the Nature Conservancy. Funding has been provided by the Saltwater Recreational Fishing Trust Flagship Fish Habitat Action Plan. While not all possible drainage management options have been considered in detail, the drainage options investigated in this study are small-to-medium scale remediation strategies that aim to improve surface water quality by reducing acid drainage from the Tuckean floodplain, whilst quantifying potential hydrological impacts to adjacent landholders.

ES.2 Field data collection

Extensive field data collection campaigns were undertaken between March 2018 and February 2019. The data collection was targeted to filling information gaps identified in the existing literature. Data collected primarily related to:

- Water levels at strategic locations throughout the drainage network;
- Floodplain topography;
- Drain cross-sections (bathymetry);
- Size and elevation of major drainage structures; and
- Water quality.

Existing soil profile data was also examined to identify areas with high ASS occurrence throughout the floodplain. As a substantial amount of information on soil types and acidity already existed, minimal additional soils data was required to be collected during this study.

ES.3 Priority ASS areas

To guide the development of the management strategies, it is necessary to divide the floodplain into management sub-areas and to prioritise which areas should be targeted to improve overall floodplain water quality. This prioritisation specifically targets water quality and is not intended to be the only source of information used when considering the on-going management of the floodplain.

The Tuckean floodplain was divided into 10 major floodplain sub-sections representing major drainage areas. Based on the conceptual understanding of the floodplain drainage, topography and acid generation on the site, the sub-areas were ranked in order of priority for addressing ASS issues. The management sub-areas and prioritisation are shown in Figure ES-2. The highest priority areas around Meerschaum Vale and Slatteries Drains, and in the lower Tuckean Nature Reserve are broadly consistent with the priority areas identified by previous studies.

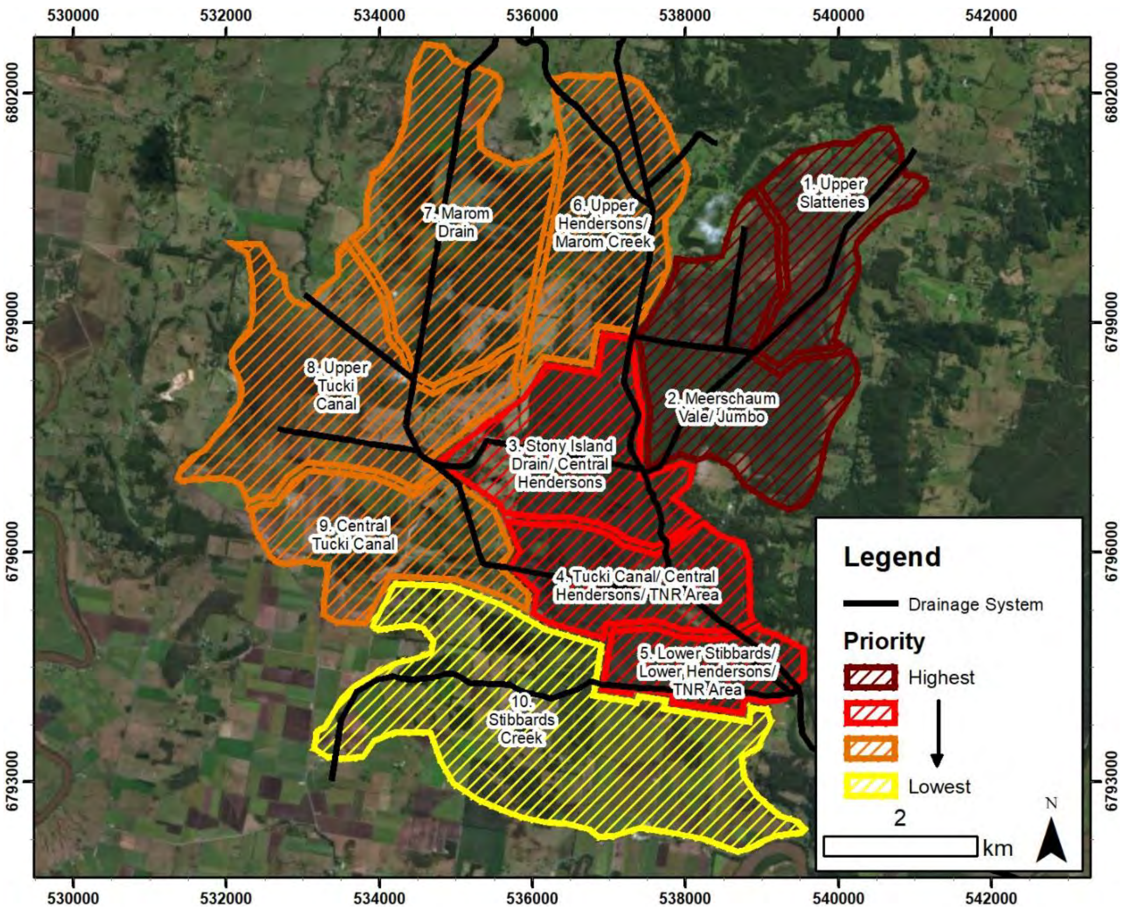

Figure ES-2: ASS prioritisation of the Tuckean floodplain

ES.4 Modelling summary

Based on the field data collected and other existing information, a detailed, dynamically linked 1-D/2-D hydrodynamic numerical model of the Tuckean Swamp floodplain was developed using the MIKE suite of models. The model was constructed to represent the floodplain as it exists today and collected data was input into the model and used to verify the model's ability to replicate the present (often referred to as the "Base Case") day to day conditions. Once the existing Base Case was verified, modifications were made within the model and used to test "what if" scenarios of different drainage management options (referred to as "modelling scenarios"). Using a numerical model allows for any number of management options to be tested to understand what impacts they might have during different hydrological conditions.

Based on the prioritisation of the floodplain, six (6) drainage management scenarios were chosen through discussion with the Tuckean Steering Committee. The management scenarios can be broadly divided into two (2) categories, summarised in Table ES-1. The freshwater management options target the highest priority areas around Meerschaum Vale and Slatteries Drains, while the saltwater management options focus on the high priority areas centred around the Tuckean Nature Reserve.

Table ES-1: Summary of model scenarios

Category	Model Description
Current	**Base Case** – the model was run to replicate existing floodplain hydrodynamics
Freshwater management options *Focus on the north-eastern (Slatteries) corner of the floodplain*	**Scenario 1** – Reshaping of major drains in the north-eastern corner of the floodplain (Slatteries, Meerschaum Vale and Jumbo Drains) **Scenario 2** – Weir implementation at the downstream end of Meerschaum Vale Drain **Scenario 5** – Reshaping of drains (as per Scenario 1), but encouraging small catchment flows onto the floodplain
Saltwater management options *Focus on the Bagotville Barrage management, targeting the Tuckean Nature Reserve*	**Scenario 3** – Alternative management of barrage sluice gates during dry periods **Scenario 4** – Hinging open the Bagotville Barrage **Scenario 6** – Hinging open the Bagotville Barrage, and installing structure upstream of the Tuckean Nature Reserve on all the major drains

The model results for each scenario were interrogated to understand not only the potential environmental benefits, but also the impact on surrounding landholders relating to:

- Floodplain inundation;
- Drainage times; and
- Saltwater intrusion.

ES.4.1 Scenario 1 – Reshaping Slatteries, Meerschaum Vale and Jumbo Drains

Description:

Scenario 1 investigates the impacts of reshaping, or ‘swaling’, major drains in the north-east section of the floodplain (see Figure ES-3). Raising drain invert levels while maintaining the effective drain cross-sectional area aims to reduce groundwater discharge while maintaining the drainage capacity of the existing system. Ideally, the invert would be raised above the ASS layer to effectively prevent advective acid transport. However, the ASS layer in this area is near the surface, so inverts of the drain have been raised within the model to a level that will reduce acid transport while still allowing sufficient gradient within the channels to maintain drainage. An example of a swaled drain cross section is shown in Figure ES-4.

Model Outcomes:

The results of the model indicated the following:

- Water levels increase by 20 – 30 cm within the drainage network during dry periods.
- Drainage is prolonged after rainfall events (Figure ES-4).
- Reduced diffusive and advective acid transport from the highest acid contributing area on the floodplain around Meerschaum Vale and Slatteries Drains.
- As the ASS layer is at or near the surface in this area, drains will still intersect ASS layers and some acid discharge will continue.
- Minimal changes to mean and maximum floodplain inundation over the five (5) month modelling period.

Implementation considerations:

In addition to the model results, the following implementation considerations have been identified:

- Swale drains require a larger footprint than the narrower, deeper drains that they replace, which would require agreement from landholders.
- Fill material may be required.
- ASS management plan would be required.

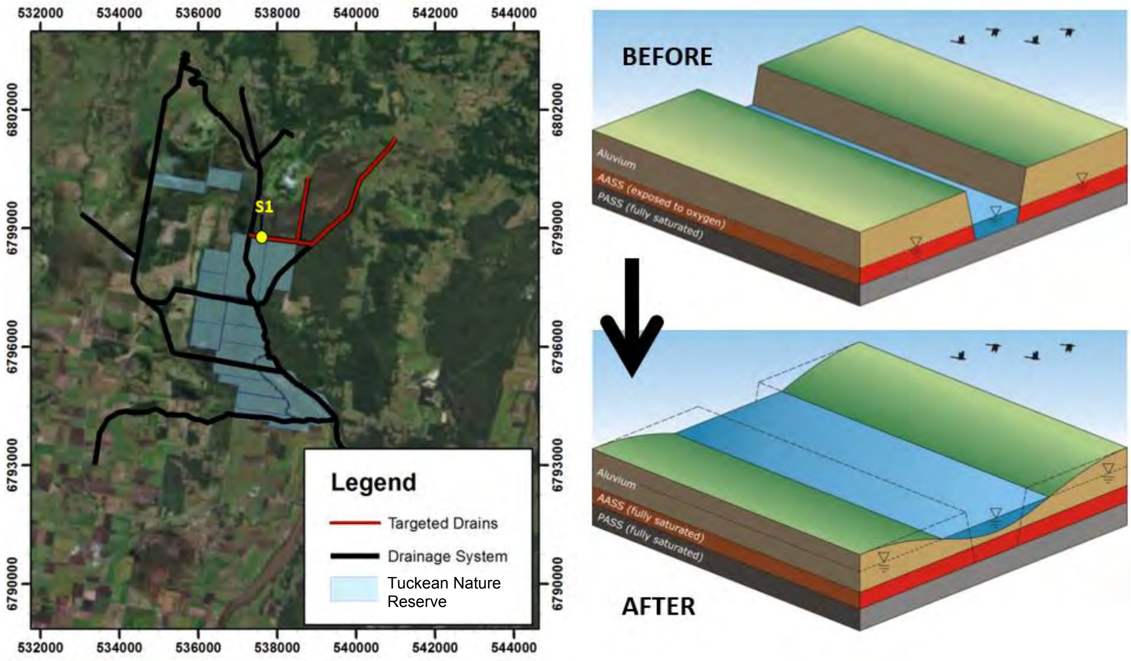

Figure ES-3: Left – Drains targeted for drain reshaping, Right – example of new profile sitting above the ASS layer after the drain reshaping (Water level extraction point S1 highlighted)

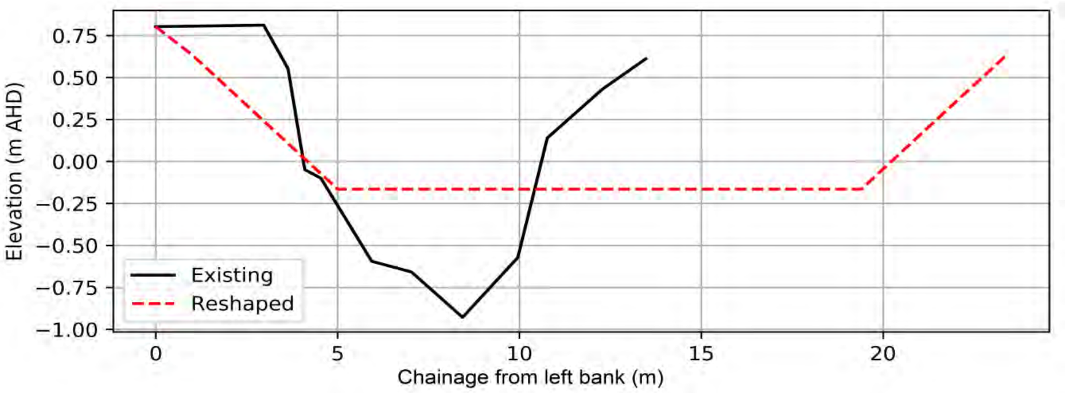

Figure ES-4: Example of reshaped drain cross section

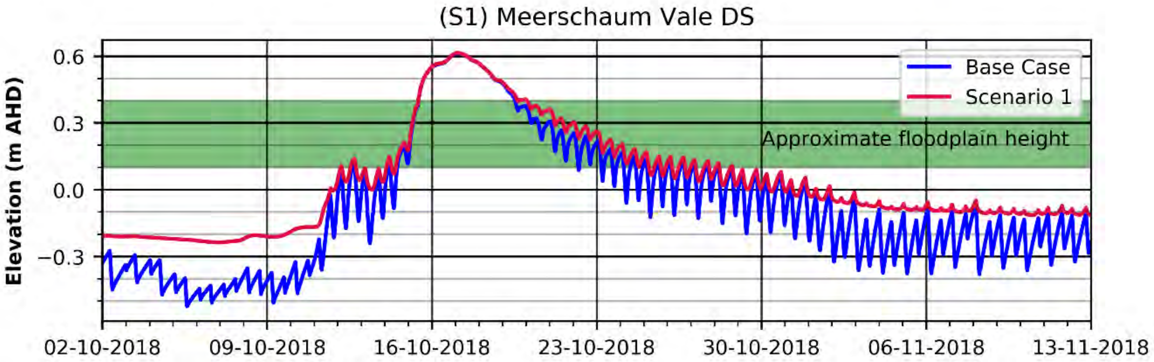

Figure ES-5: Water level changes in Meerschaum Vale Drain (location shown in Figure ES-3)

ES.4.2 Scenario 2 – Weir at Meerschaum Vale Drain

Description:

Scenario 2 investigates the impacts of the installation of a weir structure at the end of Meerschaum Vale Drain, as shown in Figure ES-6, with an invert level of 0 m AHD. Weirs promote higher surface water and groundwater elevations to reduce groundwater drawdown by minimising the hydraulic gradient between groundwater and drainage channels, resulting in reduced acid discharge. An invert of 0 m AHD was chosen to minimise impacts to surrounding landholders, while significantly increasing the water level control within Meerschaum Vale Drain, as shown in Figure ES-7.

Model outcomes:

The results of the model indicated the following:

- Increased water levels during dry periods and significantly prolonged drainage after rainfall events (Figure ES-8).
- Reduced advective acid transport from the highest acid contributing area on the floodplain.
- Diffusive acid transport will remain similar.
- ASS exist above 0 m AHD on the floodplain. This option will reduce acid transport, but not eliminate it.
- Minimal changes to mean and maximum floodplain inundation over the five (5) month modelling period.

Implementation considerations

In addition to the model results, the following implementation considerations have been identified:

- Weirs often result in stagnation of water behind the structure, leading to a potential build-up of weeds that need to be managed.
- A higher weir would further reduce acid transport but would have greater implications for local floodplain inundation and drainage times.

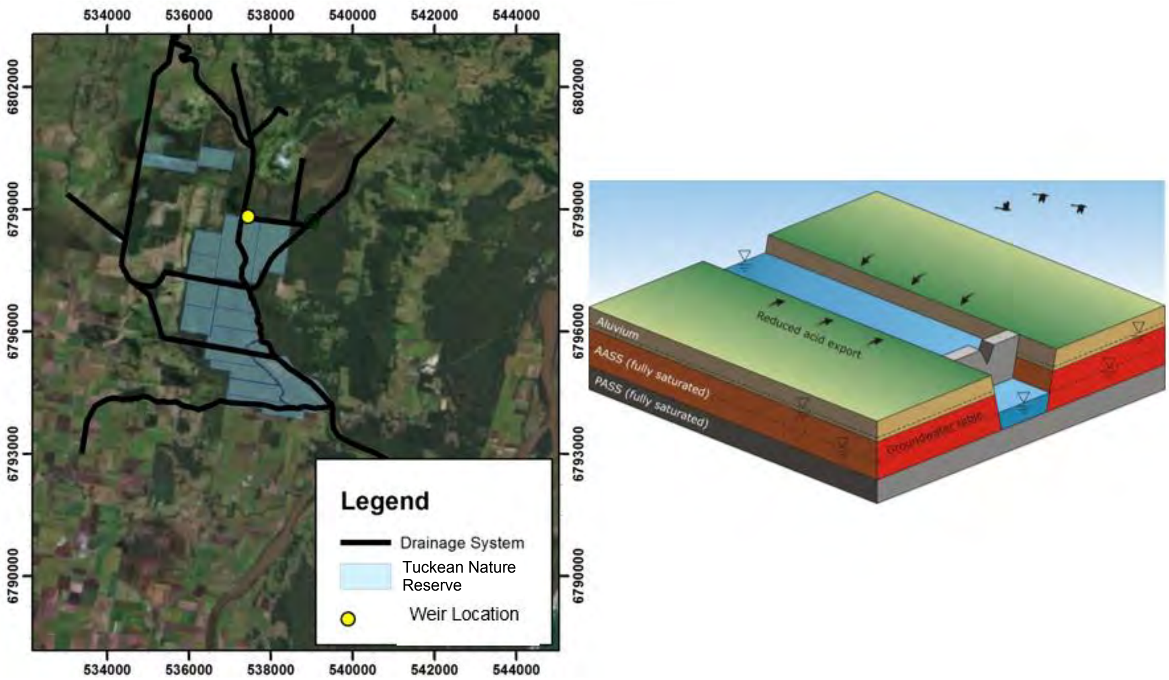

Figure ES-6: Left – Location of weir structure, Right - Reduced acid export as a result of a weir structure holding up water levels

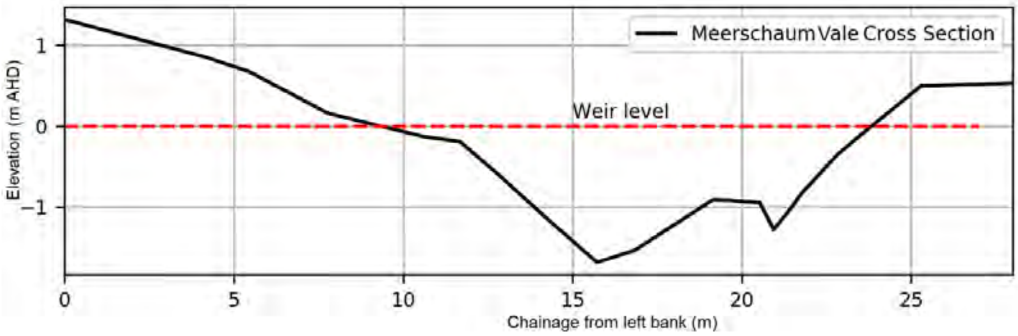

Figure ES-7: Weir level, compared to Meerschaum Vale Drain cross section

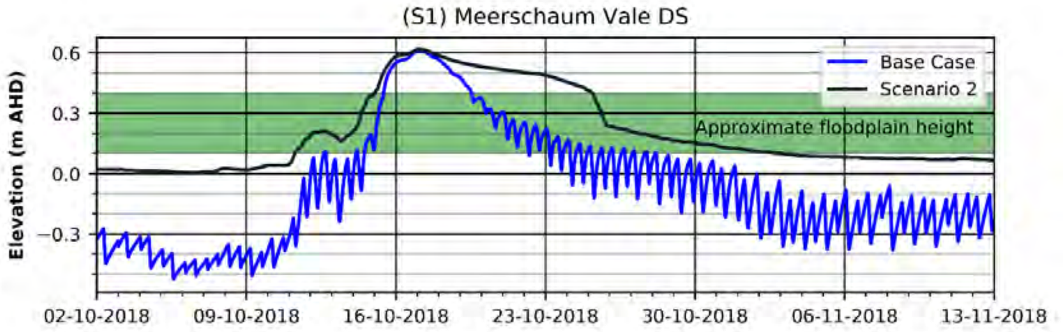

Figure ES-8: Water level changes at key locations (location shown in Figure ES-3, immediately upstream of weir)

ES.4.3 Scenario 3 – Existing sluice gate management

Description:

Three (3) 1 m x 1 m sluice gates were previously installed in 2003 on the three (3) northern Bagotville Barrage gates. Flows through the sluice gates allow controlled tidal inflows into Hendersons Drain, which increases salinity within the lower Tuckean Nature Reserve and promotes better flushing. The sluice gates are shut prior to catchment rainfall to maintain flood capacity.

The model was run for three (3) alternative sluice gate configurations (during dry periods only):

- **Scenario 3a:** One sluice gate open 150 mm;
- **Scenario 3b:** One sluice gate open 500 mm; and
- **Scenario 3c:** Two sluice gates open 500 mm.

Model Outcomes:

The results of the model indicated the following:

- Floodplain inundation under all three (3) configurations is largely contained within the Tuckean Nature Reserve boundary, except for a small area east of Hendersons Drain, shown in Figure ES-9.
- If the sluice gates are shut 24 hours before the onset of rainfall, there is no change to drain storage capacity.
- Salinity remains low (<5% of Tuckean Broadwater) at the confluence of Hendersons and Meerschaum Vale Drain under all three scenarios, shown in Figure ES10.
- Natural buffering capacity in saltwater acts to neutralise acid within surface waters.
- Acid discharge during dry conditions from within the Tuckean Nature Reserve area will reduce, however acid will continue to be discharged from the remainder of the floodplain.

Implementation Considerations:

In addition to the model results, the following implementation considerations have been identified:

- Salinity will be higher in Stibbards Creek with potential impacts to adjacent floodplain areas through high hydraulic conductivity sand layers in this area (and other areas) may have to be managed. This may require the installation of additional monitoring equipment and additional soil investigations.
- Significant changes to salinity within the Tuckean Nature Reserve will change the ecology of the system, and an environmental assessment may be required.

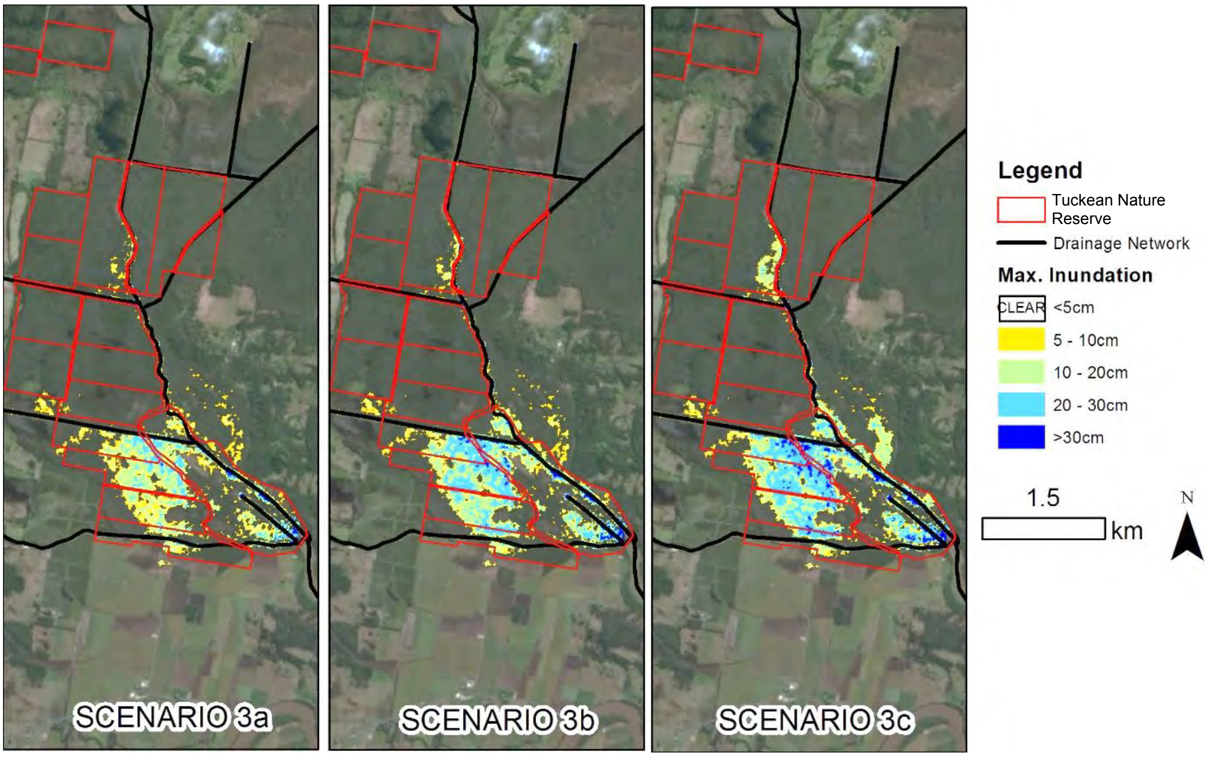

Figure ES-9: Maximum floodplain inundation in Scenario 3a, 3b and 3c

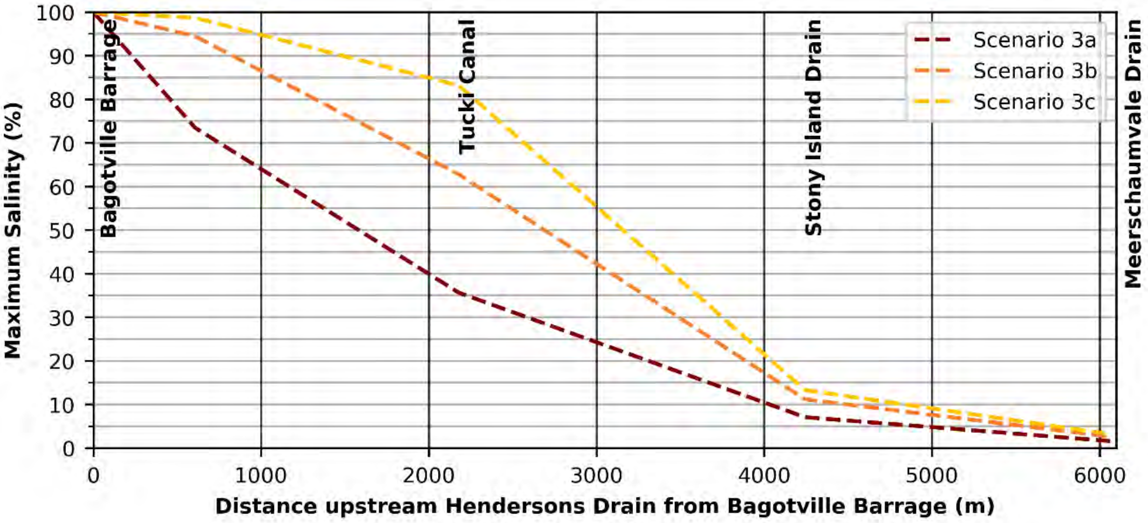

Figure ES-10: Maximum salinity (as a percentage of salinity in the Tuckean Broadwater) up Hendersons Drain

ES.4.4 Scenario 4 – Hinging open the barrage gates

Description:

There are eight 3 m x 3.5 m one-way flood gates on the Bagotville Barrage that allow flows to discharge into the Richmond River, but prevent tidal flows into the swamp. This option aims to quantify the impacts of hinging open the gates on the floodplain. By hinging open the gates, but leaving the structure intact, this option allows for the broadscale reintroduction of tidal flows into the swamp in desirable periods, while still allowing for the opportunity to close the gates to prevent backwater flooding from the Richmond River. Improved tidal connectivity increases flushing and increases the natural acid buffering capacity of the system.

Model Outcomes:

The results of the model indicated the following:

- A large portion of the floodplain becomes inundated during day to day tidal cycles, including almost all the Tuckean Nature Reserve and privately-owned areas south of Stibbards Creek, along Tucki Canal and east of Hendersons Drain.
- During extended dry periods, salinity in Hendersons Drain at the confluence of Meerschaum Vale Drain can reach as high as 20% of the salinity in the Tuckean Broadwater, and up to 10% in Jumbo Drain (shown in Figure ES-11).
- Average water levels increase throughout the floodplain (illustrated in Figure ES-12).
- Advective acid transport would be reduced due to higher average water levels.
- High salinity in the drains will improve the natural acid neutralisation capacity.
- Peak water levels during small to medium catchment events increase, and drainage times increase significantly.

Implementation Considerations:

In addition to the model results, the following implementation considerations have been identified:

- Groundwater connectivity to private land would require additional consideration and monitoring.
- Large changes in the ecosystems would likely occur on the impacted areas of the floodplain which would require further environmental assessment.
- The increased floodplain and drain salinity would require substantial changes in land management practises in some privately-owned properties. This may involve some land acquisition or landholder compensation.

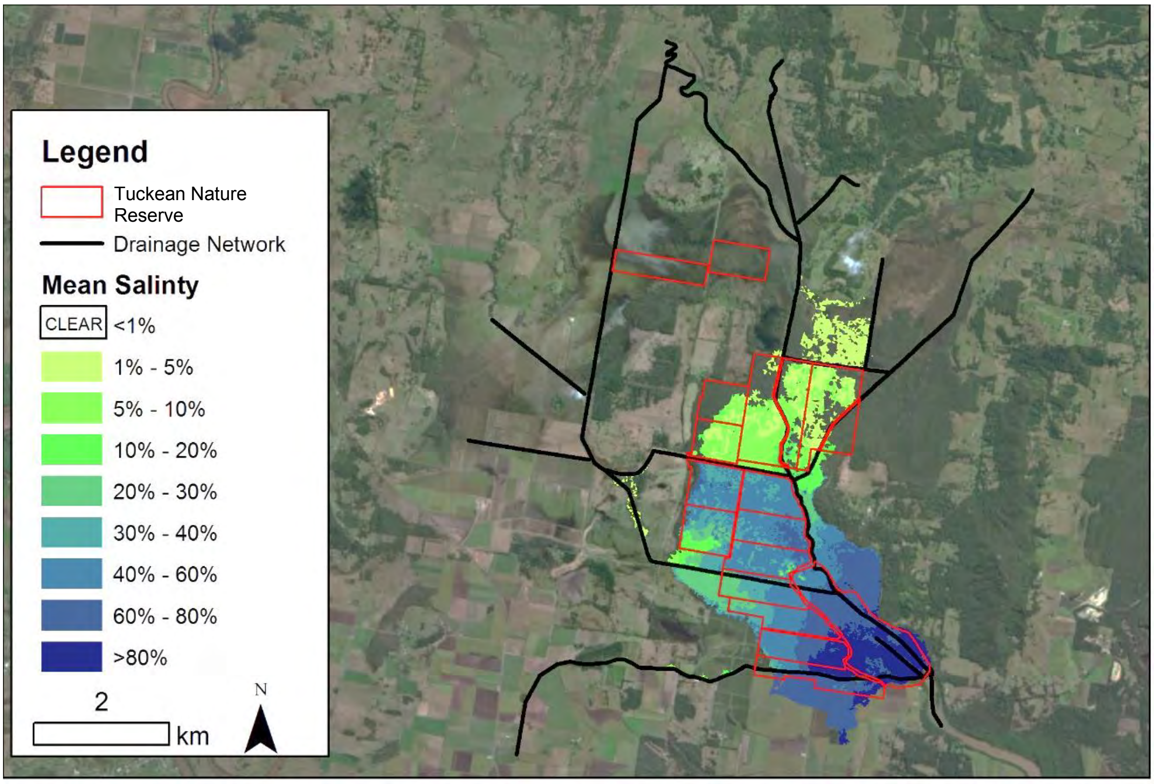

Figure ES-11: Mean salinity (as a percentage of salinity in the Tuckean Broadwater) for Scenario 4

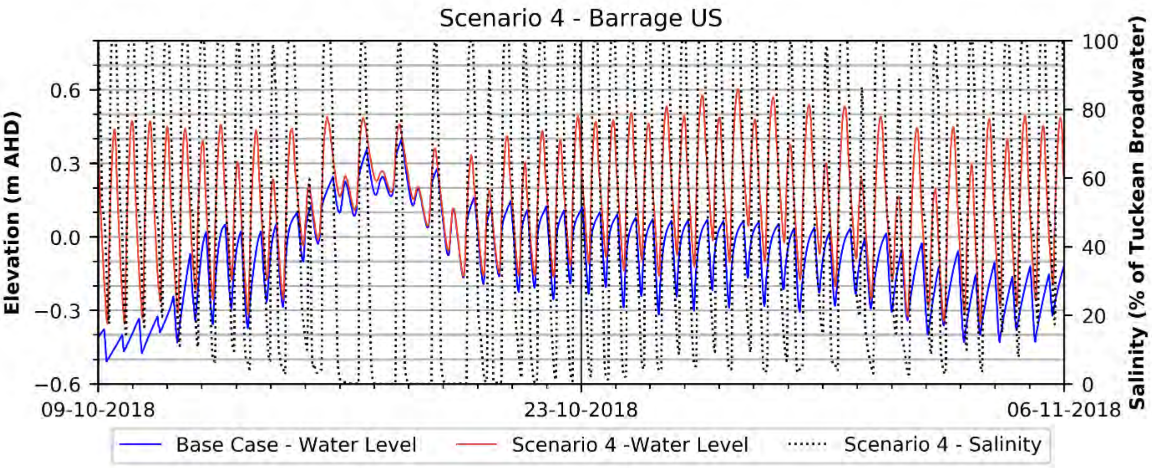

Figure ES-12: Water levels and salinity upstream of the Bagotville Barrage in Scenario 4

ES.4.5 Scenario 5 – Reflooding near Slatteries Drain

Description:

Scenario 5 uses the modified drainage network that was developed for Scenario 1. However, small to medium catchment flows from the Slatteries catchment are diverted onto the floodplain to increase runoff residence time on the low-lying land immediately west of Slatteries Drain. This aims to promote acid containment via elevated groundwater levels and increase the coverage of water tolerant vegetation. Figure ES-13 shows the modifications to the model (beyond those described in Scenario 1) for this scenario, including an additional drain, a weir (invert +0.7 m AHD) and lowered floodplain bathymetry. The aim of this is to redirect low flows onto the floodplain, while still maintaining flood conveyance through Slatteries Drain.

Model Outcomes:

The results of the model indicated the following:

- A 25 ha area would be inundated most of the time, with typical water depths of 0.1 to 0.2 m. This area would only dry during extended droughts. Otherwise changes to mean (shown in Figure ES-14) and maximum floodplain inundation do not change significantly.
- Drainage times after rainfall increase upstream of the new weir structure but remain largely unchanged from Scenario 1 otherwise.
- Advective acid transport would reduce, particularly from the 25 ha of area that is actively re-flooded, and due to the swaling of the drains.
- The incremental improvements (compared to Scenario 1) are largely limited to the 25 ha of reflooded land.

Implementation Considerations (additional to Scenario 1):

In addition to the model results, the following implementation considerations have been identified:

- This drainage option would require the discontinuing to current land management practices on the affected property. This may require land acquisition or landholder compensation.
- ASS management plan would be required.
- Potential ecological changes should be considered.
- Active re-flooding elsewhere on the floodplain (such as off Meerschaum Vale Drain) could be considered depending on the land available.
- Higher groundwater levels in surrounding area.

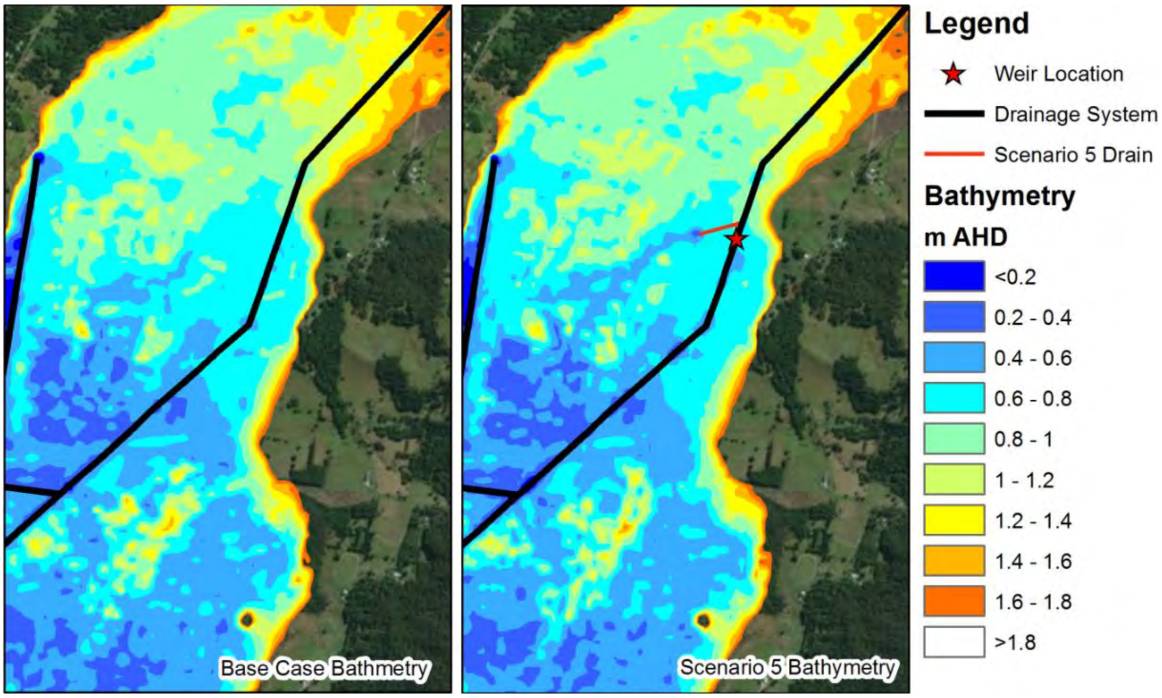

Figure ES-13: Modifications for Scenario 5 (Left – original bathymetry, Right – Scenario 5 bathymetry, with new channel in floodplain)

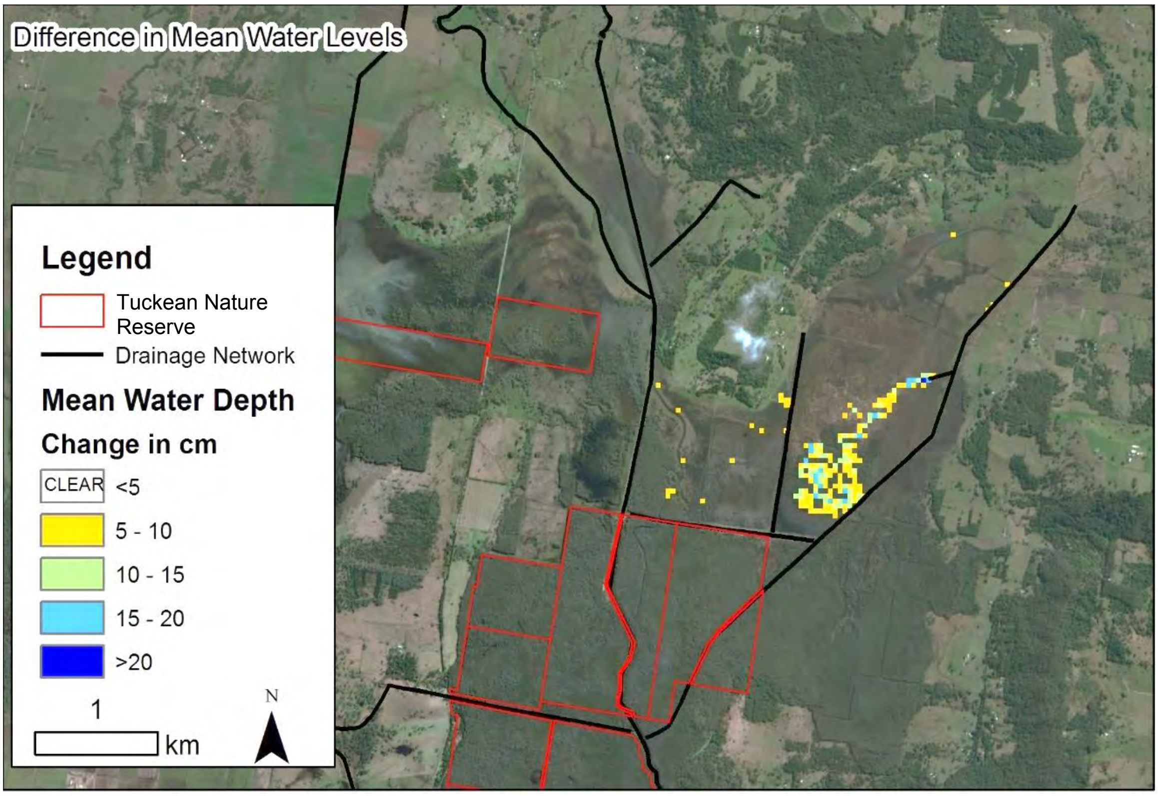

Figure ES-14: Change in mean water levels (compared to Base Case) in Scenario 5

ES.4.6 Scenario 6 – Hinging open the barrage gate and installing upstream floodgate structures

Description:

Scenario 4 considered a scenario where the barrage gates are hinged open, but there are no upstream flood mitigation structures in place to reduce the impact to areas upstream of the Tuckean Nature Reserve. Scenario 6 assesses the impact of installing four (4) new one-way floodgate structures at the edge of the Tuckean Nature Reserve on Stibbards Creek, Tucki Canal, Stony Island Drain and Hendersons Drain (locations shown in Figure ES-15). The aim of this scenario is to improve tidal flushing within the Tuckean Nature Reserve without impacting adjacent landholders

Model Outcomes:

The results of the model indicated the following:

- A large portion of the floodplain becomes inundated during day to day tidal cycles, including almost all the Tuckean Nature Reserve and privately-owned areas south of Stibbards Creek, along Tucki Canal and east of Hendersons Drain, shown in Figure ES-16.
- Floodplain flows continue to allow saltwater intrusion beyond the Tucki and Hendersons gates. Substantial drain levee improvements and bunding would be required to minimise saltwater intrusion.
- Levee improvements would be required along Stibbards Creek (downstream of the new floodgate) to prevent tidal overtopping. Levee improvements are shown in Figure ES-17.
- Saltwater does not flow upstream of the Stibbards Creek gates.

Implementation Considerations:

In addition to the model results, the following implementation considerations have been identified:

- Substantial earthworks would be required in addition to the floodgates structures to improve the drain levee to the south of Meerschaum Vale Drain and south of Stibbards Creek and to create a bund to contain saltwater within the boundaries of the Tuckean Nature Reserve near Tucki Canal.
- Salinity will be high in Stibbards Creek, downstream of the new floodgate structure. Saltwater transport through high hydraulic conductivity sands in this area (and other areas) may have to be managed.
- Large changes in the ecosystems would likely occur on the impacted areas of the floodplain which would require further environmental assessment.

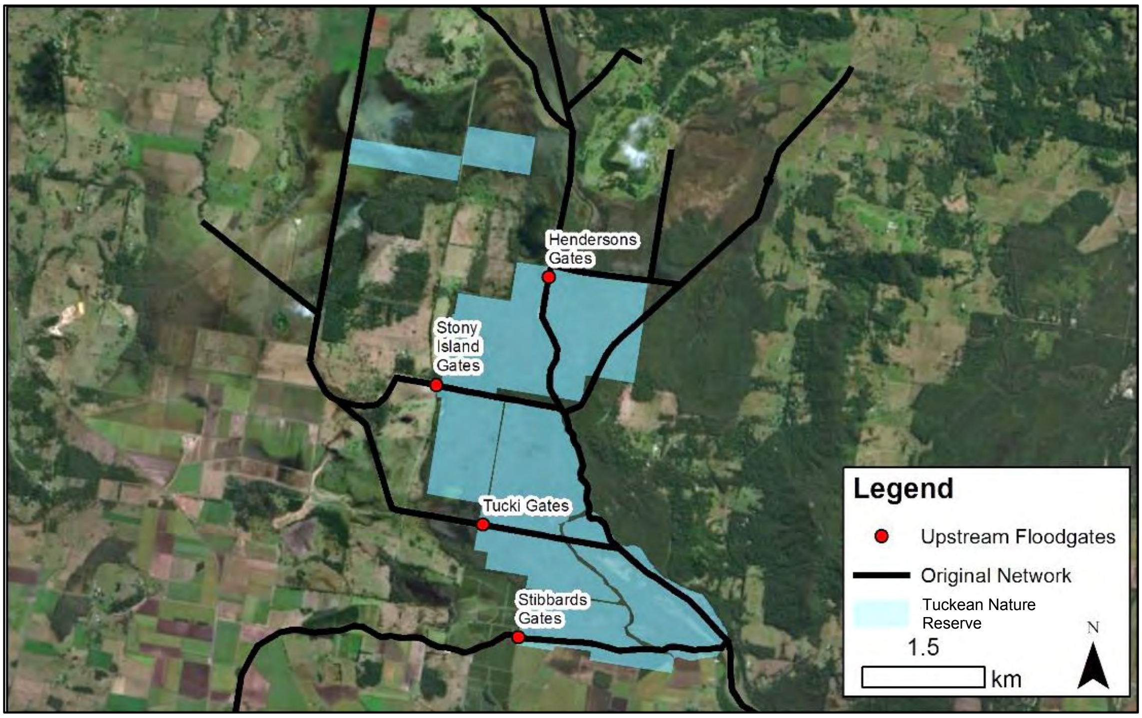

Figure ES-15: Location of new floodgates for Scenario 6

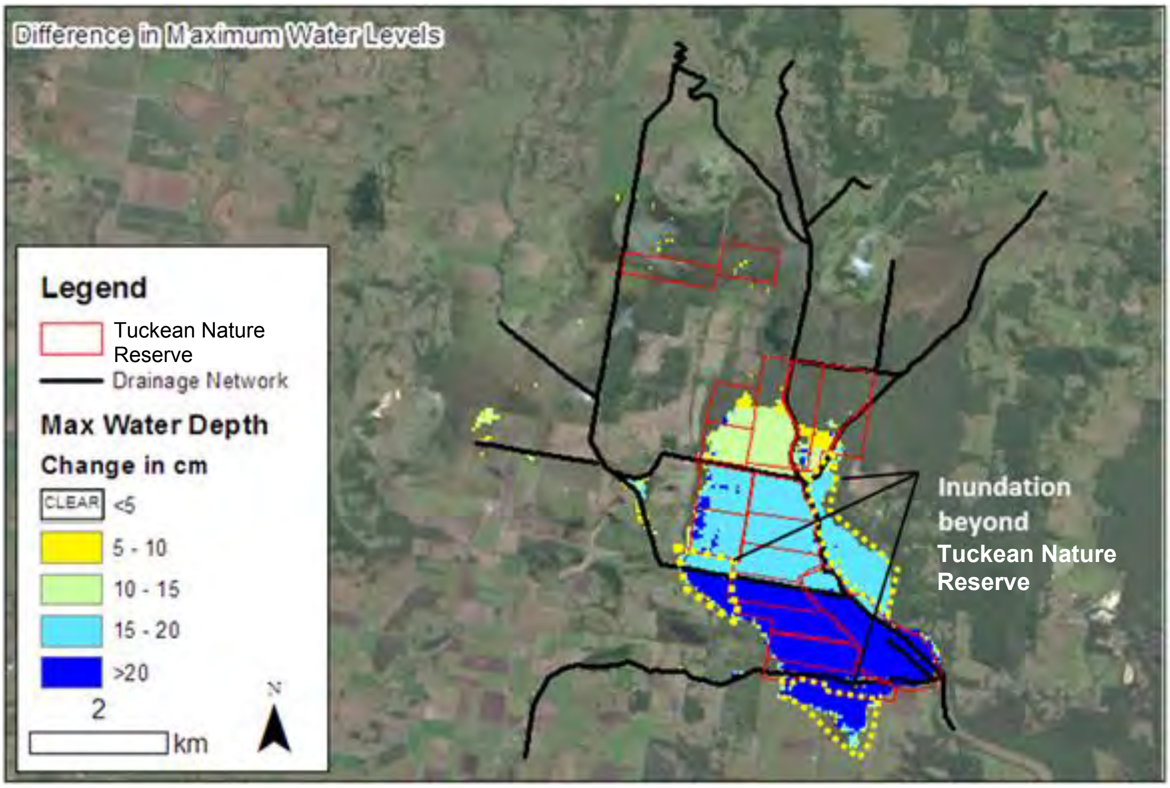

Figure ES-16: Change in maximum inundation for scenario 6, including areas beyond Tuckean Nature Reserve (TNR) area

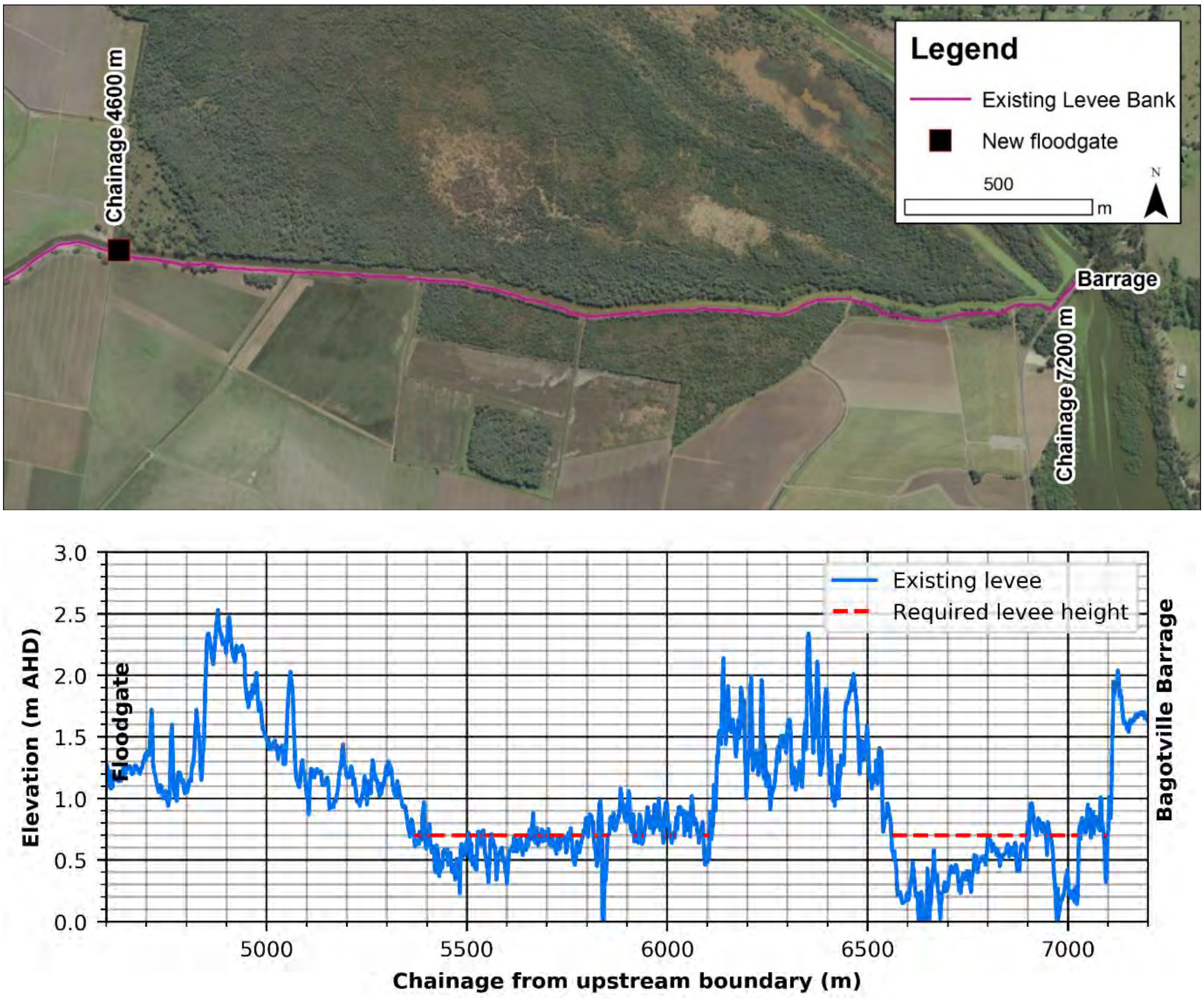

Figure ES-17: Example of levee improvements required along Stibbards Drain

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1 Introduction

Tuckean Swamp is located on the north bank of the lower Richmond River estuary upstream of the Tuckean Broadwater, approximately 25 km upstream from the entrance of the Richmond River at Ballina. The study area is shown in Figure 1-2 and the major drainage system is outlined in Figure 1-3. The low-lying area of the swamp (below 2 m AHD) covers approximately 6,000 hectares (ha), with an upland catchment of approximately 20,000 ha. The Tuckean floodplain and upstream catchment account for approximately 3.5% of the catchment of the greater Richmond River. As shown in Figure 1-3, a significant area of the lower swamp is contained within the Tuckean Nature Reserve (TNR) managed by National Parks and Wildlife Services (NPWS).

Enhanced drainage systems were constructed in the early 1900's to facilitate agriculture across the floodplain (Kijas, 2019), with further flood mitigation works completed in the following decades. While the drainage system efficiently routed catchment flows off the floodplain, it also facilitated greater tidal penetration within the drainage network. Ultimately, this led to the construction of the Bagotville Barrage in 1971, which provides a physical barrier between the upstream floodplain and tidal inflows from the Tuckean Broadwater. The Bagotville Barrage comprises eight (8) large culverts with one-way floodgate flaps (Figure 1-1) that enable drainage from Tuckean Swamp, whilst excluding tidal inundation and backwater flooding from the Richmond River. These floodgates also promote the lowering of the groundwater table to low tide levels across the upstream floodplain during extended dry periods.

Figure 1-1: Bagotville Barrage

The flood mitigation works in the Tuckean Swamp have led to significant changes in the hydrology and ecology of the Tuckean floodplain over time (Charley and Sharpe, 1995 and Cawley, 1995). Overall, there has been a reduction in the environmental values of the area (including fish passage and habitat, birds and native vegetation) and the deep, artificial drains have facilitated the release of Acid Sulfate Soil (ASS) by-products into the surface water systems. These impacts have been shown to have broader implications across the lower Richmond River estuary (Sammut et al., 1995).

The impacts of poor water quality originating from the Tuckean floodplain, and the associated drainage system, have been noted since 1919 (Sammut, 1998, referencing documents from the Tuckean Drainage Trust in 1920). A number of previous studies have investigated and characterised acidic soils within the Tuckean floodplain (e.g. Smith, 1995, Baldwin, 1997, Sammut, 1998 and Brodie, 2007) and provided recommendations on how management of the floodplain and drainage network could be improved. Despite the implementation of some management recommendations (namely management of the Bagotville Barrage), poor water quality issues within the drainage system remain an ongoing issue, impacting the Tuckean area and the broader Richmond River (e.g. Wong et al., 2016 and Moore, 2007).

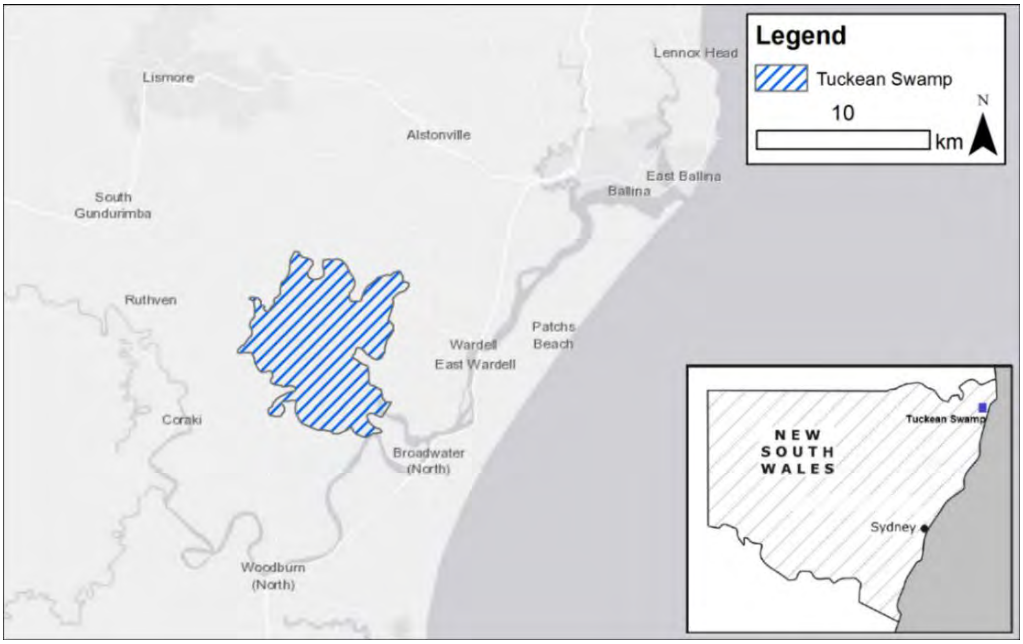

Figure 1-2: Location of Tuckean Swamp on the Richmond River estuary

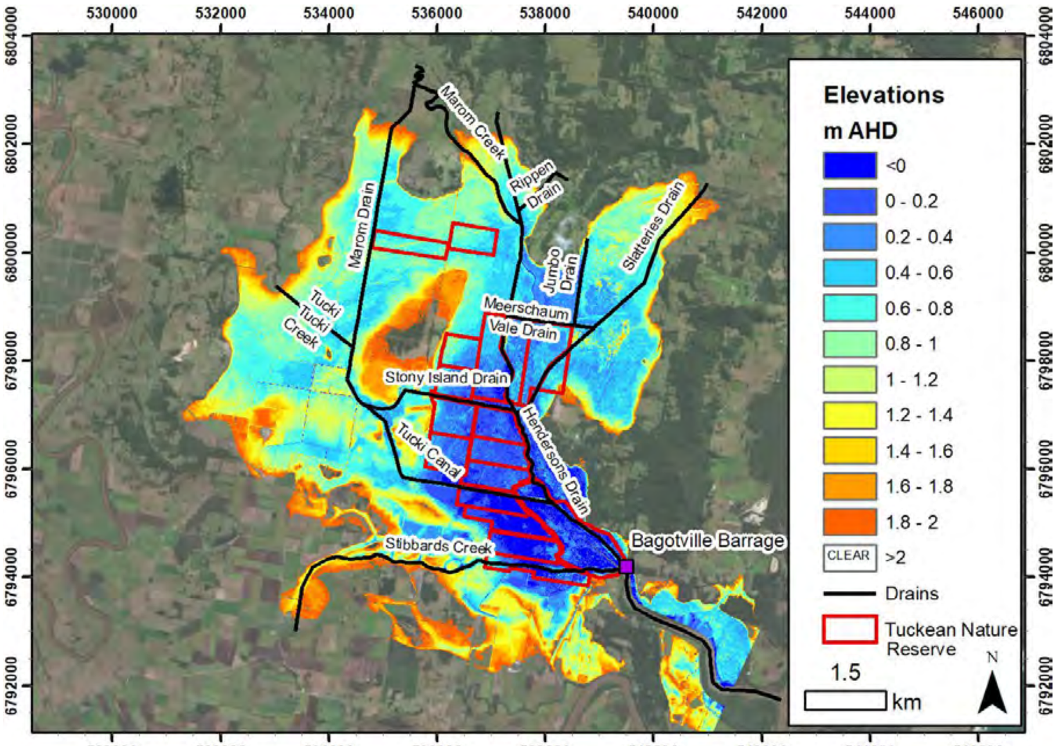

Figure 1-3: Major drainage network*

*Some studies refer to Stony Island Drain as Nature Reserve Drain, Hendersons Drain as the Main Drain and Meerschaum Vale Drain as Slatteries Link Drain.

Since the last major hydrologic investigation of Tuckean Swamp (Baldwin, 1997), our understanding of backswamp wetland hydrology and the tools available to investigate hydrological processes have significantly improved, enabling detailed investigation of potential acid sulfate soil remediation strategies and the quantification of potential outcomes. An aim of this project is to improve the overall understanding of the hydrology of Tuckean Swamp and floodplain through extensive field data collection and numerical modelling. With a better understanding of how the site currently functions, different management options can be investigated targeted at decreasing acidic discharges from the site and improving overall water quality. While the environmental benefits are important, it is vital that any hydrologic impacts to the wider floodplain and adjacent landholders are equally considered.

1.1 About this Report

This report is comprised of the following sections:

- **Chapter 2** provides background information on the Tuckean Swamp floodplain, including a brief history of the drainage of the swamp and a summary of the key studies previously undertaken in the area;
- **Chapter 3** provides a conceptual overview of the floodplain processes that drive the hydrodynamics and water quality throughout the floodplain, including the presence of ASS throughout the area;
- **Chapter 4** provides an overview of the general remediation strategies that are used to improve environmental outcomes of ASS affected areas;
- **Chapter 5** describes the modelling undertaken to assess the impact of implementing remediation strategies specifically on the Tuckean Swamp and floodplain; and
- **Chapter 6** provides a study summary and key findings.

In addition to the main body of the report, several appendices have also been included to provide additional information to develop an improved understanding of the floodplain.

- **Appendix A** provides background theory on ASS;
- **Appendix B** provides a summary of the data collection for this study;
- **Appendix C** provides a summary of the model development; and
- **Appendix D** provides a summary of the model calibration.

This study has been guided by the Tuckean Steering Committee, consisting of representatives from OzFish, Rous County Council, Ballina Shire Council, Lismore City Council, Richmond Valley Council, National Parks and Wildlife Services, Department of Planning, Industry and Environment (formerly OEH), Local Land Services, Jali LALC, Department of Primary Industry – Fisheries and the Nature Conservancy. Funding has been provided by the Saltwater Recreational Fishing Trust Flagship Fish Habitat Action Plan.

2 Background

2.1 Preamble

A detailed environmental history of the Tuckean Swamp was recently completed as part of a series of projects related to this study. This section provides a brief summary of Tuckean Swamp's drainage history as it is relevant to this hydrological study. More details on the history of Tuckean Swamp can be found in Kijas (2019).

2.2 History of drainage works

Prior to European settlement, Tuckean Swamp was historically a combination of estuarine and freshwater wetlands that supported diverse habitats for a wide range of flora and fauna. The topography of the floodplain is low, with a substantial area within 0.5 m of mean sea level. This low-lying land historically remained near permanently inundated, making it an ideal habitat for an array of waterbirds and fish (Tulau, 1999). The Bundjalung people, the local aboriginal people, used the swamp and its surrounds as a rich source of food and materials (Smith and Baldwin, 1997). Indigenous history notes that estuarine stingrays found habitat in Marom Creek which flows from the north-west of the floodplain (Kijas, 2019).

A brief timeline of the drainage works after European settlement is summarised below, based on the information provided by Kijas (2019), Smith and Baldwin (1997), Pattersons Britton (1996) and Tulau (1999):

- 1870s: European settlement began in the area, primary land usage was grazing of dairy and beef cattle.
- 1880s: Individual landholders began building drainage networks on their properties to allow improved passage of floodwaters off the low-lying floodplain areas. This initial drainage scheme resulted in more efficient catchment flows.
- 1880s – 1890s: A series of large floods caused damage to homes and livestock.
- 1900: An inquiry was held to discuss the future drainage of Tuckean Swamp. Two (2) main options were considered (although it appears neither were settled on at the time):
    1. Diversion of the north arm of the Richmond River through Tuckean Swamp and out via the Tuckean Broadwater, to improve drainage of the greater Richmond River; and
    2. Construction of drainage channels within the Tuckean floodplain to divert local floodwaters quickly through the Tuckean Broadwater.

- 1907: Drought periods followed the inquiry in 1900, and the drainage plan was not enacted. However, in 1907 the Public Works Department (PWD) wrote a report comparing the two proposed drainage schemes.
- 1910: Funds were allocated for the drainage works on the Tuckean Swamp and floodplain, however a decision had not been made as to which scheme would proceed. PWD stated that diversion of the north arm of the Richmond River would render Tuckean Swamp unsuitable for most agriculture, which concerned local residents.
- 1911: An inquiry was held into the proposal, with many residents citing their concerns about increased flooding if the diversion scheme went ahead. As a result of the enquiry, it was decided that the floodplain would be drained, but the diversion would not proceed.
- 1912: PWD commenced work on the drainage scheme.
- 1915: Construction of the drainage scheme was completed, and approximately 5,000 acres of Crown Land were sold in small parcels for farming.
- 1920: By this time, it was evident that there were significant issues associated with the new drainage scheme. The improved drainage efficiency allowed more tidal water into the swamp, enabling saline water to flow overbank on the floodplain, particularly in the low-lying north-east areas of the swamp. Landowners sought assistance from the government and began calling for floodgates to prevent tidal waters moving upstream, however no action was taken during this time.
- 1956: Following a series of significant floods across the state, the NSW government passed legislation that prioritised flood mitigation to reduce the severity of flood damage.
- 1967 - 1969: A proposal for flood mitigation works was accepted by Richmond River County Council, including improvements for the drainage of the Tuckean Swamp and floodplain. In 1969, plans for the Bagotville Barrage were unveiled.
- 1971: Works on the barrage were completed. The barrage featured one-way floodgate flaps that allowed for drainage of the floodplain but ensured that tidal inflows were restricted from the Tuckean Broadwater. The barrage also allowed vehicle access across the Broadwater. Improved drainage resulted in the conversion of some of the floodplain from grazing land to sugar cane. The barrage consists of eight (8), 3 m wide by 3.5 m high floodgates with an invert (bottom) of approximately -1.75 m AHD (Australian Height Datum). The barrage prevents brackish water from the Tuckean Broadwater flowing into the Tuckean floodplain, effectively resulting in a freshwater system in the main Tuckean drainage network.
- 1982: 550.5 ha of the remaining Crown Land were declared a Tuckean Nature Reserve;
- 2001: Mass fish kill in the Richmond River estuary (Moore, 2007).
- 2003: Three (3) 1m by 1 m sluice gates (invert of -0.64 m AHD) were installed on the Bagotville Barrage to improve fish passage. The sluice gates have been periodically opened and closed

since their installation; however Council records show that all three (3) gates have not been simultaneously open since 2010.

2.3 Acid sulfate soils

Acid Sulfate Soils (ASS) occur extensively across NSW's coastal floodplains (Wong et al., 2010). More information on the formation and impacts of ASS can be found in Appendix A. The dangers of draining ASS were not fully understood during the drainage of many of the coastal floodplains throughout the late 19th and 20th centuries. While some impacts were observed and documented before the 1960s, the flood mitigation programs implemented after World War II generally failed to address the potential risks associated with increased drainage.

By the late 1990's however, ASS were recognised as one of the biggest environmental issues facing estuaries in NSW. Over the next two (2) decades, there was widespread confirmation of the significant impacts of acid drainage from drains and floodgates in high-risk ASS landscapes (Tulau, 2011). This was supported by broad acre risk mapping of ASS in NSW (Naylor et al., 1998), indicating that more than half of the Tuckean Swamp and floodplain were identified as 'high risk of occurrence of ASS' (Figure 2-1).

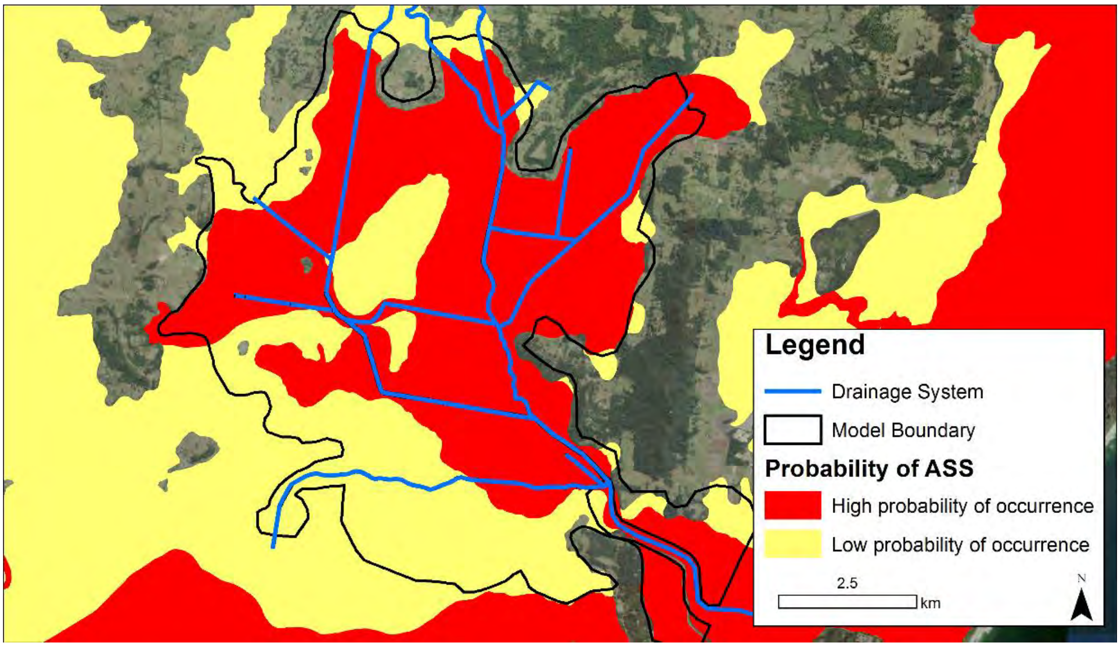

Figure 2-1: Acid sulfate soil risk map (Naylor et al., 1998)

The occurrence of ASS within Tuckean Swamp has been confirmed by numerous investigations, including Tulau (1999), Smith (1995), Sammut et al., (1995), Burton et al., (2006), Brodie (2007) and Maher (2013). The drainage scheme and the installation of the Bagotville Barrage at Tuckean Swamp have resulted in the oxidisation of acidic sediments. As described in Appendix A, oxidised ASS pose numerous environmental threats to estuaries, including contributing to mass fish kills that have happened periodically in the Richmond River (Moore, 2007). Moore (2007) identified the Tuckean Swamp sub-catchment as the highest risk area on the Richmond River with respect to water quality, acidic discharges and low dissolved oxygen ‘blackwater’, including an impact to fisheries and biodiversity. Blackwater discharges in the estuary are considered to be largely responsible for the mass fish kills that occurred in 2001, when it is estimated that 2 million fish and crustaceans were killed (Wong et al., 2018). Field indicators of soil acidity at Tuckean Swamp are discussed further in Section 3.2 and Appendix B.

2.4 Previous studies at Tuckean Swamp

Extensive research into the hydrology, drainage and related acidity of Tuckean Swamp has been undertaken since the 1980s. In the early to mid-1990s, a Land and Water Management Plan for Tuckean Swamp (Baldwin, 1997) was developed. To assist in the development of this plan, a series of technical investigations were undertaken, and corresponding documents were published, including:

- Technical Report #1: Tuckean Swamp Hydraulic Study (Patterson Britton, 1996);
- Technical Report #2: Tuckean Swamp Acid Sulfate Soil Survey (Smith, 1995);
- Technical Report #3: Process and Impacts of Acidification in Tuckean Swamp (Sammut, 1996);
- Technical Report #4: Survey of Terrestrial Flora and Fauna of the Tuckean Swamp Catchment (Charley and Sharpe, 1995);
- Technical Report #5: Brief for an Aboriginal Study of Tuckean Swamp (Heron, 1996);
- Technical Report #6: A Landuse History of Tuckean Swamp (Smith and Baldwin, 1997);
- Technical Report #7: Tuckean Swamp Economic Study (Read Sturgess & Associates, 1996); and
- Technical Report #8: An Inventory and Assessment of Aquatic Flora and Fauna of the Tuckean Floodplain (Cawley, 1995).

Technical Reports #1, #2 and #3 are particularly relevant to this study and are discussed further below.

Sammut (1996) provides a background of the impacts of ASS in the Tuckean, showing the soils in the floodplain are characterised by high acidity (pH < 4.5) and, in many of the sampling locations, high acidity persists to depths of 2 m below the surface. More information on the presence of ASS within Tuckean Swamp was collected by Smith (1995), as discussed further in Appendix B. Sammut (1996) describes the processes through which acid generated in the sub-surface groundwater system can be transported into the surface drainage channels (and eventually into the Richmond River), as per the processes described in Appendix A. High acidity (pH < 4) was observed throughout Hendersons Drain and in the lower 3 km of Stibbards Drain after a significant rainfall event (Sammut, 1996). Acidity in Tucki Canal (upstream of where the Tuckean Nature Reserve exists today) was observed as more pH neutral, which Sammut (1996) attributes to higher ground levels around the drain, low hydraulic conductivity in the sediments in this region and high dilutions from the upstream catchments discharging into the drain. This study provided several potential remediation options/recommendations as summarised from Sammut (1996):

- Development of an expert panel to effectively manage the floodplain to reduce the impacts of ASS with a holistic and cross-disciplinary way;
- Modify floodgate operations: Sammut (1996) suggested that the floodgates be modified to allow tidal inflow during select periods of time. This would increase the water table, increase tidal inflows (and the acid neutralising capacity of the system), improve fish passage and allow for the re-establishment of estuarine habitat upstream of the barrage. The report suggested that tidal inflows would be most feasible in the drainage period after a flood event, when salinities in the Richmond River are low, due to the risks of increased salinity during dry periods. It was also suggested that inclusion of upstream structures should not be encouraged as continued acid discharges would continue from upstream of the new structures and the problem would persist;
- Modification to drains: Sammut (1996) stated that the drains could be reshaped to sit above the acid sulfate soil layer to reduce acid export, however the feasibility of such works in the primary drainage system due to the size of the existing drains was questioned;
- Freshwater flooding: installation of a weir (or similar structure) to hold up the water table using freshwater. However, Sammut (1996) states that increasing the water table will not necessarily reduce acid discharges in the Tuckean region in the short to medium term as the soil profile data suggests that a high level of acidity persists well below the water table.

Patterson Britton (1996) developed a 1D – 2D RMA hydraulic model of the Tuckean floodplain to assess the impact of changes to the operation of the Bagotville Barrage. This model was not calibrated to observations and only approximated relative changes in hydrodynamics. This study assessed two (2) distinct options, as summarised in Table 2-1.

Table 2-1: Summary of modelling scenarios in Patterson Britton (1996)

Scenario	Summary of Results*
Replacement of floodgate flap gates on the Bagotville Barrage to vertical drop gates to allow tidal intrusions into the floodplain	• Tidal intrusion would largely be restricted to downstream of the Stony Island Drain; • Saline intrusion is limited by catchment baseflows; and • Tidal inundation would largely be contained within the Tuckean Nature Reserve between Tucki Canal and Stibbards Creek. Approximately 100 m to the west of Hendersons Drain would also be inundated by spring tides, as was some areas south of Stibbards Creek.
Widening the barrage through the installation of another 4 culverts to improve flood drainage	• Minimal changes to peak water levels except immediately upstream of the structure, as the shallow floodplain gradient is a major control in the system; and • Drainage times decrease between 5 – 15%.

* Drainage naming conventions have been changed to reflect the names used in this report.

Baldwin (1997) summarised the technical reports and identified seven (7) objectives and strategies through which the objectives could achieved. These objectives and related strategies can be viewed as "aspirational and management action targets respectively" (Brodie, 2007) and were not intended to be immediately acted upon (some of the strategies are mutually exclusive). The objectives and strategies included:

1. Manage potential ASS - primarily through avoiding new drainage works or the deepening of existing drains;
2. Manage actual ASS - primarily through liming of small drains and acid scalds, as well as encouraging re-flooding on some of the low-lying areas of the swamp;
3. Facilitate better drainage - by increasing the capacity of the barrage with an additional four (4) culverts, or by improving drain maintenance;
4. Manage the barrage to mitigate acid water discharges - either by allowing managed tidal inflows, or through the creation of a freshwater reserve in the area behind the barrage;
5. Enhance habit values on Crown Land area upstream of the barrage – through either of the two strategies for objective 4;
6. Improve freshwater wetland habitat within the floodplain – this would involve inundating small areas of land nominated by landholders to a target depth of 30 – 40 cm to improve water quality and habitat throughout the floodplain; and
7. Enhance remnants of terrestrial habitat in the Tuckean Swamp catchment – through protection of vegetation and fauna, reduction in feral predators, and improved wildlife passage.

Since the completion of this management plan, liming trials were conducted throughout selected areas of the floodplain (Lines-Kelly, 1996). While there were immediate benefits from the liming on acid scalds in the swamp, generally no long-term changes in soil acidity were observed as a result of the treatment (Wong et al., 2016). Further, the Bagotville Barrage was modified in 2003 to include three (3) 1 m by 1 m manually operated sluice gates, to allow limited tidal flushing of the drainage network and to improve fish passage. The sluice gates are actively managed by Rous County Council, however they are periodically closed to prevent increased inundation during rainfall events and concerns of saltwater inundation of private properties during extended dry periods.

Brodie (2007) completed an extensive investigation of the presence of acid sulfate soils and the groundwater-surface water interactions at Tuckean Swamp. This study confirmed the extensive presence of ASS observed by Smith (1995) and Sammut et al., (1995), including the observation that actual ASS typically occur near the surface and high acidity (pH < 4.5) commonly persists at depths below the water table. Brodie (2007) noted that Hendersons Drain and Meerschaum Vale Drain were responsible for most of the acid export in the Tuckean region, compared to the flows originating from the western side of the swamp (through Marom Drain and Tucki Canal). Brodie (2007) suggested that while the objectives of the Baldwin (1997) management plan were appropriate, they did not set specific targets or timelines for actions to occur. Without specific targets, it is difficult to measure the effectiveness of such plans. As a result of the lack of detailed targets at Tuckean Swamp, the on-ground works that have occurred have generally been minimal, lacking engineering design and, as a result, water quality discharging from the floodplain and associated drainage network remains poor. ANZECC (2000) guidelines suggest that the default trigger value (used to justify when remedial actions should occur) for acidity in estuaries is a pH of 6.5. Long term monitoring of water quality by Rous County Council downstream of the Bagotville Barrage suggests that water discharging from the Tuckean Swamp is regularly below a pH of 4, which causes risks to aquatic life.

3 Floodplain processes

3.1 Preamble

This section provides an overview of the conceptual understanding of the floodplain processes throughout Tuckean Swamp. It includes a brief summary of the data collection campaign completed as part of this project and a generalised sub-catchment prioritisation of the Tuckean Swamp floodplain. More details on the fieldwork completed for this study can be found in Appendix B and an overview of the impacts of acid sulfate soils can be found in Appendix A.

3.2 Data collection and conceptual process understanding

Data for this project was collected during three (3) field campaigns over a period of approximately 12 months during 2018 and 2019. The aim of these investigations was to collect sufficient data to develop and validate a numerical computer model that can accurately simulate existing and potential drainage options onsite. The data collected includes:

- Medium-term (6 – 12 month) water level data at 11 locations across the swamp, covering different climatic conditions;
- Identification of significant flow control structures and surveys of 38 hydraulic structures across the floodplain;
- Bathymetric surveys, including 91 cross sections in 11 of the creeks and drainage channels;
- Spot measurements of water quality at key locations during each field campaign; and
- Topographic surveys in key locations in the swamp to verify an existing aerial topography survey dataset collected in 2010.

3.2.1 Topography

Topographic survey data was collected to accurately measure landforms using a Trimble RTK GPS with base station correction via CorsNET. Details of the surveyed areas can be found in Appendix B, Section B.2.2. The spatial coverage of the topographic surveys was limited in some areas due to site access limitations on private property. This may constrain the topographic data in some areas.

The topographic data was used to correct the 2010 aerial LiDAR data (which often does not capture the actual ground elevation due to dense vegetation or surface water), through a process that is described in Section B.2.3. The LiDAR data was found to typically over-estimate the ground surface by up to 30 cm and was less accurate at ground levels near mean sea level (0 m AHD). By comparing surveyed ground elevations to LiDAR elevations across a range of floodplain elevations and vegetation types, it was possible to apply corrections to the LiDAR datasets. Using this information, a ground-truthed LiDAR dataset was developed for use in the numerical model. The resulting digital elevation model (DEM) is shown in Figure 3-1.

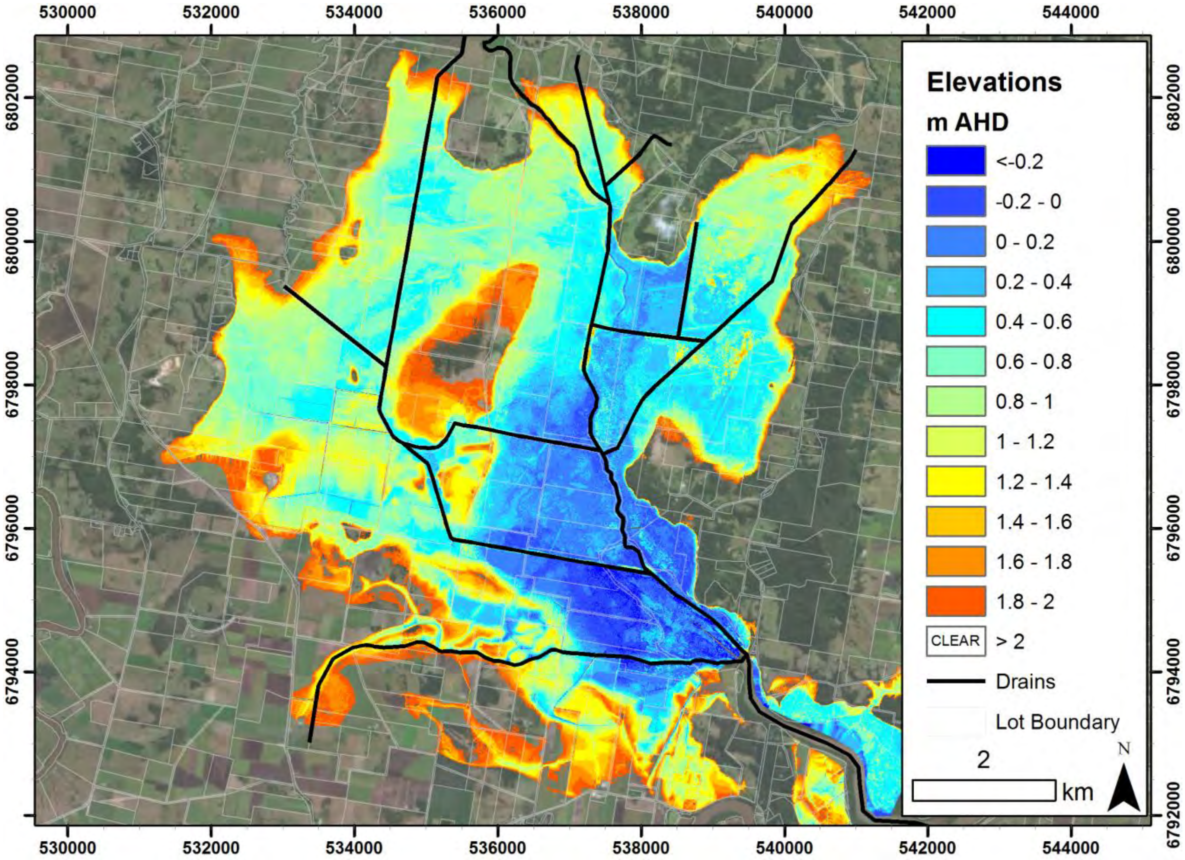

Figure 3-1: Ground-truthed Digital Elevation Model (DEM)

Figure 3-1 shows that there is a significant area of Tuckean Swamp below 0.4 m Australian Height Datum (AHD), particularly in the Tuckean Nature Reserve and near Jumbo Drain (see Figure 1-3 for drain names). This is reflected in the poor floodplain drainage and prolonged inundation (or waterlogging) due to the low gradient between the floodplain (identified by Patterson Britton, 1996) and low tide levels in the Tuckean Broadwater (which typically vary between -0.2 and -0.5 m AHD).

3.2.2 Drainage tenure

Most of the large, deep, major drains at Tuckean Swamp are owned and managed by Rous County Council as part of their flood mitigation network. Rous County Council own approximately 43 km of the drainage network in the floodplain, as shown in Figure 3-2. These drains are typically the deepest and widest channels in the drainage network. The remainder of the drains (approximately 110 km) are privately owned and vary in width, depth and connectivity throughout the floodplain.

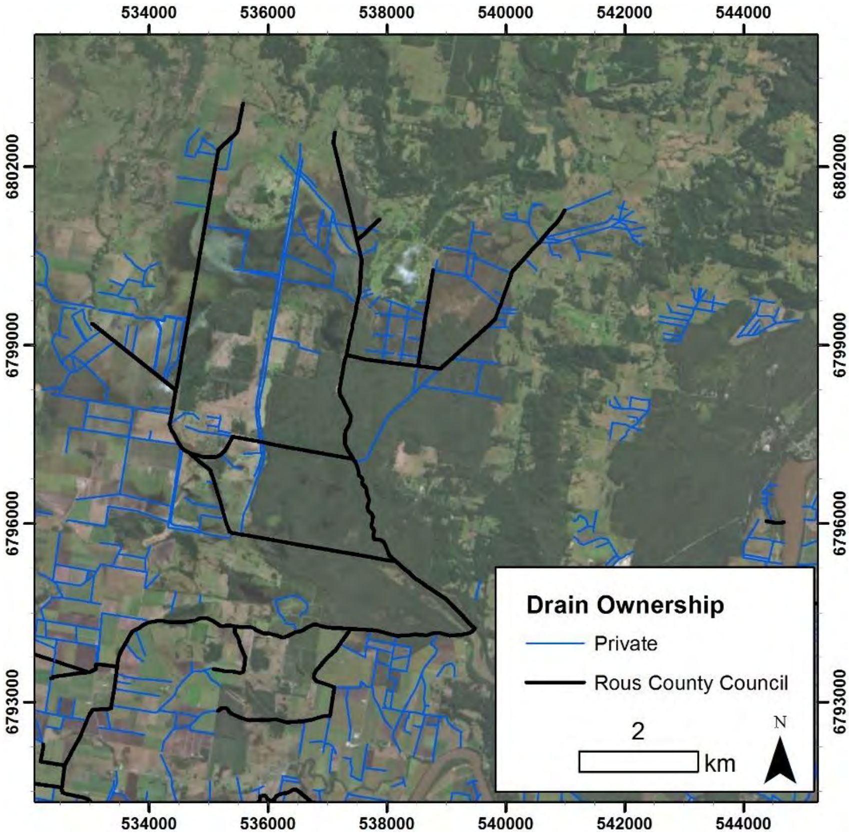

Figure 3-2: Drain tenure (Hydrosphere, 2011)

3.2.3 Bathymetry and hydraulic structures

Bathymetric (i.e. sub-surface topography) drain cross sections were also surveyed at key locations throughout Tuckean Swamp drainage network to detail the sub-aqueous landforms using a Trimble RTK GPS. Similar to the topography data, some locations were not accessible due to restricted access restriction. Cross sections were collected on:

- Hendersons Drain (from the barrage to the confluence with Marom Creek);

- Stibbards Creek (within the Tuckean Nature Reserve and at road crossings upstream);
- Tucki Canal (within the Tuckean Nature Reserve and at road crossings upstream);
- Stony Island Drain (within the Tuckean Nature Reserve);
- Marom Drain (upstream of confluence with Tucki Tucki Creek);
- Meerschaum Vale Drain;
- Jumbo Drain; and
- Slatteries Drain (upstream of confluence of Meerschaum Vale Drain).

Surveys targeted areas where there were obvious constrictions in the drainage network or were otherwise conducted at regular intervals. Where cross-sections were not able to be collected, bathymetry data has been inferred from LiDAR, aerial imagery and nearby cross-sections. Flow control structures, including culverts and floodgates were also surveyed throughout the Tuckean floodplain (including the Bagotville Barrage). The barrage is the major flow control structure in the Tuckean region, preventing tidal flows from entering the floodplain whilst promoting drainage to low tide levels. While there are currently three (3) sluice gates in the barrage, these are opened intermittently, and the conveyance of the sluices substantially reduces the tidal exchange that would occur without the barrage structure in place. While there are several floodgates on the paddocks throughout the swamps, there are a limited number of structures (mostly large culverts) on the main drainage network upstream of the barrage.

All surveyed cross-sections are provided in Appendix B Section B.4 and a summary of surveyed structures is provided in Section B.3.

3.2.4 Relative magnitude of flows

While no flow data was collected during the field campaign, observations about the connectivity of drains, observations of flow rates, and GIS techniques (summarised in Appendix C Section C.3) allow for a conceptual understanding of flow paths to be developed. Figure 3-3 depicts the relative magnitude of flows in the drainage network. The two largest catchments discharge into Marom Drain and Tucki Tucki Creek, resulting in large catchment flows through Tucki Canal. The Stony Island Drain is highly vegetated and partially infilled with sediment, so it is assumed to be poorly connected to Marom Drain during average water level conditions and thereby does not convey large flows. Slatteries Drain also drains a significant upstream catchment with the majority of flow passing through Meerschaum Vale Drain. Jumbo Drain, despite being of significant size, appears to only drain the immediate floodplain area surrounding it.

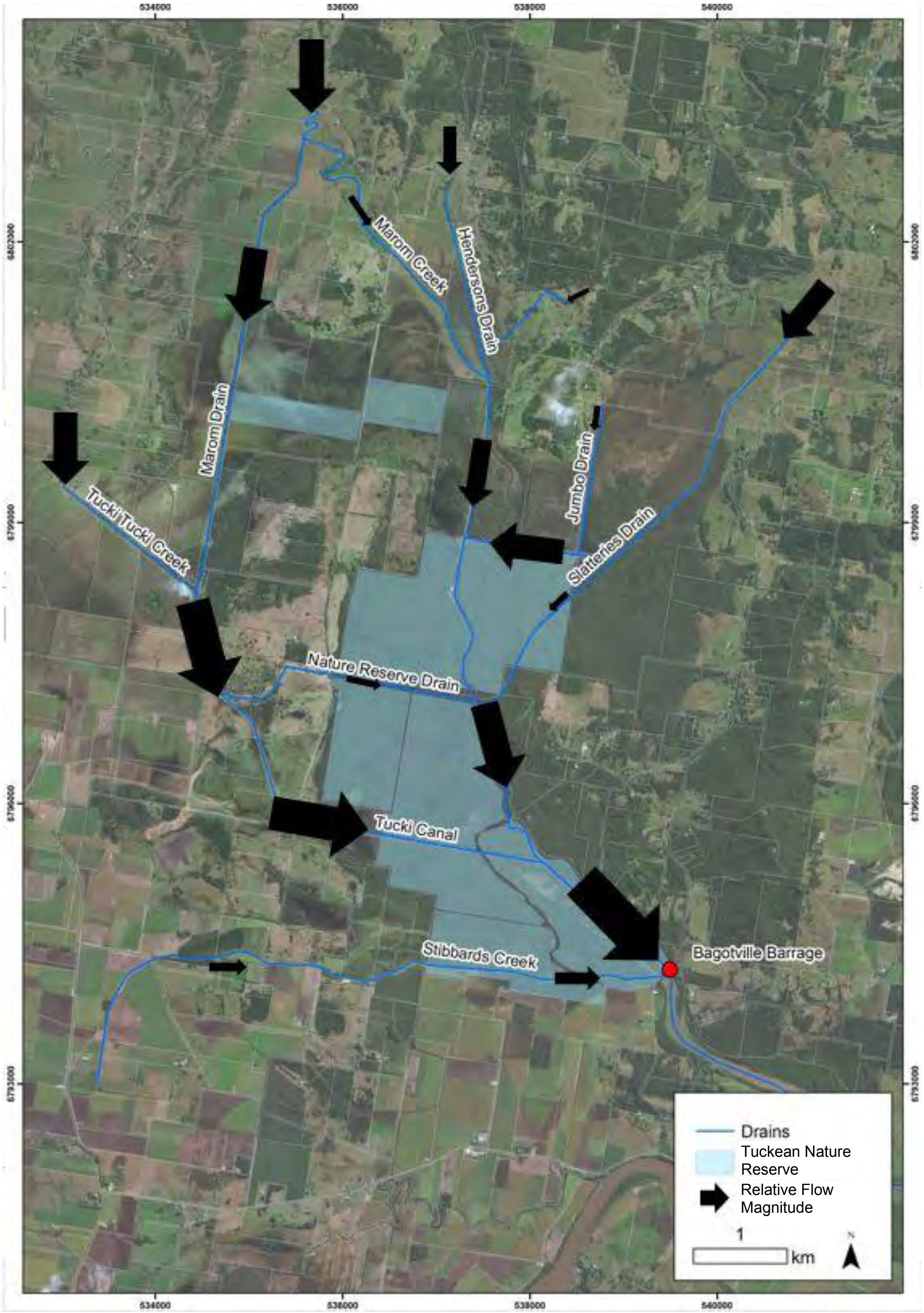

Figure 3-3: Relative magnitude of catchment flows

3.2.5 Water and soil quality

Spot measurements of water quality (pH and electrical conductivity) were taken across the floodplain on an opportune basis throughout the field campaigns. While details of the measurements can be found in Appendix B Section B.6 and Section B.8, a summary of the findings is provided in this section.

The results of the water quality measurements have shown:

- High acidity (pH < 5) in surface waters was observed within the Tuckean Nature Reserve and in the north-east corner of the floodplain in both March and June 2018;
- A pH of 2.1 was observed in Jumbo Drain;
- Water in the drains was typically fresh, except during extended dry periods when the sluice gates were opened (such as during January and February 2019) when electrical conductivity upstream of the barrage was similar to the Tuckean Broadwater;
- Lower acidity (pH > 5) was observed in Marom Drain and the upper parts of Tucki Canal, which was likely due to the large freshwater catchment inflows through Tucki Tucki Creek and Marom Drain, which was consistent with the findings of Brodie (2007);
- Neutral acidity (mostly pH > 6.5) was typically observed from the catchment inflows at the upper edges of the floodplain (e.g. along Marom Creek Rd);
- Large volumes of iron floc were observed in Hendersons Drain, discharging through the barrage in June 2018; and
- Thick deposits of iron and monosulfidic black ooze (MBOs) were observed in the bed sediments throughout the drainage system (see photos in Appendix B).

Existing soil profile data (from the NSW SALIS database, Brodie, 2007 and from Smith, 1995) was also interrogated. Due to the extensive existing information, minimal additional soils data was collected during this study. The following observations were made from the soil quality data:

- The highest acidity sediments are typically in the Tuckean Nature Reserve and in the north-east corner of the swamp;
- Soil pH values as low as 2.8 have been observed; and
- Actual Acid Sulfate Soils (AASS) were observed at or near (within 0.3 m depth) the surface.

The mechanisms for acid transport on the Tuckean Swamp and floodplain are similar to what has been observed in many drained coastal floodplains across NSW. Acid transport typically occurs following rainfall events that result in an elevated ground water table within the acidic soil layer. Following the drainage of surface waters (promoted by the efficient drainage network), a hydraulic gradient between the surface level and groundwater table promotes drainage of the soil matrix into the surface water (illustrated in Figure 3-4). Details of ASS and the broader impacts on the environment are provided in Appendix A . Based on the water and soil quality, the worst acidity appears to be generated from within the Tuckean Nature Reserve and in the north-east corner of the floodplain, around Meerschaum Vale, Jumbo and Slatteries Drains.

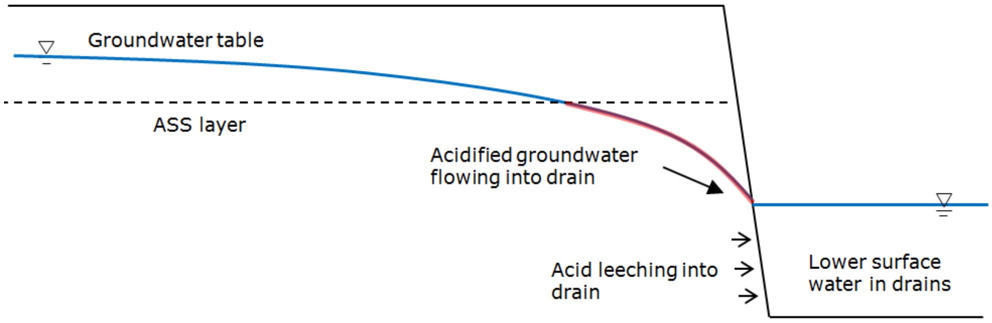

Figure 3-4: Cross section pathway of acidic groundwater transport into surface waters

3.3 Prioritisation of the floodplain

Tuckean Swamp is a large coastal floodplain with significant water quality issues. Due to the size of the floodplain, nature of the land use and extensive drainage, it is not practical to return the swamp to a pre-European natural condition. However, water quality originating from parts of the Tuckean floodplain is, at times, extremely poor and has implications for the environment and for the viability of farming and agriculture in the floodplain and the wider Richmond River estuary. As such, it is necessary to divide the floodplain into management sub-areas and to prioritise which areas should be targeted to improve overall water quality. The prioritisation method detailed below specifically examines water quality and is not intended to be the only source of information used when considering the on-going management of the floodplain.

3.3.1 Considerations for prioritisation

There are a number of factors considered when prioritising the remediation of ASS affected areas, some of which are summarised in Figure 3-5, as adapted from Glamore et al. (2016). In general, low-lying land with deep drains, below the ASS layer, and observations of high levels of soil and surface water acidity, results in a greater environmental risk for ASS discharges. These factors are well accepted variables which influence acid transport and downstream implications.

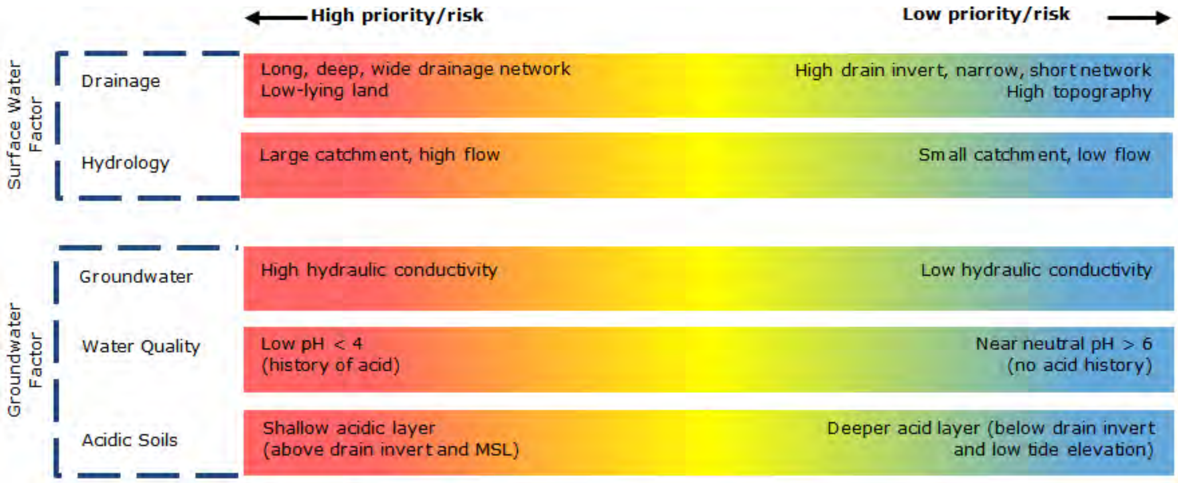

Figure 3-5: Environmental factors influencing the risk of impacts from ASS discharge (adapted from Glamore et al., 2016)

3.3.2 Prioritisation of Tuckean management sub-areas

The Tuckean floodplain was divided into 10 floodplain sub-areas representing sub-catchment drainage areas. Based on the conceptual understanding of the floodplain drainage, topography and acid generation on the site, the sub-areas were ranked in order of priority for ASS remediation. The management sub-areas are shown in Figure 3-6 and the justification of the prioritisation is summarised in Table 3-1. The highest priority areas are around Meerschaum Vale and Slatteries Drains, and in the lower Tuckean Nature Reserve, which are broadly consistent with the priority areas identified by Baldwin (1997). Similarly, Brodie (2007) identified Meerschaum Vale Drain as a substantial contributor of acid discharges, while acid discharges from Marom Drain were identified as being less common, which is also reflected in the prioritisation presented below. However, the prioritisation method above is able to utilise much more extensive datasets including field information specifically targeted for this study.

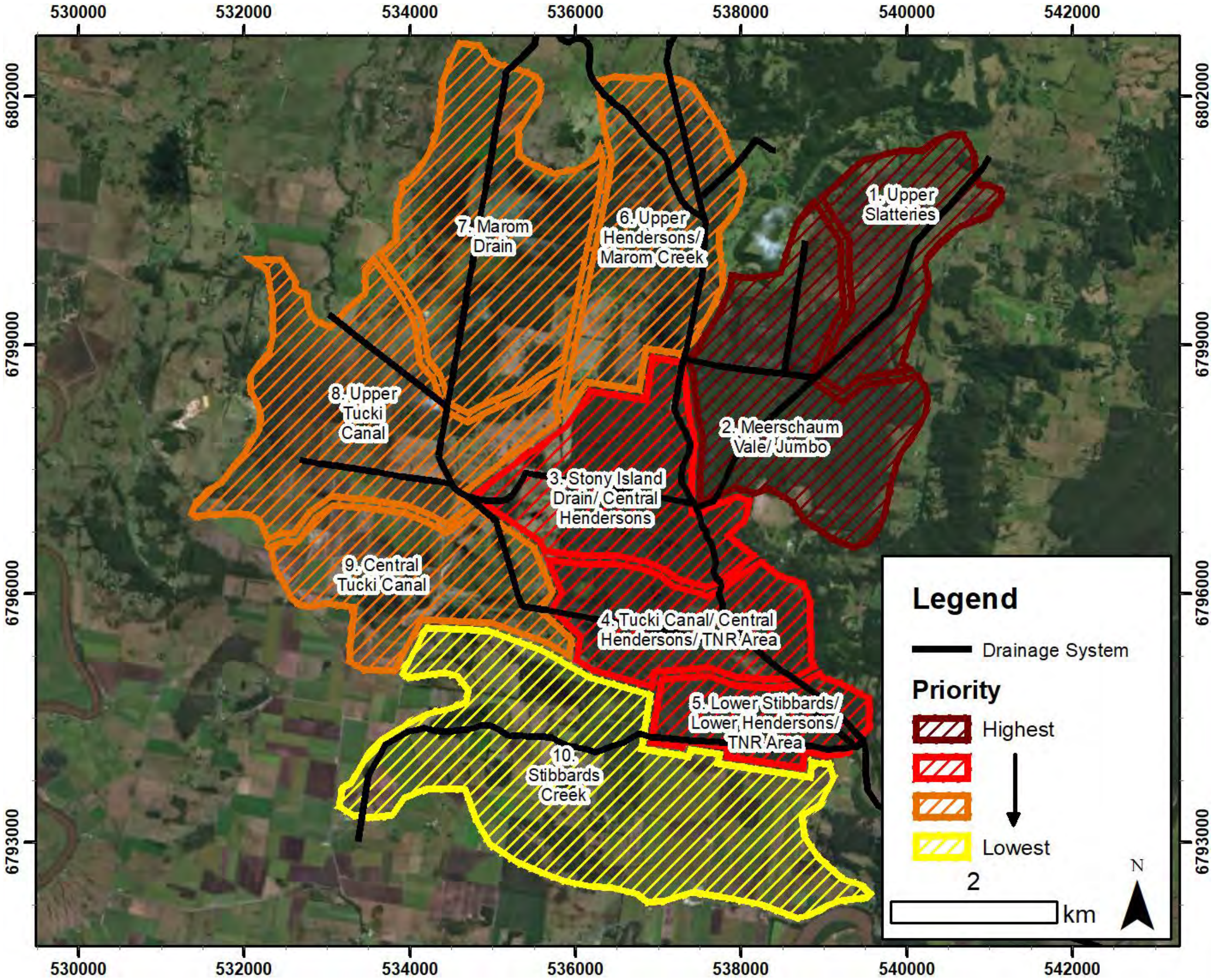

Figure 3-6: Prioritisation of the floodplain

Table 3-1: Justification of prioritisation

Area	Priority	Justification
1. Upper Slatteries	**Highest**	• Large catchment flows • High soil acidity observed • Acidic surface waters observed, particularly at the confluence with Meerschaum Vale Drain • No aquatic life observed • Significant iron floc settlement observed • Low lying topography
2. Meerschaum Vale/ Jumbo	**Highest**	• Worst surface acidity observed in 2018 in Jumbo Drain (pH of 2, approximately the same as a lemon) • High soil acidity observed at most profiles • Significant iron plumes observed discharging from Meerschaum Vale Drain into Hendersons Drain • Low lying topography, significant area between 0 – 0.2 m AHD (where 0 is approximately mean sea level) • No aquatic life observed
3. Stony Island Drain/ Central Hendersons/ Tuckean Nature Reserve Area	**High**	• Surface water pH in Hendersons Drain was typically between 3 – 4 for the length of the Tuckean Nature Reserve • Extensive iron staining observed in Stony Island Drain and Hendersons Drain • Stony Island Drain appears to convey little flow during drier periods and appears to be infilling with soft sediments and other flow impediments • Low lying topography • No aquatic life observed
4. Tucki Canal/ Central Hendersons/ Tuckean Nature Reserve Area	**High**	• Surface water pH in Hendersons Drain was typically between 3 – 4 for the length of the Tuckean Nature Reserve • Extensive iron staining observed in Hendersons Drain (however not in Tucki Canal) • High soil acidity observed at most profiles • Low lying topography • High catchment flows • No aquatic life observed
5. Lower Stibbards/ Lower Hendersons/ Tuckean Nature Reserve Area	**High**	• Lowest lying area of Tuckean Swamp, with significant area below 0 m AHD (mean sea level) • Surface water pH in Hendersons Drain was typically between 3 – 4 for the length of the Tuckean Nature Reserve • Extensive iron staining observed in Hendersons Drain • Significant iron discharge observed in March 2018 • High soil acidity observed at most profiles • Lower sections of Hendersons Drain are very deep (invert as low as -4 m AHD) • High flows • No aquatic life observed
6. Upper Hendersons/ Marom Creek	**Moderate**	• Cross sections surveyed of Hendersons Drain in the lower portion of this section is deep (drain invert around -1.5 m AHD), but narrow

Area	Priority	Justification
		• Most of the area is below 1 m AHD • Some poor surface water quality observed in minor drains • Smaller catchment inflows • High soil acidity observed at some profiles
7. Marom Drain	**Moderate**	• Large catchment flows but a larger baseflow appears to dilute the impact of any ASS • Surface water acidity greater than 5 • Some aquatic life observed in this drain • High soil acidity observed at some profiles • Mostly of the area is above 0.6 m AHD
8. Upper Tucki Canal	**Moderate**	• Very large catchment flows from both Marom Drain and Tucki Tucki Creek but a larger baseflow appears to dilute the impact of any ASS • Low soil acidity observed at available profiles • Most of the area is above 0.6 m AHD
9. Central Tucki Canal	**Moderate**	• Very large catchment flows from both Marom Drain and Tucki Tucki Creek but a larger baseflow appears to dilute the impact of any ASS • High soil acidity observed at available profiles • Most of the area is above 0.6 m AHD
10. Stibbards Creek	**Lowest**	• Highest topography, with significant area above 1 m AHD • More natural creek line • Low hydraulic conductivity observed in dense clays • Near neutral surface water pH observed • Low soil acidity observed at available profiles • Smallest catchment inflows

4 Potential remediation strategies

4.1 Preamble

A range of medium-term (1 to 10 years) and long-term (>10 years) strategies exist to remediate and rehabilitate acid sulfate soil (ASS) affected drains and floodplains. The effectiveness and applicability of each strategy is highly dependent upon on-site specific factors such as hydraulic conductivity, catchment topography, acid layer stratigraphy, drainage conditions, tidal amplitude, climate, land use and landholder willingness. Some strategies include interim remediation options for limiting acid production and discharge, whereas other options aim to permanently limit acid production and export via landscape rehabilitation. This section provides a brief description of medium and long-term remediation strategies for the management of high-priority ASS affected areas. Further information regarding each management strategy and design considerations can be found in the Acid Sulfate Soils Remediation Guidelines for Coastal Floodplains in New South Wales (Tulau, 2007).

The information provided in this section is not specific to the Tuckean Swamp and floodplain and not all options may be suitable for this project. However, it is important to understand the range of options that are available prior to developing scenarios specific to this site.

4.2 Summary of costs for remediation options

Table 4-1 provides a summary of the indicative costs (based on standard commercial rates) for the design, construction, implementation and annual maintenance of various remediation options proposed.

Table 4-1: Indicative costs for various ASS management options

Management Option	Design Cost*	Implementation	Maintenance (per annum)
Weir	$15,000	$10,000 to $35,000	$5,000 to $15,000
Floodgate modification	$20,000	$10,000 to $30,000 per gate	$5,000 to $15,000
Liming	$20,000	$20/m^3 acid soil per application (dependent on acid content)	Dependent on required repetition of liming
Culvert relocation	$20,000	$70,000 to $120,000 per culvert	$10,000
Drain infilling	$20,000	Equipment establishment ($8,000) + unit rate ($12,000/500 m)	None
Drain reshaping	$20,000	Equipment establishment ($8,000) + unit rate ($24,000/500 m)	None
Permeable Reactive Barrier (PRB)	$50,000	$15,000/100 m to $150,000/100 m	$25,000
Wet pasture	$20,000	Potential: Structure relocation + Land acquisition + Drain infilling	None
Land raising	Design and potential flood impact assessment.	Equipment establishment + fill + daily rate	None
Full Rehabilitation	$40,000	Land acquisition (per ha) + Drain infilling + Drain reshaping + Infrastructure removal + Infrastructure relocation	None

*Engineering design only, does not consider additional studies (e.g. environmental impact assessments, flood studies etc.).

4.3 Medium term solutions

Interim remediation options aim to reduce the production and export of existing acidity and have a design life of approximately 10 years. These medium-term acid management options can be characterised as:

- Low implementation cost;
- Low agricultural/landholder impact; and
- High ongoing maintenance cost.

4.3.1 Groundwater manipulation

Weir installations in drainage channels have been shown to reduce the production of acid across ASS affected floodplains (Blunden and Indraratna, 2000). Weirs promote higher drain and groundwater elevations that reduce groundwater drawdown, thereby minimising the hydraulic gradient between groundwater and drainage channels.

Weirs are generally applicable in higher elevation locations on the floodplain, where increases in drain water levels do not result in inundated paddocks or decreased agricultural productivity. Lawrie and Eldridge (2002) noted that the impact of weirs on agricultural activity is minimal, while Blunden and Indraratna (2000) found weir installations to be a successful strategy to minimise acid exports in the upper Broughton Creek floodplain, within the Shoalhaven River estuary. The optimal weir crest elevation is dependent on the elevation of the acidic soil layer. Ideally, the weir crest elevation is situated at or above the elevation of the actual acid sulfate soil (AASS) layer. This minimises the potential for the lateral flow of acidic water from the ground into the drain (Figure 4-1).

Weirs are often designed to reduce acid export whilst maintaining effective drainage during wet periods. Adjustable weirs (i.e. drop boards) are desirable to maintain agricultural productivity following flood periods, while raising the weir crest during dry periods to reduce the groundwater hydraulic gradient and minimise acid export. Figure 4-1 depicts how a weir reduces acid generation and export.

Tulau (2007) listed several criteria that need to be considered for design and installation of weirs to be successful, including:

- Suitable to local conditions;
- Maintains the efficiency of the flood mitigation system;
- Controls different water levels;
- Uses low maintenance and durable materials;
- Complies with workplace health and safety (WHS);
- Vandal resistant;
- Cost effective;
- Landholder willingness and approval; and
- Complies with current legislation.

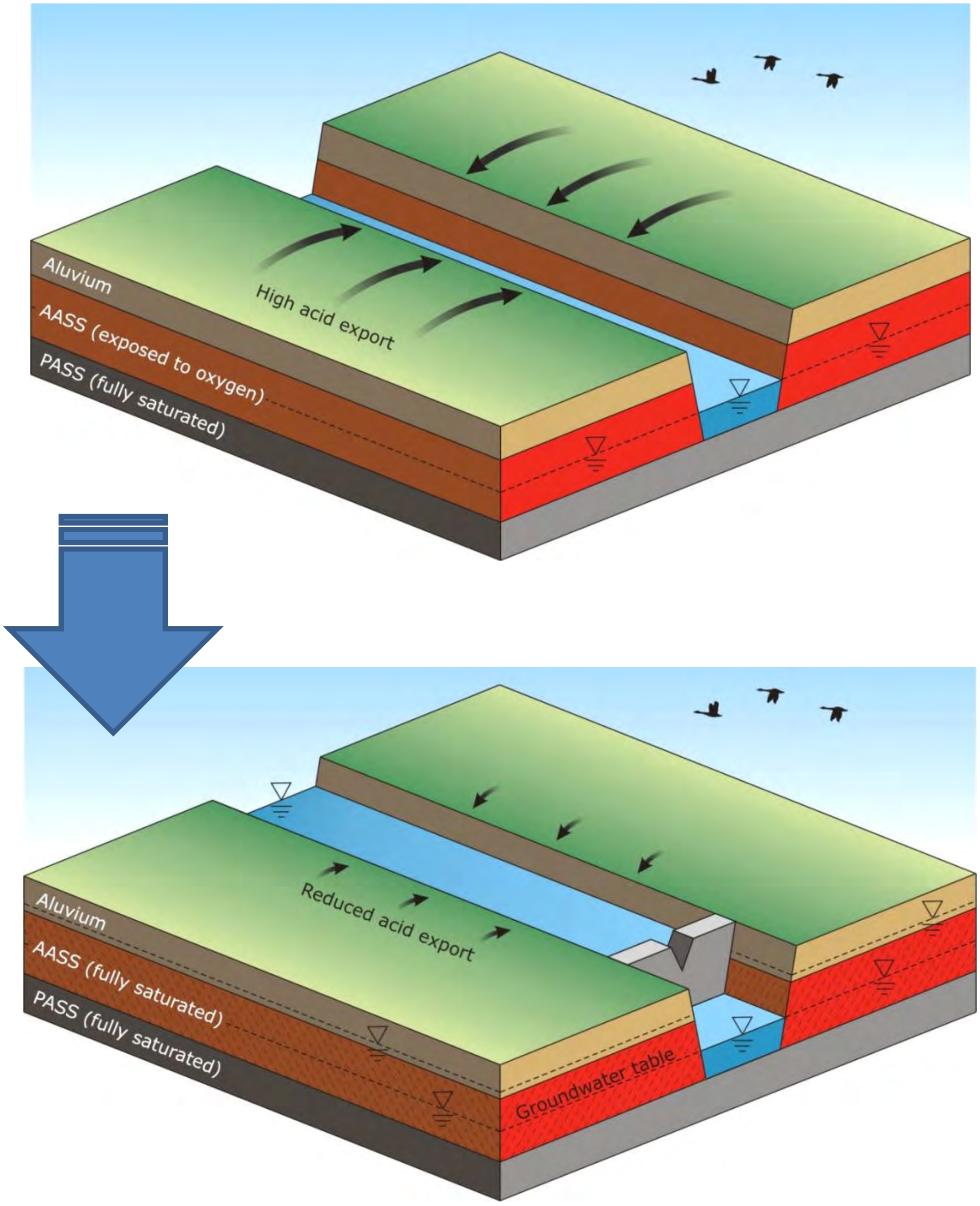

Figure 4-1: Weir implementation before (top) and after (bottom)

4.3.2 Tidal/saline manipulation

One-way floodgates prohibit tidal inundation, maximise pasture drainage, and maintain drain water levels at low tide elevations. When ASS are present, tidal floodgates increase acid discharge and restrict in-drain tidal buffering of acidic waters. Floodgate management and/or modification is widely practiced in NSW. Glamore (2003) showed that in the Shoalhaven River Estuary modified floodgates that permit two-way tidal flows significantly improved water quality, and generally reduced the downstream impacts of ASS discharges. Similar findings have been shown for floodplain remediation on the Manning River (Ruprecht et al., 2017). Specific benefits of floodgate modification include:

- Improved drain water quality through flushing and acid buffering;
- Reduced exotic drain vegetation; and
- Increased fish passage (NSW DPI, 2007).

The extent of tidal restoration at a site is often dependent on the site topography, tidal elevations, available bicarbonate/carbonate within tidal waters, and current land use practices. Typically, landholders utilise in-drain tidal flushing to control weed vegetation, while not impacting adjacent floodplain areas of agricultural production. Uninhibited tidal restoration is rarely undertaken, except when tidal amplitude is low, where agricultural land use practices are abandoned, or where private land is publicly acquired. The installation of auto-tidal gates permits tidal flushing to a pre-determined elevation based on design. Maximum inundation elevations are usually dependent on the topography of the backswamp and the tidal range. Figure 4-2 depicts how a modified floodgate can restore tidal flushing to an ASS affected drainage channel.

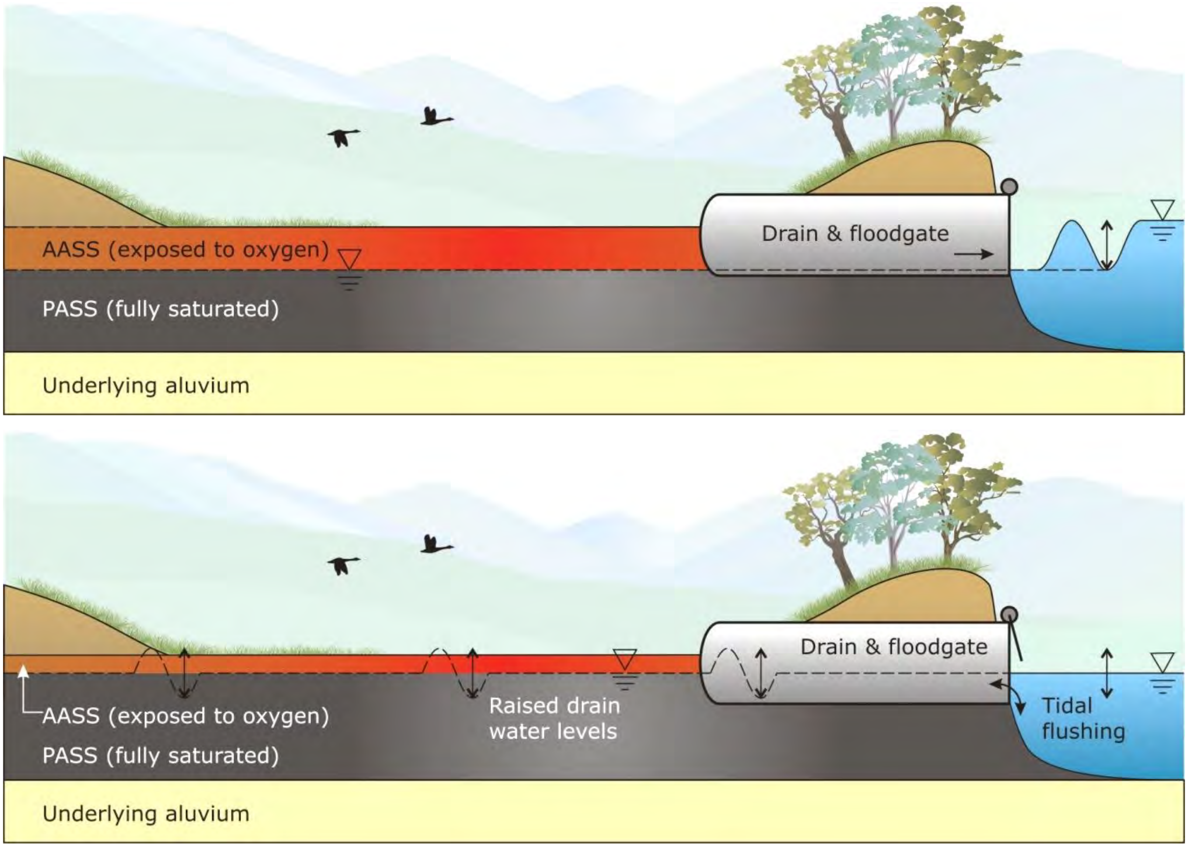

Figure 4-2: Before and after floodgate modification

4.3.3 Liming for acid neutralisation

When applied to ASS, lime reacts with the sediments to neutralise acidity. Lime is comprised of calcium hydroxide (CaOH) and is often applied directly to disturbed or exposed ASS as a dry powder or slurry. Liming is commonly undertaken when soil acidity levels are below neutral or when ASS are excavated and small-scale neutralisation is required. Lime is rarely applied as a broad-acre solution to ASS acidity as the large quantities required for neutralisation and the difficulty in mixing the lime with clayey soils limits the long-term effectiveness.

The injection or application of lime to deep or shallow ASS-affected areas requires large quantities of lime mixed with water to form a slurry to facilitate pumping. Deeper lime injection requires the construction of a borehole network. Large scale application of lime on either the surface or sub-surface of acid affected soil is not a cost-effective management strategy in the Tuckean Swamp floodplain due to the acid content and distribution, and soil structure, Single applications of lime has been shown to not be effective in the long-term (Wong et al., 2016). Liming is often used in conjunction with other remediation strategies that require small scale earthworks such as, levee removal, excavation/dewatering and drain reshaping.

4.4 Long-term rehabilitation options

Long-term management options aim to completely rehabilitate ASS-affected sites and prohibit future acid production. These strategies mainly target changes to the drainage scheme and/or land use practices. Long-term management options are characterised by:

- Minimal ongoing maintenance;
- Changed land-use practice or management regime; and
- Higher upfront capital cost (in contrast to short term options).

Although long-term management options may result in significant changes to land use practice, application of these management options have the potential to be implemented over a sub-portion of an ASS-affected area to maintain agricultural activities. These areas can be targeted for long-term remediation, while lesser affected areas can be managed on a medium-term, reactive timescale. This approach allows for agricultural productivity to continue, whilst addressing key areas of concern. A good example of this approach is shown by the rehabilitation of low-lying, high-priority areas at Big Swamp on the Manning River (Glamore et al., 2014), whereby overland tidal flushing was introduced to a portion of the lowest-lying, worst acid affected area of the floodplain.

4.4.1 Wet pasture

Wet pasture, or reflooding, involves retaining fresh surface water on pastures during dry periods by limiting drainage. Tulau (2007) asserted that this option aims to contain acid and other oxidation products within the soil and surface water by raising water levels in the drain (Figure 4-3). This is usually achieved via the installation of structures in the drainage channel such as a weir, and/or modification of pasture drainage pathways by drain infilling or reshaping.

Johnston et al., (2003) showed that the acid discharge rate from a wet pasture system significantly reduces acid export where groundwater seepage is the main export pathway. This is achieved by reducing the frequency and volume of groundwater interflow. Subsequently, this option is particularly suitable to a site with high to extreme hydraulic conductivity (i.e. very slow groundwater flow rate).

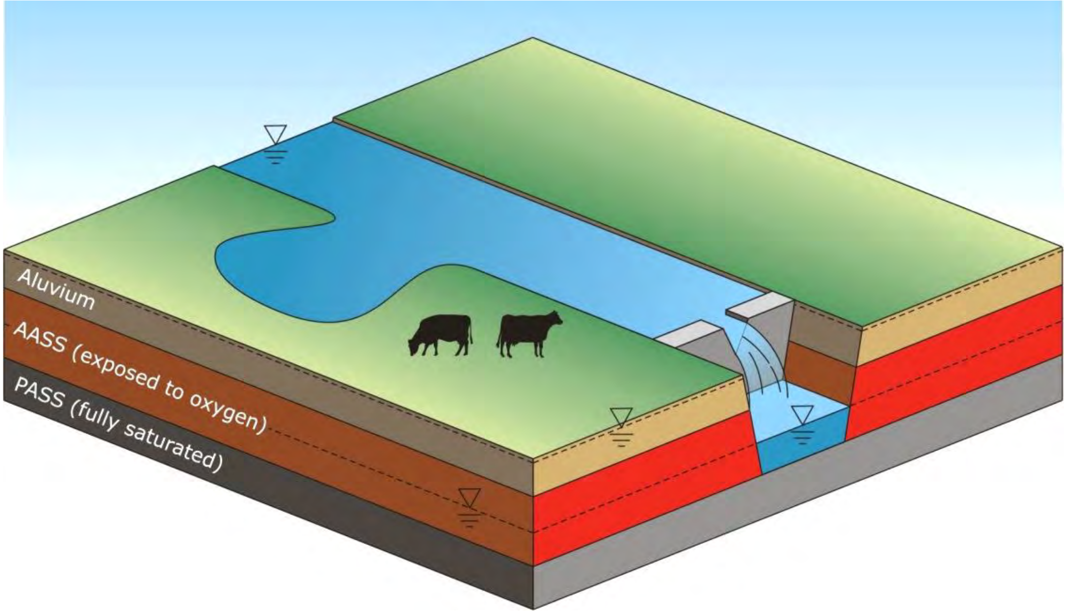

Figure 4-3: Wet pasture management

4.4.2 Drain infilling and reshaping

Infilling, shallowing and reshaping drains can be an effective means of reducing acid discharge and other negative impacts of over drainage, particularly in ASS-affected backswamps (Johnston et al., 2003). Raising drain invert levels, while maintaining the effective drain cross-sectional area, acts to reduce acid seepage and maintains the drainage capacity of the existing system. These drains are commonly referred to as ‘swale drains’ and are depicted in Figure 4-4.

Narrow, deep drains are ideal candidates for drain reshaping, as the drain cross-sectional area required to provide efficient drainage can be maintained through the conversion to a shallow, wide swale drain. Conversely, a wide, deep drain would require a significantly wider swale drain to be constructed to maintain the effective cross-sectional flow area. This strategy is applicable where the acid soil layer is sufficiently deep to enable an efficient drainage slope from the backswamp to the estuary without the drain invert disturbing the acid layer.

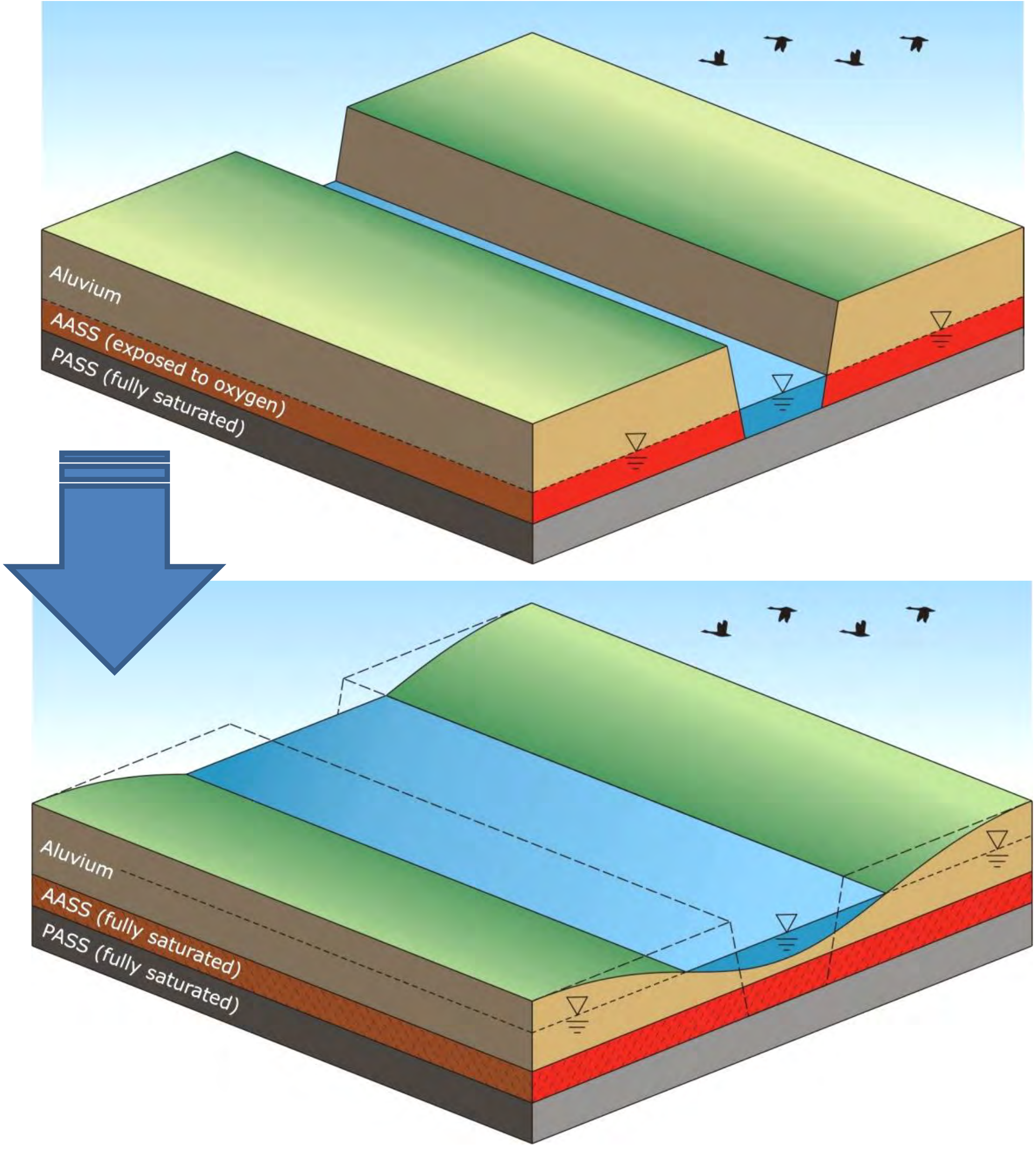

Figure 4-4: Before and after swale drain construction

4.4.3 Land raising

Raising of land by addition of fill (or reshaping) enables acid remediation strategies to be applied without affecting agricultural practices. Depending on the site, land raising would require significant volumes of soil to be transported and levelled across the pastures. This could be implemented where saline tidal inundation is likely to be detrimental to the upper soil profile and existing agricultural practices (Figure 4-5). Examples of this strategy being applied are primarily seen in residential developments in Western Australia, near the Peel Harvey Estuary.

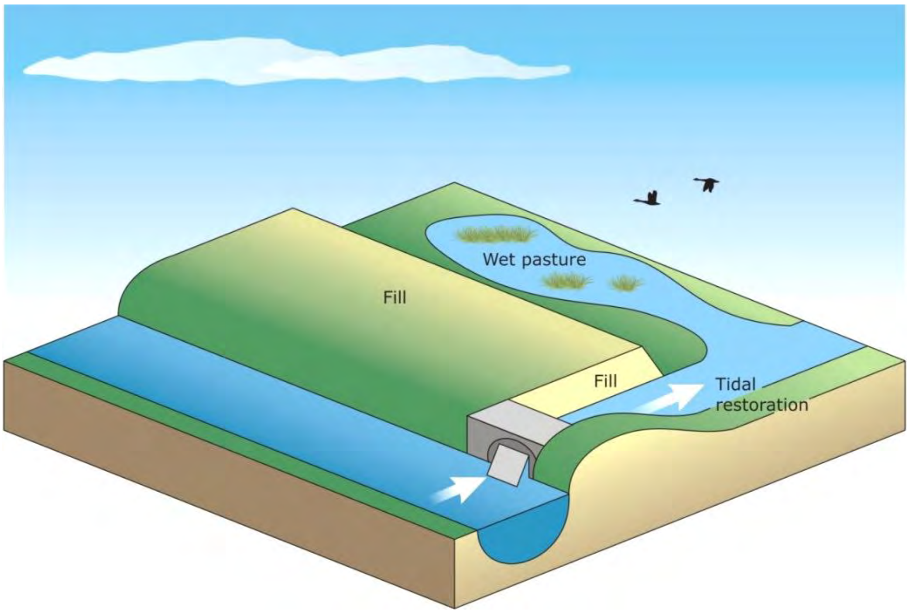

Figure 4-5: Schematic of partial land raising

4.4.4 Full rehabilitation

The floodplains of the north coast rivers once included extensive areas of largely freshwater backswamps. The wettest sites were formerly dominated by grasslands, sedgelands, reedlands, or open water. The character and extent of backswamp vegetation has been confirmed by historical land survey records for the Tuckean Swamp and other backswamps in the Richmond region. The full rehabilitation of the former backswamp areas to reinstate their former condition may effectively limit acid export and provide habitat for primary production. In a similar manner to land raising and wet pasture management options, site rehabilitation to create saltmarsh or tidal/freshwater wetlands could be undertaken over an entire ASS-affected drainage area, or on a sub-portion of the floodplain. This strategy has been effectively applied at other acid affected sites in NSW, including Tomago and Hexham wetlands near Newcastle (Rayner and Glamore 2010), Yarrahapinni Wetlands on the Macleay River and Big Swamp on the Manning River (Glamore et al., 2014, Ruprecht et al., 2017).

Wetland or saltmarsh creation would require onsite hydrological changes including the removal or relocation of levees and floodgates, as well as drains to be infilled or reshaped (depicted in Figure 4-6). Where partial rehabilitation is optioned, structures may be relocated to maintain existing agricultural land-use conditions for other areas of the floodplain. Where full rehabilitation is considered, regular tidal inundation would provide immediate natural buffering of ASS affected areas and maintain high groundwater levels. This management option has the greatest immediate environmental benefit potential as it improves water quality, eliminates acid discharge, and provides aquatic habitat and fish passage. However, this option also requires the largest change to existing land management and any proposed changes should be carefully considered, engineered and assessed (as per below).

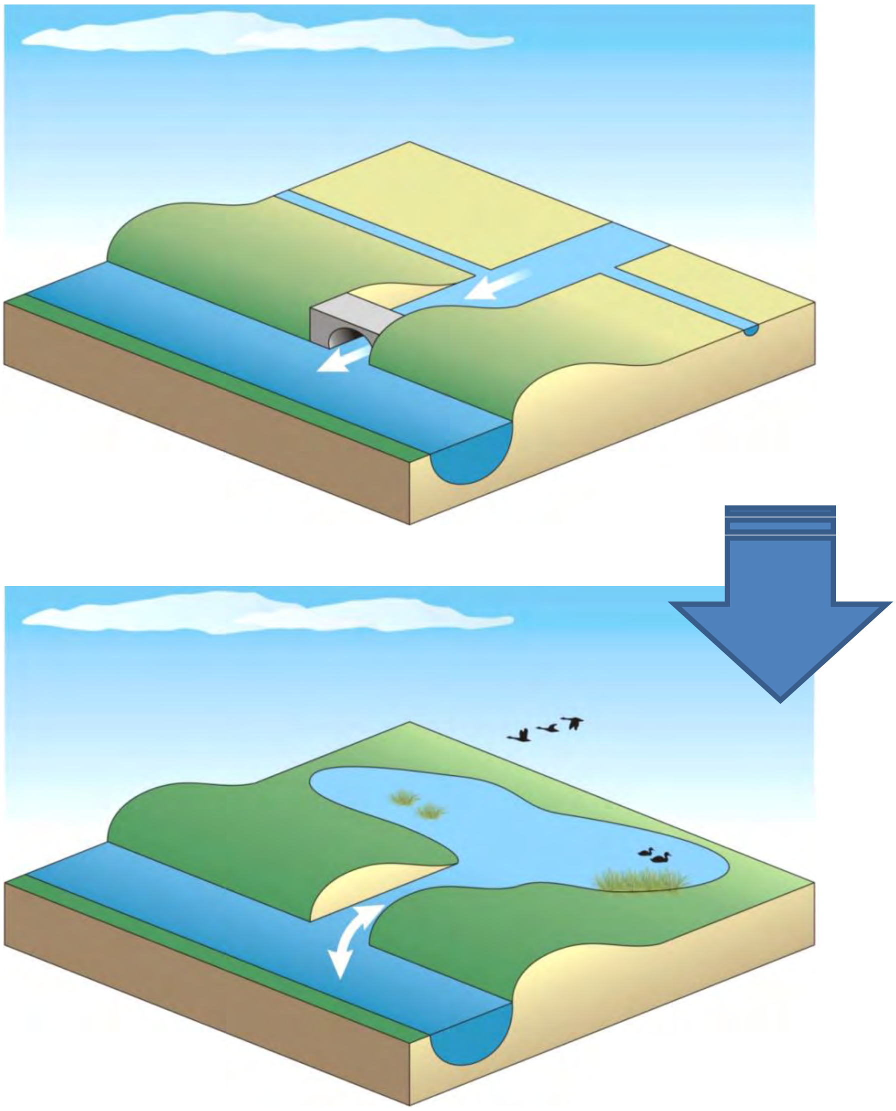

Figure 4-6: Full rehabilitation to natural, unrestricted wetland

5 Drainage management options

5.1 Preamble

A conceptual understanding of Tuckean Swamp helps to identify the origin of the acidity issues on the floodplain and potential remediation options. As discussed in Section 4, various remediation and rehabilitation strategies are available and have been implemented elsewhere. However, it is important to recognise that any changes to the drainage scheme have the potential to impact the economic, social and environmental uses and values of the floodplain. As such, on-ground remedial works require detailed understanding and site-specific analysis to asses both consequences and benefits.

A detailed hydrodynamic computer model was developed for the Tuckean Swamp and floodplain using the commercially available MIKE suite of models to assess the consequences and benefits of potential remedial works. The model was initially constructed to represent the floodplain as it exists today. Field data that had been collected was input into the model and used to verify the model's ability to replicate the present (often referred to as the "Base Case") drainage conditions. Once the Base Case model was developed, modifications could be made to the model to test "what if" scenarios comprising different drainage management options (referred to as "modelling scenarios"). Under this approach, the computer model could be used to simulate a number of potential on-ground scenarios and the results used to assess the impacts during different hydrologic conditions. The purpose of this assessment was to develop a detailed understanding of the implications of any potential change to the drainage system and provide improved future management options for the floodplain.

Through stakeholder discussions, six (6) modelling scenarios were proposed for the Tuckean Swamp drainage scheme:

- **Scenario 1:** Reshaping Meerschaum Vale Drain and Slatteries Drain;
- **Scenario 2:** Installation of a weir on Meerschaum Vale Drain;
- **Scenario 3:** Improving the management of the existing sluice gates;
- **Scenario 4:** Opening the barrage floodgates;
- **Scenario 5:** Reshaping Meerschaum Vale and Slatteries Drains and encouraging re-flooding of a sub-section of the floodplain; and
- **Scenario 6:** Opening the barrage floodgates and installing new upstream floodgates at the borders of the Tuckean Nature Reserve.

These scenarios have been tested to enable better understanding of the potential impact of each management option presented in this report. This is an important step in understanding which options may be feasible given the current land management practices. Note that model testing of a drainage management option is simply the first step in the assessment process and should in no way be misconstrued as a commitment to on-ground changes either now or into the future. Any changes to on-ground infrastructure, including the management of the Bagotville Barrage or changes to flood mitigation drains, would only be implemented in consultation with landholders and other stakeholders. Detailed assessment of all potential environmental impacts and a benefit cost assessment would also be required to support the implementation of any on-groundworks.

This section provides further details on the six (6) modelling scenarios that were developed for the Tuckean floodplain, including the rationale for each scenario and potential impacts to the floodplain and site drainage, compared to the existing, present-day Base Case.

5.1.1 Model limitations

Numerical models, by their nature, are simplifications of the reality under investigation and, because of these simplifications, all computer models provide an approximation of the real world. The development and calibration of the numerical model of the Tuckean Swamp and drainage scheme is outlined in Appendix C and Appendix D, respectively. Where possible, the model is based on recent field data collected specifically for this project and represents best practice in the field of hydrologic simulations. However, despite the extensive data collection, there are some important model limitations as discussed below.

The MIKE suite of modelling software was used to develop a dynamically linked 1-D/2-D hydrodynamic numerical model of the Tuckean Swamp floodplain. The 1-D section of the model includes the primary drainage network of deep, wide channels, shown in Figure 5-1. Based on the conceptual understanding of the site, these drains convey most of the flows on the Tuckean floodplain. However, there are numerous, smaller, secondary drains throughout many of the properties which are included at a lower resolution in the 2-D floodplain model. While it is not expected that this will make an appreciable difference to water level results within the drainage network, it may mean that drainage from the floodplain is slower in the model (compared to reality) due to the reduced connectivity of secondary drains to the major channels. Nonetheless, the model is appropriate for understanding the relative changes to floodplain inundation and in-drain water levels from different drainage management options.

The model has been calibrated to water levels observed in the drainage network during October 2018 (see Appendix D). The model has not, however, been calibrated to water velocities or flows in the drainage network or across the floodplain as there is insufficient data available to describe these variables.

One of the main internal model parameters is the Manning's "n" parameter, a measure of channel roughness or friction, as summarised in Section D.2.2. Many of the channels within the Tuckean Swamp drainage network are heavily vegetated (primarily by water lilies, as shown in Figure 5-2), which have resulted in high friction in many of the channels. While this represents the drainage system as it was observed in March and June 2018, changes in drainage management may affect vegetation growth and channel roughness (such as increased salinity which may result in conditions unsuitable for water lilies and effectively clear the drains). No changes to the internal model parameters, such as the Manning's n, have been included in the modelling scenarios as these changes are uncertain. However, reducing the roughness of the drains may impact channel conveyance and potentially underestimate tidal intrusion within the drainage network. This should be considered before undertaking on-ground works at the site.

Bathymetry data was collected throughout the floodplain in March and June 2018. However, due to the size of the site and limited property access throughout the field campaign, some areas were not surveyed, particularly around confluence of Tucki Canal, Marom Drain and Stony Island Drain. As a result, there is more uncertainty in this region of the model and the accuracy of the model in the western portion of the swamp (i.e. Marom Drain) may be limited.

Overall, the model developed for this project is considered 'fit for purpose' to simulate the impacts of alternative drainage management scenarios during dry periods and small to medium catchment events. Usage of the model for purposes other than this study (such as large-scale flooding) would require further calibration and refinement.

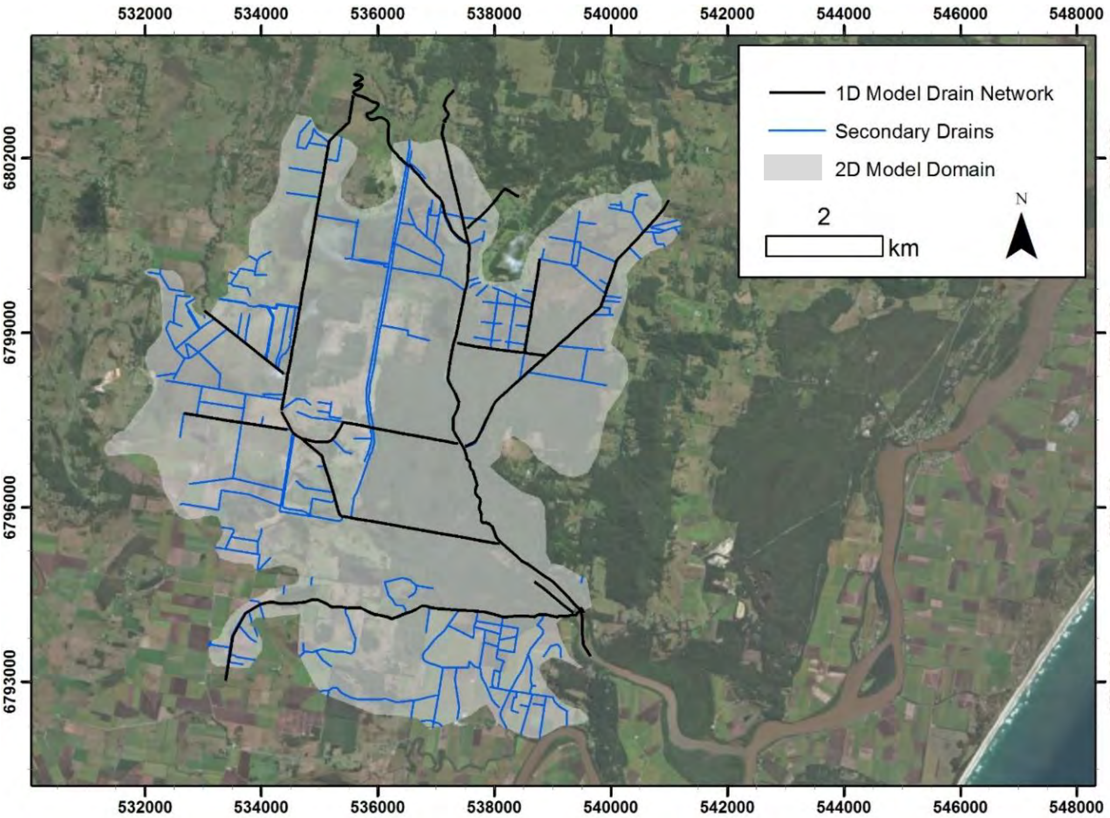

Figure 5-1: Model drainage network and secondary drains

Figure 5-2: Vegetation in Meerschaum Vale Drain

5.1.2 Result comparison

To understand the impact of each drainage management scenario, water levels and floodplain inundation changes before/after each scenario (compared to the Base Case) are required. During periods of limited rainfall, catchment inflows to drained coastal floodplains, such as Tuckean Swamp, typically remain constrained within the drainage channel network with limited overbank flow. However, these floodplains are low-lying and often become partially inundated during periods of significant rainfall. While minor local changes to the drainage scheme are unlikely to impact drainage during/after a large flood event (greater than 1 year average recurrence interval, when water levels in the greater Richmond River are the primary control of water levels in the floodplain), these local changes may alter the drainage during nuisance flood events (that occur once or twice a year on average). To assess these potential impacts, the model results have been extracted during two (2) distinct periods.

Each model was run to simulate the period from 1st October 2018 to 28th February 2019, which includes a rainfall event in October 2018 (equivalent to an event which typically occurs once or twice every year), and a prolonged dry period during January and February 2019. All models were run to simulate hydrodynamics (how water moves across the floodplain). For models where there was capacity for tidal inflows from the Tuckean Broadwater (Scenario 3, 4 and 6), salinity concentrations were also simulated.

For the purpose of comparing the results in each modelling scenario to the Base Case, a number of standard measurements are provided. The results from the two-dimensional floodplain model are presented as the change in mean and maximum inundation depth across the model domain. A positive change indicates that the inundation depth is greater than the Base Case, while a negative change indicates a smaller inundation depth compared to the Base Case. Only changes greater than 5 cm will be considered, as changes smaller than this are beyond the anticipated model accuracy.

To highlight the change in water levels within the drainage scheme, results have been extracted at specific locations within the model drainage network. The modelling scenarios can be broadly grouped into two (2) categories – those that are targeting the highest priority areas in the north-east corner of the floodplain (Scenario 1, 2 and 5) and those requiring a change of management to the barrage (including the sluice gates – Scenario 3, 4 and 6). As the former category has negligible impacts on the wider floodplain, the 1D results have been extracted at locations shown in Figure 5-3. For the remaining scenarios, both water levels and salinity were extracted at the locations shown in Figure 5-4.

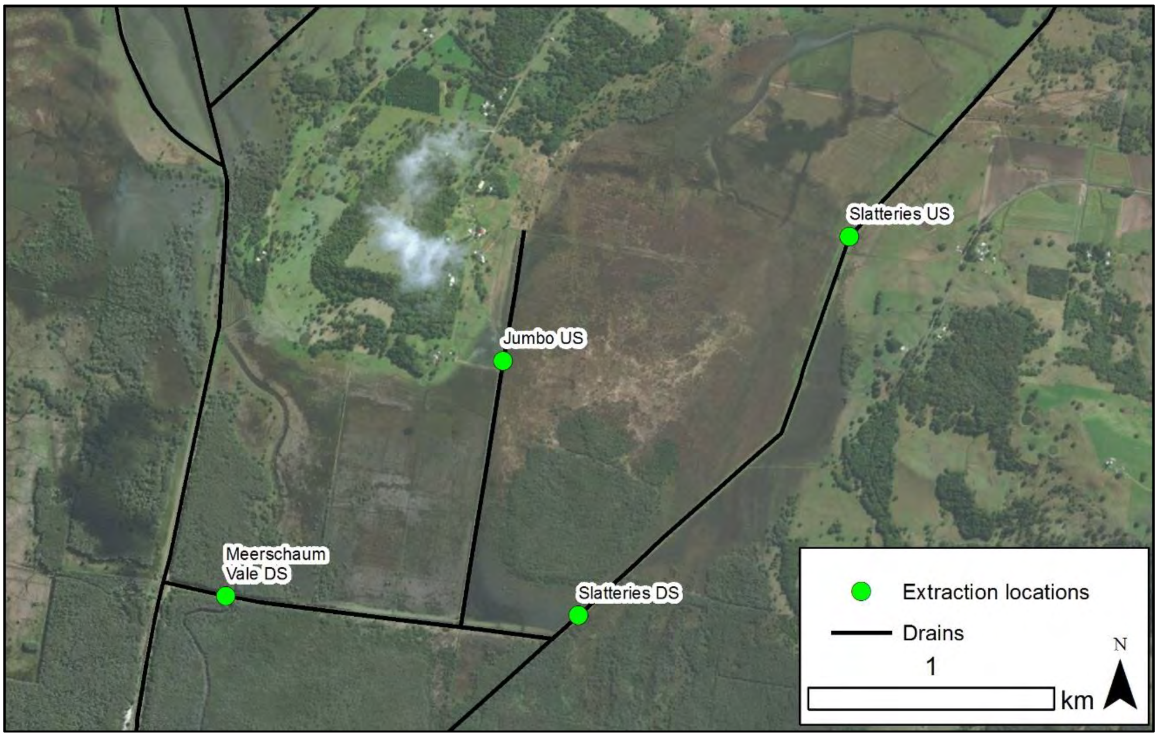

Figure 5-3: Water level extraction locations in the north-east corner of the floodplain

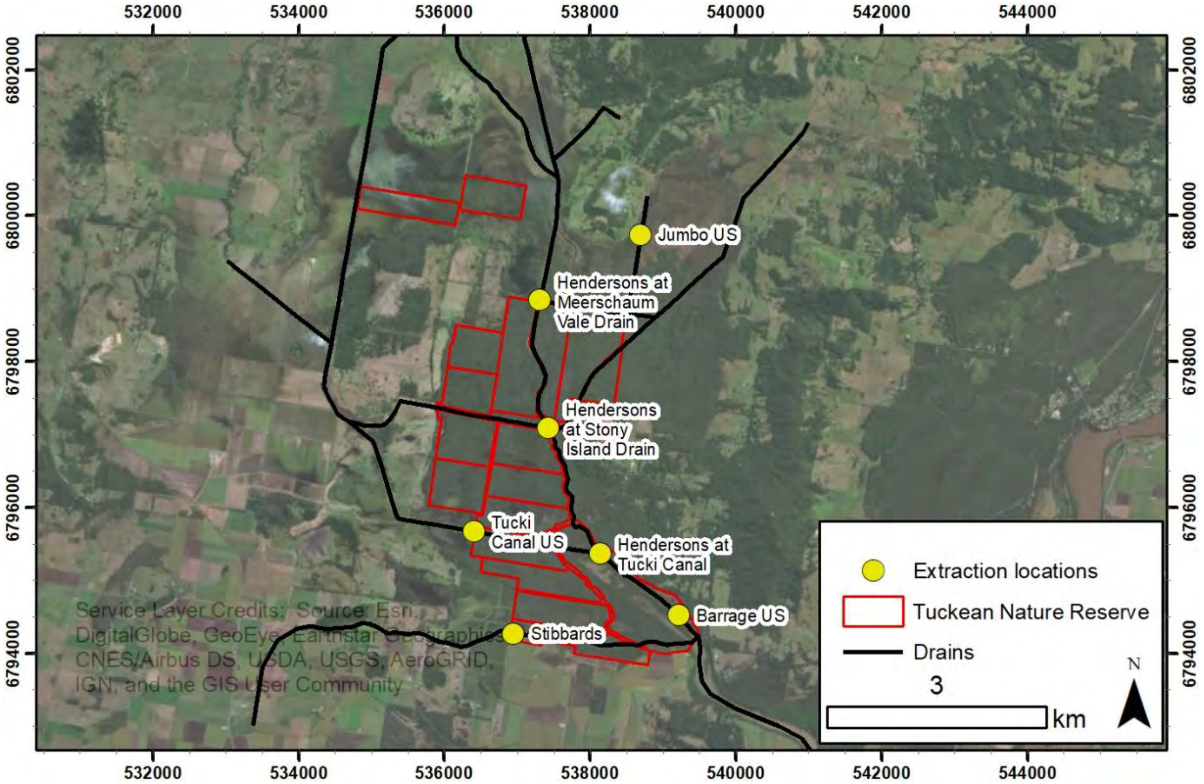

Figure 5-4: Water level locations extracted from the model for analysis

There is limited long-term salinity data available as a boundary condition for the model. To overcome this limitation, a constant water quality boundary condition of 100 (arbitrary units) was implemented in the Tuckean Broadwater. Using this approach, salinity modelled upstream of the barrage can be interpreted as a percentage of the salinity in the Broadwater. For example, a modelled salinity of 50 implies that the salinity at that location is 50% (or half) of the salinity observed in the Tuckean Broadwater.

For each model scenario, several key considerations have been specifically addressed and highlighted based on the results. The significance of each of the key considerations is provided in Table 5-1. Many of these considerations specifically relate to landholder impacts, which should be considered when comparing the results of each scenario.

Table 5-1: Summary of the significance of key considerations

Consideration	Significance
Floodplain inundation	Changes to mean and maximum inundation has important implications for land use and vegetation. In areas where land is privately owned and used for agriculture (e.g. cane farming or cattle grazing), changes to floodplain inundation can impact on the viability of the land for its current use, which should be considered when interpreting the results. In densely vegetated areas (e.g. the Tuckean Nature Reserve), increases in inundation may result in the long-term vegetation changes towards water tolerant species.
In-channel drainage after rainfall events	Drainage times within the major channels after rainfall is significant as it controls the drainage on paddock scale drains managed by landholders. Longer drainage times may impact current land practices.
Diffusive acid transport	Diffusive acid transport occurs when drains intersect the acidic layers of the soil. It contributes to everyday water quality in the drains. Decreased diffusive acid transport would improve the day to day water quality in the drainage system.
Groundwater levels	Groundwater levels are significant for several reasons. Low groundwater levels can result in the exposure and oxidisation of ASS which has an impact on water quality throughout the system. However, high groundwater levels can limit or eliminate the production from some agricultural land uses, including sugar cane which occurs on the Tuckean floodplain.
Advective acid transport	Advective acid transport typically occurs after rainfall when surface waters quickly recede, and a hydraulic gradient is present between the lowered surface water and high groundwater table. Advective acid transport from highly acidic soils, such as those found in Tuckean Swamp, can result in acute declines in pH throughout the Tuckean drainage system, the Tuckean Broadwater and in the receiving waters of the Richmond River. The acidic water can be toxic to aquatic flora and fauna. Limiting advective transport can reduce the frequency and severity of these acid events.

Consideration	Significance
Salinity	Increasing the salinity upstream of the Bagotville Barrage could have numerous impacts. Naturally occurring bicarbonates in brackish water acts as a neutralising agent, buffering acid discharges during day to day conditions. It is likely that increasing the salinity would improve median pH levels observed discharging from the barrage. Brackish water can be useful to help manage weeds throughout the drainage system that do not tolerate salt. However, saltwater inundation on many types of agricultural land, including sugar and most grazing land can kill crops and grass and eliminate productivity from the area impacted. In general, current land practices would not be able to be continued on the farmed areas of Tuckean Swamp if saltwater inundation occurs. Saltwater in the drainage system can also be an issue for some crops (including sugar cane) where high hydraulic conductivity soils exist that allow efficient transport through the drainage system.
Implementation constraints	For some of the options highlighted, there are significant constraints that should be acknowledged and considered when comparing the management scenarios. They include (but are not limited to) landholder consent, acquisition/compensation for lost productivity of land, disturbance of ASS and social costs of land use changes.

5.2 Scenario 1: Reshaping of Meerschaum Vale and Slatteries Drain

5.2.1 Description

Scenario 1 investigates the impacts of reshaping, or ‘swaling’ Meerschaum Vale Drain, Jumbo Drain and Slatteries Drain in the high priority north-east corner of Tuckean Swamp (shown in Figure 5-5). Infilling, shallowing and reshaping drains can be an effective means of reducing acid discharge and other negative impacts of over drainage, particularly in ASS-affected backswamps (Johnston et al., 2003). Raising drain invert levels, while maintaining the effective drain cross-sectional area, acts to reduce groundwater discharge while maintaining the drainage capacity of the existing system. These drains are commonly referred to as ‘swale drains’ and are depicted in Figure 5-5.

Ideally, the invert of the drain is raised above the top of the ASS layer. However, as the ASS layer is at or near the surface in the Tuckean region (see Appendix B, Section B.8 for more details), some balance has to be sought between raising the drain invert and maintaining the conveyance of the channels and providing wider floodplain drainage. The existing invert of Slatteries Drain (shown in Figure 5-6) has two natural high points, at approximate chainages 2,200 m and 3,300 m. As such, drain reshaping was designed so that the drain invert followed these natural high points to have the least impact on day to day drainage (the new inverts shown in Figure 5-6 and Figure 5-7). The Meerschaum Vale Drain invert was raised so that the confluence with Hendersons Drain was at -0.4 m AHD, approximately the lowest level that is currently reached. Jumbo Drain was given a flat invert of -0.3 m AHD.

To maintain sufficient conveyance, the drains have to be widened to approximately twice the existing bank width. Analytical methods were used to estimate the required width to maintain conveyance throughout the length of Meerschaum Vale Drain and Slatteries Drain. Jumbo Drain was not widened, as this drain provides local paddock scale drainage only. An example of a swaled drain profile is provided in Figure 5-8. At this stage, it is assumed that there would be no changes to the elevation of the levees as a result of the drain widening.

For this scenario the barrage was assumed to be closed with all sluice gates closed. Therefore, salinity was not modelled for this scenario.

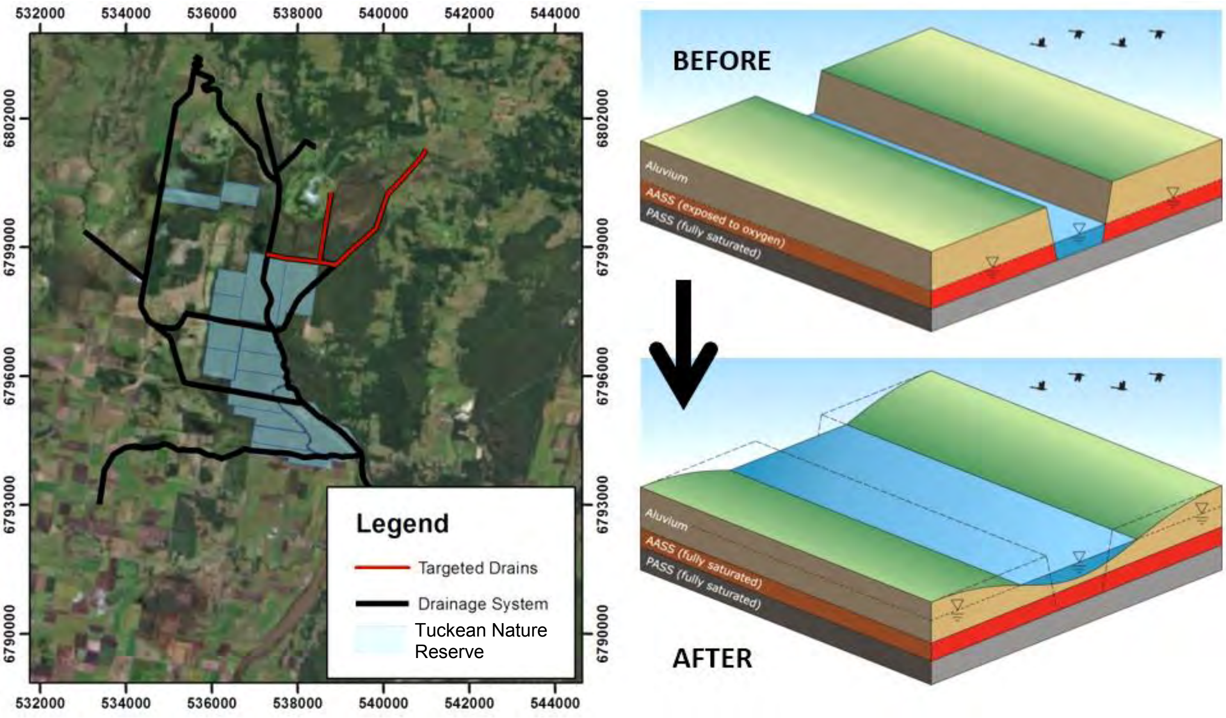

Figure 5-5: Left – Drains targeted for drain reshaping, Right – example of new drain profile positioned above the ASS layer after the drain reshaping

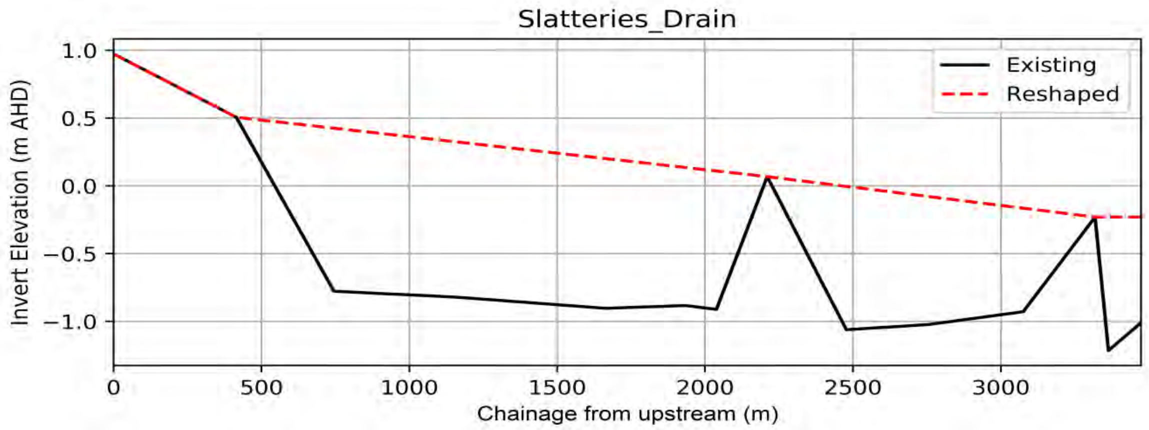

Figure 5-6: Existing and proposed invert of Slatteries Drain – including after reshaping

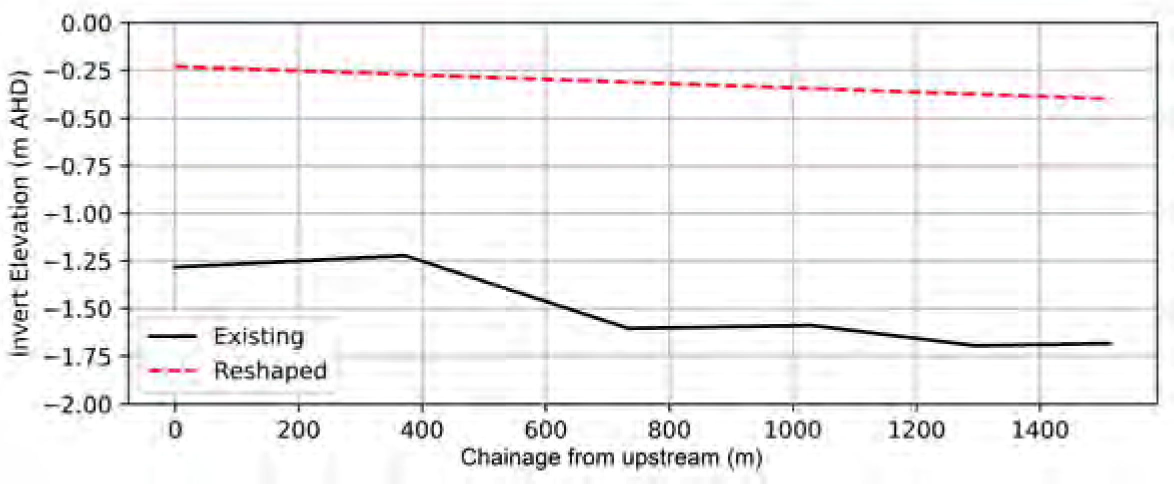

Figure 5-7: Invert of Meerschaum Vale Drain - existing and after reshaping

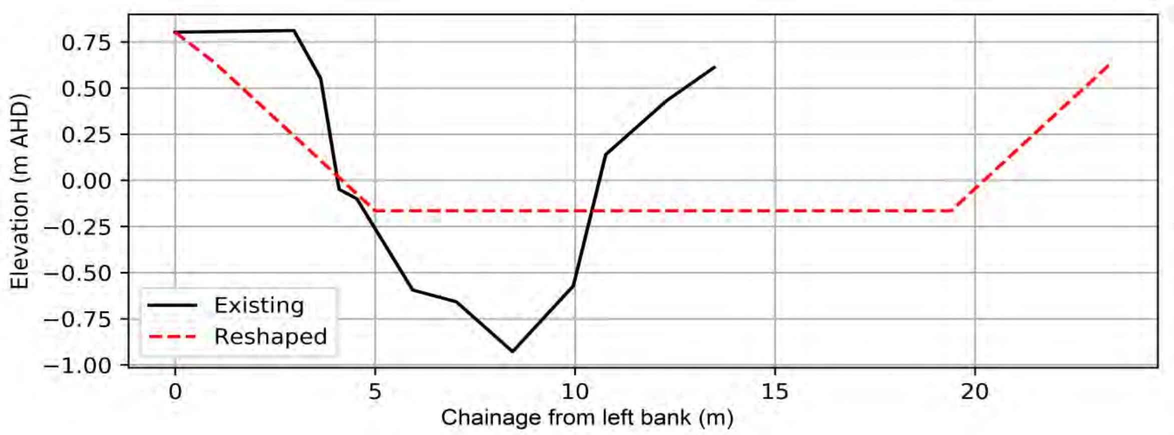

Figure 5-8: Example of reshaped drain (Slatteries Drain, chainage 2,750 m)

The north-eastern area of the Tuckean floodplain has been identified as a high priority for remediation due to the contribution to acid generation from this area. Swaling drains and increasing the invert of these drains will typically increase mean water levels in the drains (and surrounding groundwater levels) and reduce diffusive acid transport. The purpose of this scenario is to investigate whether reshaping of the drains could successfully be implemented without major impacts to drainage and inundation of the adjacent private property. The design of the swale drains could be optimised if impacts on the floodplain are considered acceptable, although further modelling would be required.

5.2.2 Changes in hydrodynamics from the Base Case

Scenario 1 alters the drainage in the north-east corner of the Tuckean floodplain. Modelling shows that there are minimal impacts for the areas west of Hendersons Drain. As such, this discussion focuses on the areas around Slatteries and Meerschaum Vale Drains.

Figure 5-9 shows the changes in floodplain mean and maximum inundation in the area of interest. As the drains have been significantly widened, as well as shallowed, the conveyance capacity during large rainfall events has been maintained. As a result, the changes in inundation across the floodplain are minimal and unlikely to influence the current land use onsite.

While the floodplain inundation does not change significantly, Figure 5-10 and Figure 5-11 show that the water levels within the drains have changed compared to the Base Case. Locations for presentation of water levels are shown in Figure 5-3. During the October 2018 rain event (Figure 5-10), peak water level did not increase throughout the north-east corner. However, the drainage after the peak of the event was influenced by the shallowed drains. For example, location ‘Slatteries US’ takes approximately 10 days to drain below 0.6 m AHD in Scenario 1, whereas it only took 6 days to reach the same level in the Base Case. This may impact landholders in this area in the week after a rain event, although the broadacre changes to floodplain inundation are generally minor.

During periods of prolonged low rainfall, such as between December 2018 and February 2019 (shown in Figure 5-11), water levels within the drains are generally 20 – 30 cm higher when compared to the Base Case. Assuming that the channels affected by this scenario drain the groundwater from an area of approximately 3 km^2, this means that there would be approximately 600,000 to 900,000 m^3 of ASS affected soil (pH typically around 3 – 4) that no longer transports acid into the surface water drainage system.

5.2.3 Summary of implications for Scenario 1

Based on the results of the numerical model, the impacts of reshaping the major drains in the north-east corner on the floodplain and drainage network hydrodynamics are summarised in Table 5-2. Indicative costs are also included, based on Table 4-1.

Table 5-2: Summary of implications for Scenario 1

Consideration	Implication
Floodplain inundation	Changes to mean and maximum floodplain drainage is minimal.
In-channel drainage after rainfall events	Drainage times will increase within the drainage network as a result of swaled drains.
Diffusive acid transport	Diffusive acid transport will be reduced as the drains no longer intersect the deeper acid sulfate soils existing on the floodplain. As ASS exist at or near the surface in this region, some diffusive acid transport is likely to continue.
Groundwater levels	Higher mean and minimum surface water levels, will increase the average groundwater levels in the north-east corner of the floodplain and reduce groundwater discharge and limit the groundwater interaction with acidic soils.
Advective acid transport	A reduced hydraulic gradient between the surface water and groundwater will decrease advective acid transport from the surrounding floodplain. Based on minimum surface water levels during a dry period, it is estimated that this will reduce acid transport from approximately 600,000 to 900,000 m^3 of ASS.
Salinity	No changes to salinity are expected as a result of this work.
Implementation constraints	Swaled drains typically have a larger footprint than the narrower, deeper drains that they replace. This work would require agreement from the private landholders that live adjacent to the relevant drains. To construct the drains actual acid sulfate soils will have to be disturbed, which would require an acid sulfate soil plan. In some areas, swaling may also require outside fill to be obtained from off-site.

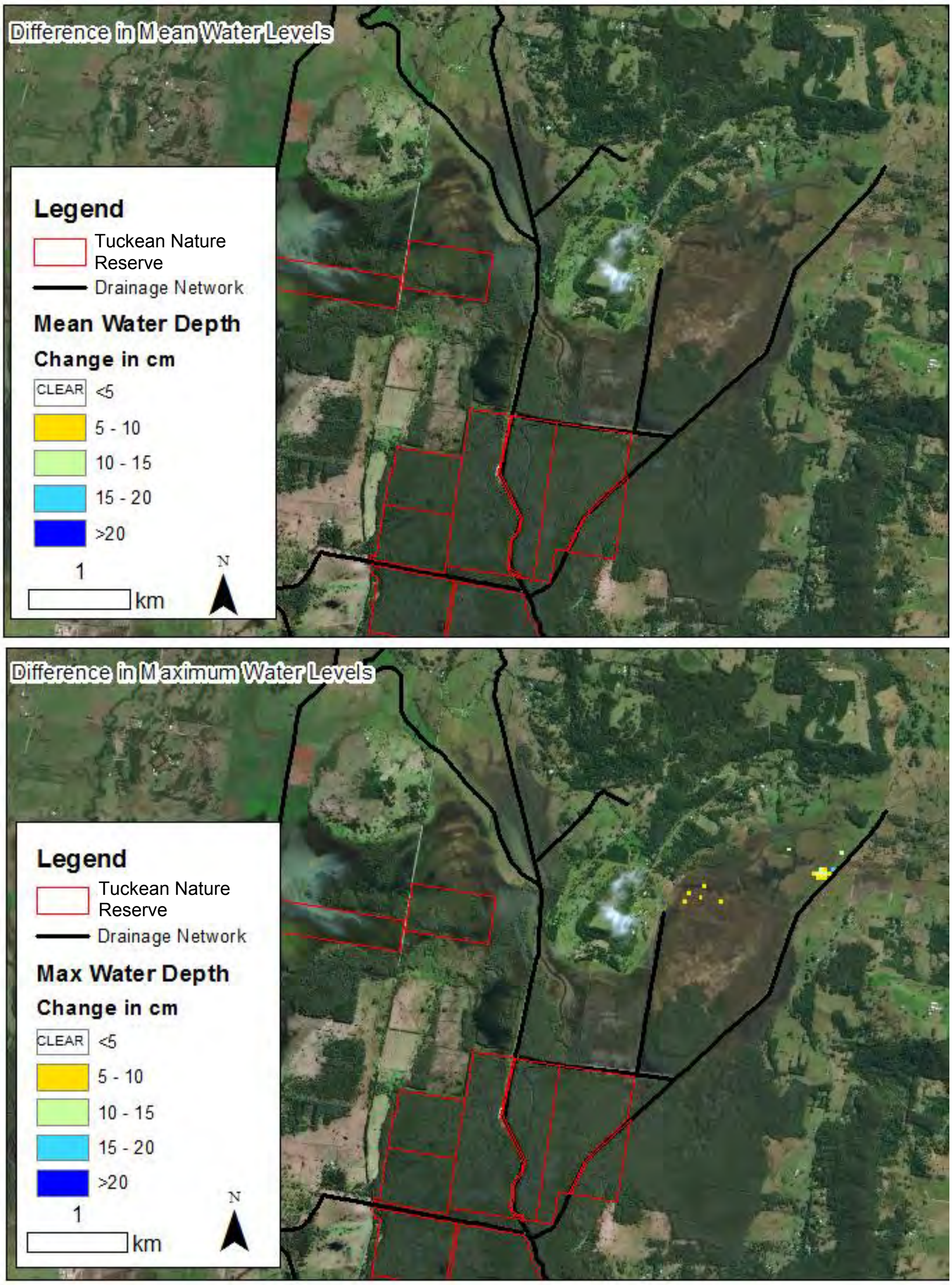

Figure 5-9: Scenario 1 - differences in mean (top) and maximum water depth on the floodplain, compared to the Base Case

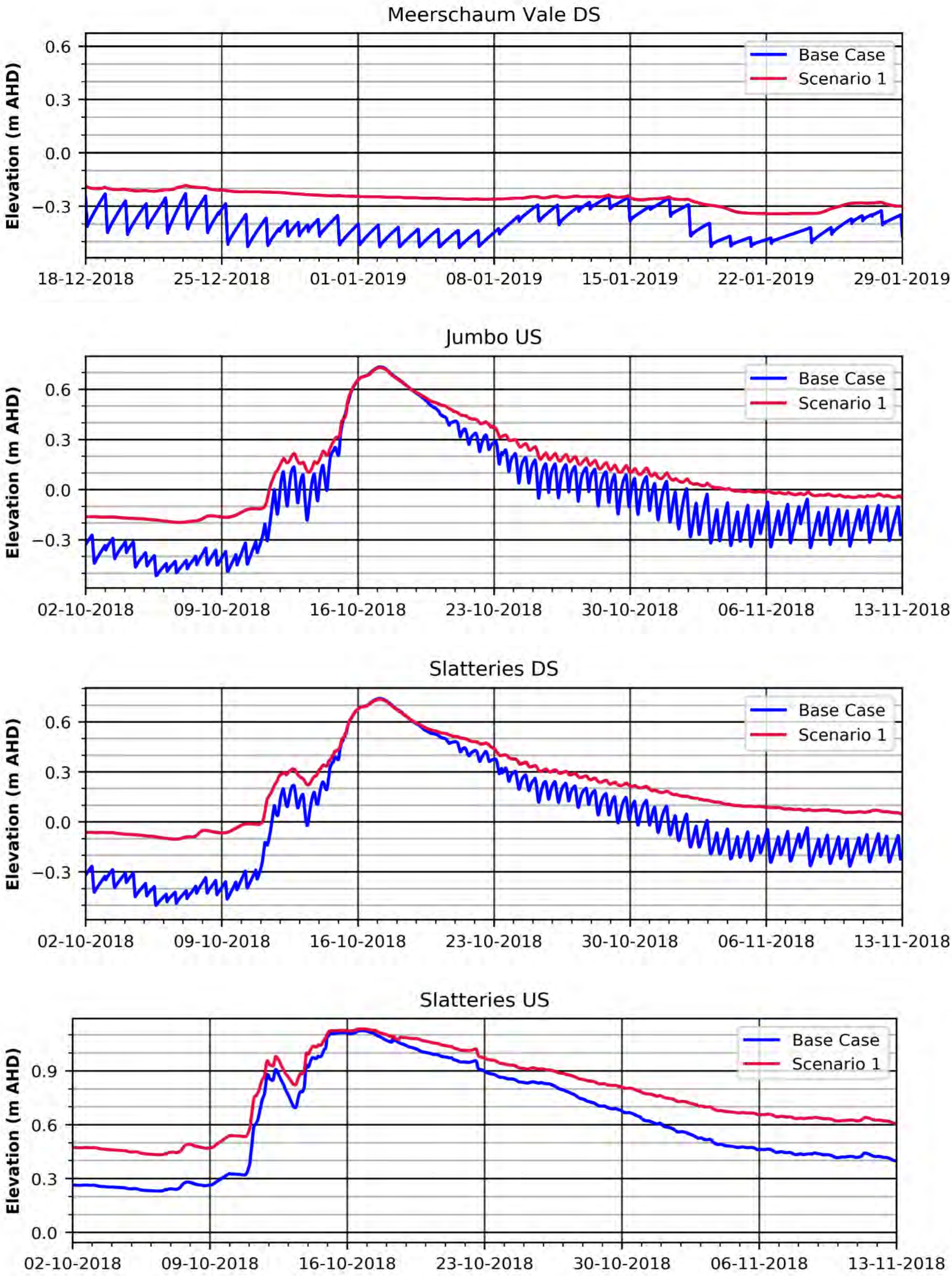

Figure 5-10: Scenario 1 - wet period drainage at key locations

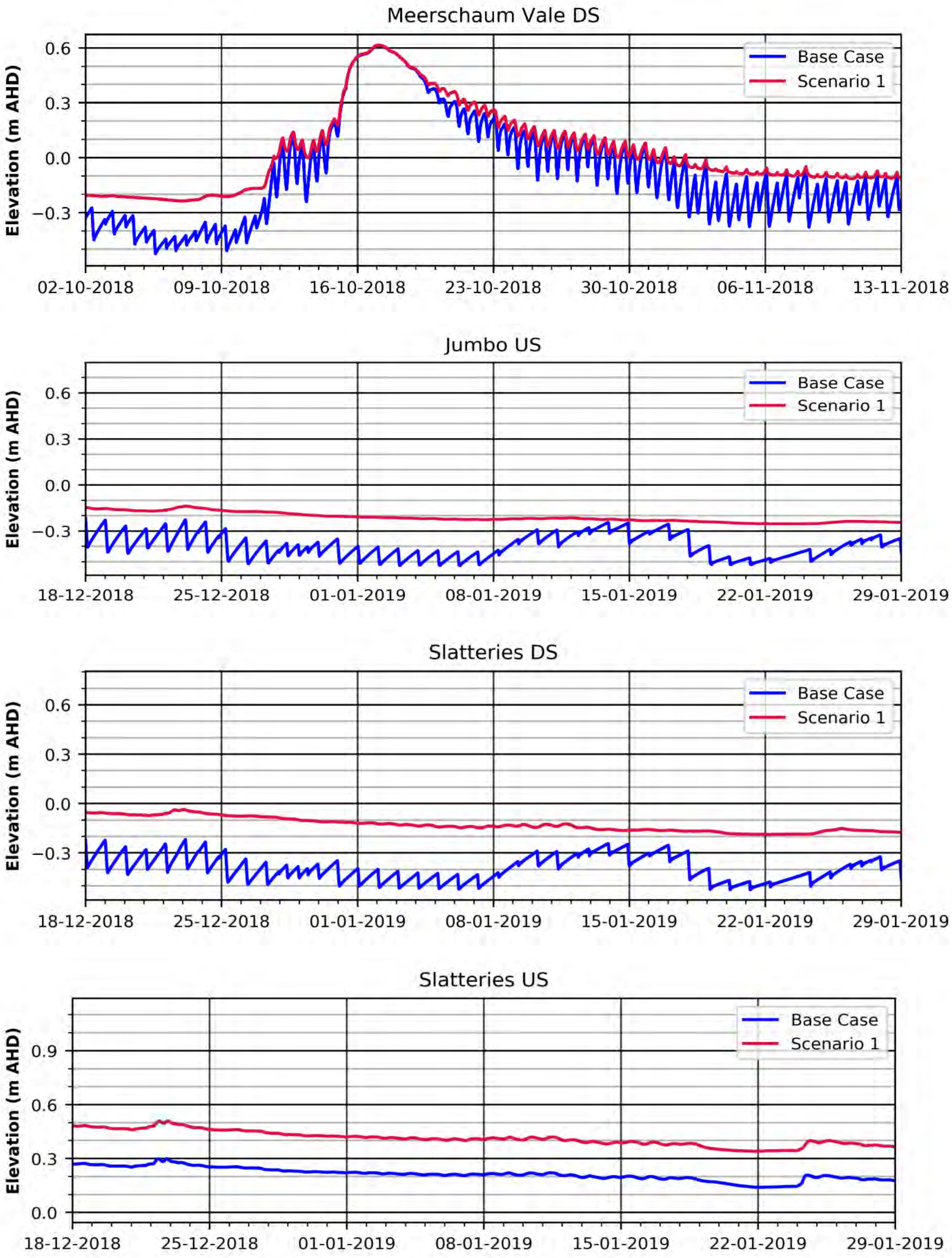

Figure 5-11: Scenario 1 - dry period drainage at key locations

5.3 Scenario 2 – Weir at Meerschaum Vale Drain

5.3.1 Description

Scenario 2 involved the installation of a weir structure at the end of Meerschaum Vale Drain, as shown in Figure 5-12. Installation of weirs in drainage channels has been shown to reduce the production of acid across ASS-affected floodplains (Blunden and Indraratna, 2000). Weirs promote locally higher drain and groundwater elevations that may reduce groundwater drawdown by minimising the hydraulic gradient between groundwater and drainage channels. The aim of this scenario is to increase the drain water levels during dry periods in the high priority areas in the north-east corner of the floodplain. This strategy aims to decrease the acid drainage from the low pH ASS that have been observed in the area.

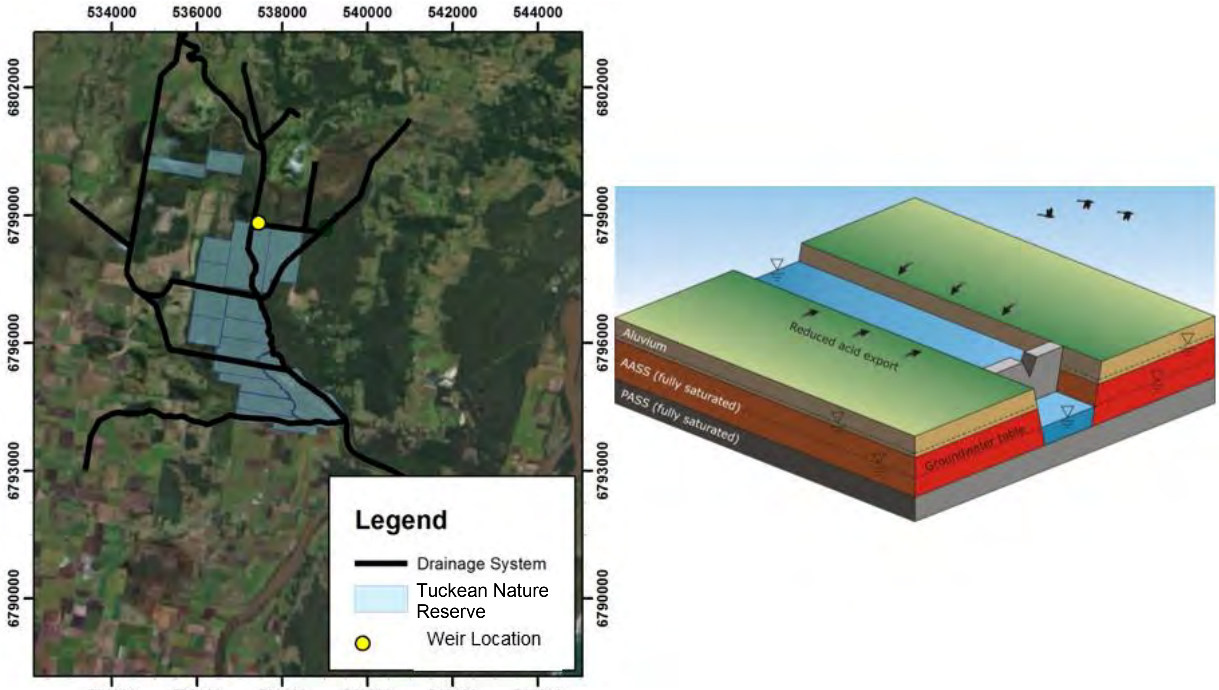

Figure 5-12: Left – Location of weir structure, Right - Reduced acid export as a result of a weir structure holding up water levels

Ideally, the weir crest elevation is situated at, or above the elevation of the actual acid sulfate soil (AASS) layer, however acid sulfate soils in the Slatteries area have been consistently observed at very close to the surface. As shown in Figure 3-1, surface elevations are very low off the right bank of Meerschaum Vale Drain, down to approximately 0.2 m AHD. Presently, water levels in Meerschaum Vale Drain can fall to approximately -0.4 m AHD. To allow water to continue to drain off the low-lying areas, while still maintaining high drain water levels during dry periods to reduce acid drainage, a weir invert of 0 m AHD was selected. While this will still allow some acid drainage from the higher elevation ASS, the reduction in acid drainage would be significant through a 0.4 m increase in drain water levels in dry periods and therefore 0.4 m less of groundwater drawdown across the floodplain.

In this scenario, the tidal gates in the barrage were assumed to be closed with all sluice gates closed. Thereby, no salinity was modelled.

The weir height (0 m AHD) was chosen to minimise impacts on the floodplain inundation and the purpose of this scenario is to test whether a weir strategy could be implemented without major impacts to the surrounding landholders. However, increasing the height of the weir further may reduce acid drainage further. Modelling would be required to ensure other weir heights do not have substantially different impacts. Further investigation and refinement of weir location and crest elevation would enable the balance between acid reduction and maintaining floodplain drainage to be optimised.

5.3.2 Changes in hydrodynamics from the Base Case

Scenario 2 alters the drainage in the north-east corner of the Tuckean floodplain. Modelling shows that there are minimal impacts for the areas west of Hendersons Drain. Therefore, this discussion of results focuses on the areas around Slatteries and Meerschaum Vale Drains.

Figure 5-13 shows that changes to the mean floodplain inundation remain largely unchanged through the installation of the weir structure. There are small, isolated areas where the maximum inundation increases, however these areas are heavily vegetated and are unlikely to greatly impact existing land uses.

While Figure 5-14 shows that there is limited change in the peak water levels in the major channels, the weir does have a substantial impact on the drainage immediately following the rainfall event in Meerschaum Vale, Jumbo and downstream sections of Slatteries Drains. At the Meerschaum Vale DS location, the results show that it takes an additional five (5) days for in-channel water levels to fall below 0.3 m AHD, as compared to the Base Case. The floodplain in this area is well connected to the drainage system for elevations above 0.3 m AHD, so this reduced drainage will result in water remaining on the floodplain for longer after moderate rainfall events. This may impact the current land uses and cause issues with blackwater due to the prolonged inundation of water intolerant vegetation. Water levels are not impacted at the Slatteries US extraction location due to existing flow control structures in the drain (see Figure 5-6) that are higher than 0 m AHD.

Figure 5-15 shows that minimum water levels during dry periods are increased by 0.2 – 0.5 m AHD (except at Slatteries US, which remains unchanged). Higher surface water levels in the drains will limit groundwater drawdown from the surrounding floodplain. Again, assuming that the channels affected by this scenario drain the groundwater from an area of approximately 3 km^2, this suggests that acid transport would be limited from approximately 600,000 to 1,500,000 m^3 of ASS affected soil (pH typically around 3 – 4).

5.3.3 Summary of implications for Scenario 2

Based on the results of the numerical modelling, the implications of installing a weir with a crest at 0 m AHD at Meerschaum Vale is summarised in Table 5-2. Indicative costs are also included, based on Table 4-1.

Table 5-3: Summary of implications for Scenario 2

Consideration	Implication
Floodplain inundation	Longer term mean and maximum floodplain inundation remain largely unchanged, however it is expected that water may remain on the floodplain longer in the period immediately following moderate to major rainfall events.
In-channel drainage after rainfall events	Drainage after a rain event takes longer (approximately 5 days) than the Base Case.
Diffusive acid transport	Diffusive acid transport will remain similar as there are no changes to the drainage cross sections.
Groundwater levels	Higher mean and minimum surface water levels will increase the average groundwater levels in the north-east corner of the floodplain and reduce groundwater discharge and limit the groundwater interaction with acidic soils.
Advective acid transport	Advective acid transport will be reduced due to higher average groundwater levels and a reduced hydraulic gradient between surface water and groundwater. Based on minimum surface water levels during a dry period, it is estimated that this will reduce acid transport from approximately 600,000 –to1,500,000 m^3 of ASS. Note that a higher weir would further reduce advective acid transport but would have greater implications for floodplain inundation and drainage times.
Salinity	No changes to salinity are expected.
Implementation constraints	Weir installations often result in the stagnation of water behind the structure. This can cause a build-up of weeds that need to be managed to ensure efficient drainage can occur during rainfall events. Also, this option would be more effective if the weir height was increased, however this would require further modelling as any further increases in weir height are likely to have impacts to the surrounding landholders.

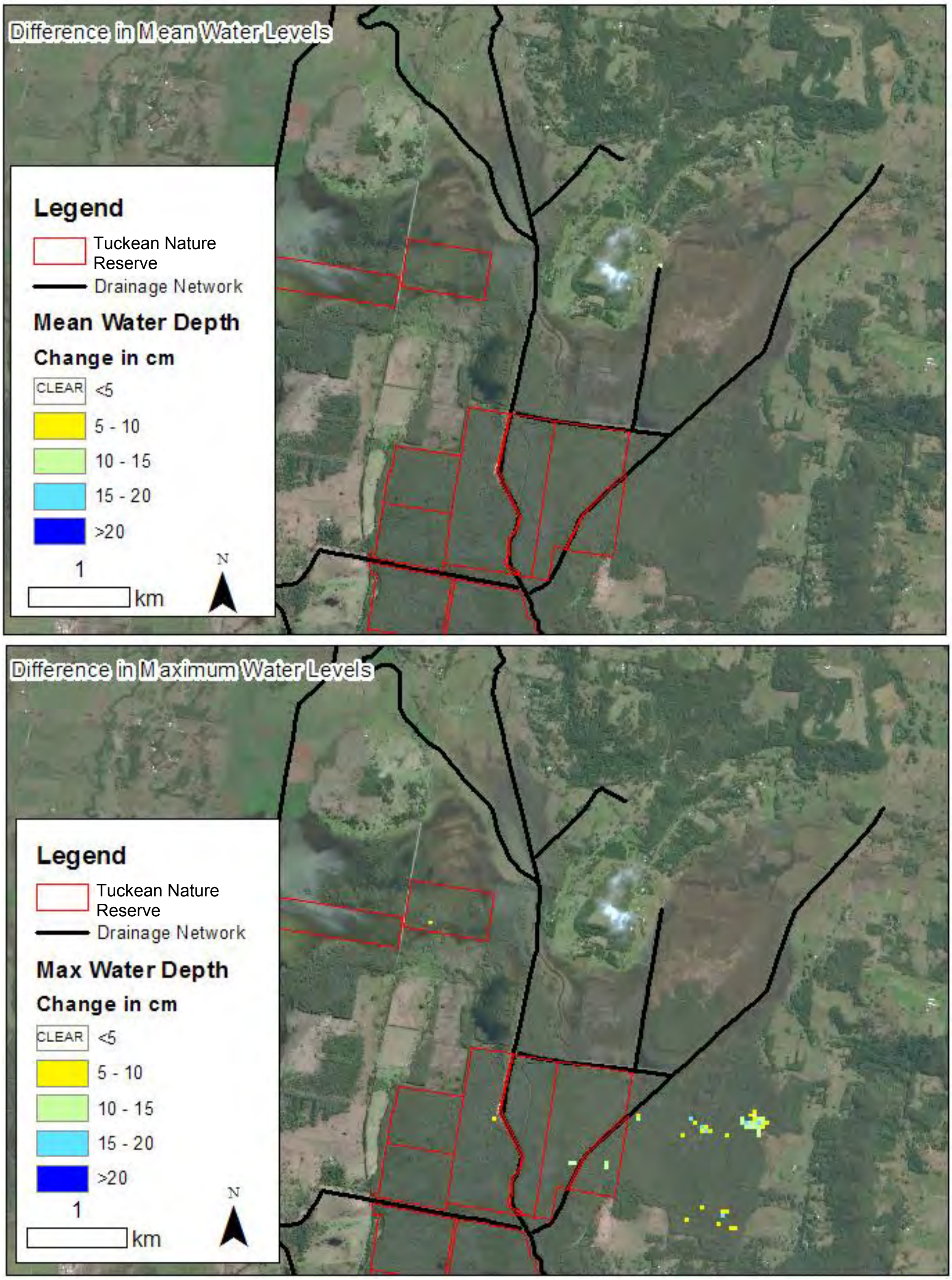

Figure 5-13: Scenario 2 - differences in mean (top) and maximum water depth on the floodplain, compared to the Base Case

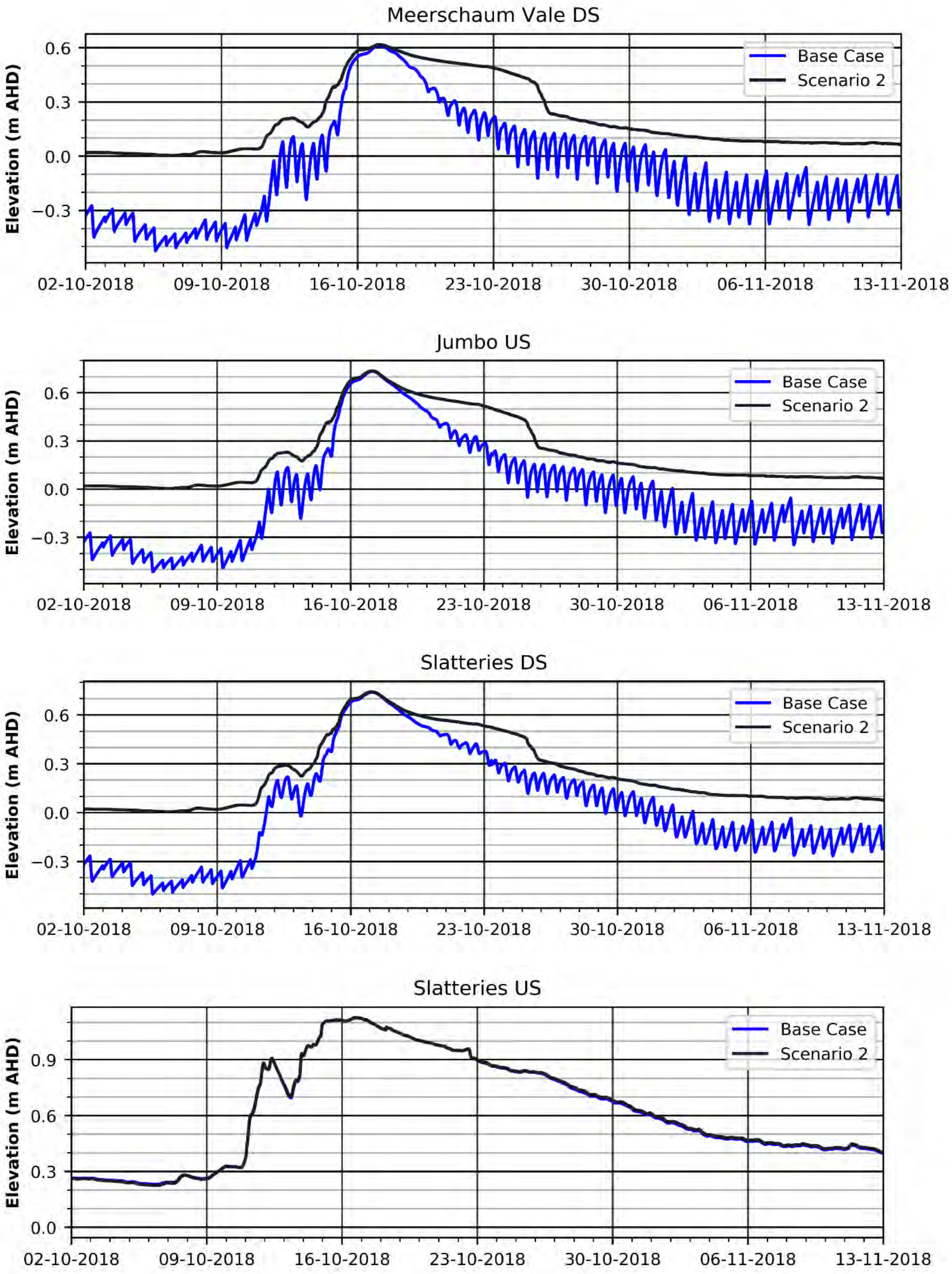

Figure 5-14: Scenario 2 - wet period drainage at key locations

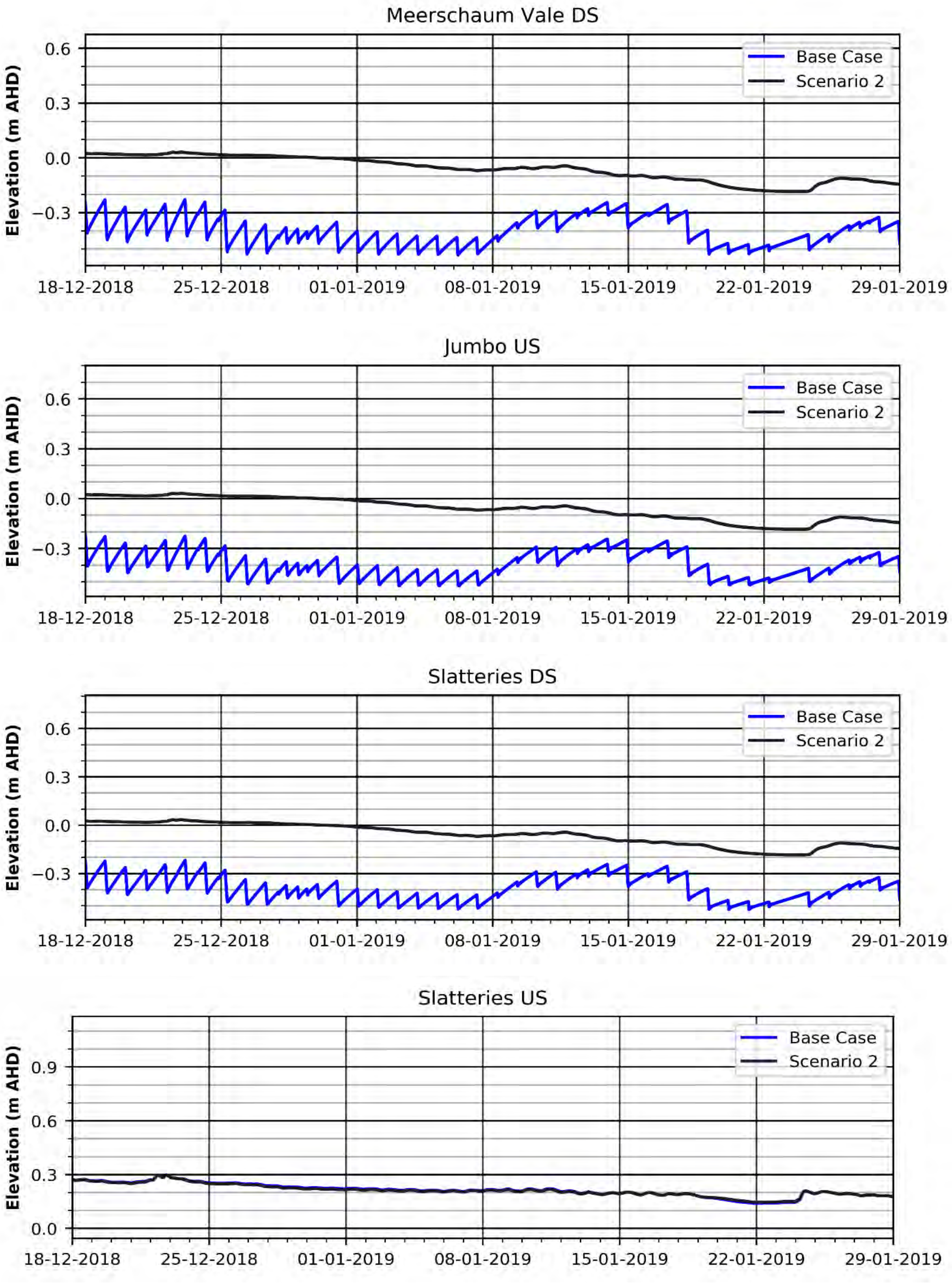

Figure 5-15: Scenario 2 - dry period drainage at key locations

5.4 Scenario 3 – Existing sluice gate management

5.4.1 Description

Three (3) 1m x 1m sluice gates were previously installed in 2003 on the three (3) left bank barrage gates. As depicted in Figure 5-16, flows through the sluice gates allow controlled tidal inflows into Hendersons Drain, which increases salinity within the lower Tuckean area and promotes better flushing. These gates are operated by Rous County Council, who typically open one (1) sluice gate 150 mm during extended dry periods and close the sluice gates entirely when there is a forecast for significant rainfall (per comms, C Clay). However, Rous County Council currently has limited guidance on the potential effects on water levels and saline intrusion of further opening the sluice gates. The purpose of this scenario is to improve understanding of the impact of opening the sluice gates to different levels.

Salinity has been modelled for this scenario as there are saline inflows from the Tuckean Broadwater into Hendersons Drain. The boundary of the model was assigned a constant concentration of 100 and salinity results are presented as a percentage of the salinity in the Broadwater.

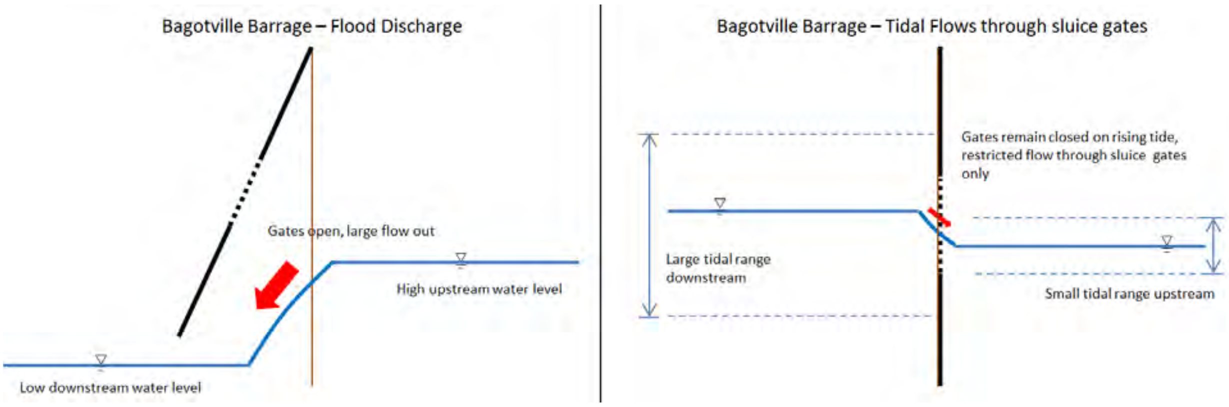

Figure 5-16: Flows through Bagotville Barrage with sluice gates open

The purpose of this scenario is to test the effect of opening the sluice gates at different levels during dry periods, when there are minimal catchment inflows and salinity in the Tuckean Broadwater is high. It is assumed that the sluice gates will remain shut during any significant rainfall (such as the October 2018 rain event). Therefore, this scenario was simulated over an alternative time period, from 1/1/2019 to 28/2/2019, in which rainfall was limited and the potential for tidal flushing was high (i.e. dry conditions).

Initially, a 1-D only model of the system was run for nine (9) different gate configurations:

- 1 gate open 150 mm;

- 2 gates open 150 mm;
- 3 gates open 150 mm;
- 1 gate open 500 mm;
- 2 gates open 500 mm;
- 3 gates open 500 mm;
- 1 gate open 1000 mm;
- 2 gates open 1000 mm; and
- 3 gates open 1000 mm.

Based on these initial model results, the following observations were made:

- With one gate open 150 mm, salinity upstream of the barrage can change substantially if the salinity is high in the Tuckean Broadwater;
- Opening one gate 1000 mm has a relatively small incremental benefit compared to opening one gate 500 mm due to the invert of the gates relative to the tidal planes downstream of the barrage;
- Table 5-4 shows the cumulative volume of water that flowed through the sluice gates over the initial 2 month 1-D modelling tests. Opening one gate 500 mm allows in more flow than two gates open 150 mm, but less than three open 150 mm. Opening two gates 500 mm allows a significant additional volume upstream of the gates.

Table 5-4: Total volume inflow over a two month period for different sluice gate configurations (1-D results only)

Sluice Configuration	Estimated total inflow volume over 2-month period (x10^9 m^3)
1 gate open 150mm	4.1
2 gates open 150 mm	7.9
3 gates open 150 mm	11
1 gate open 500 mm	9.5
2 gates open 500 mm	19
3 gates open 500 mm	27
1 gate open 1000 mm	11
2 gates open 1000 mm	22
3 gates open 1000 mm	33

Based on the preliminary 1-D results, three (3) scenarios were selected to run in the 2-D coupled model, as detailed below:

- **Scenario 3a:** One sluice gate open 150 mm (current operating standard except during flood conditions);
- **Scenario 3b:** One sluice gate open 500 mm; and
- **Scenario 3c:** Two sluice gates open 500 mm.

Each scenario has been run for the period 1/1/2019 to 28/2/2019 to test sluice gate operations during dry conditions and at normal estuary levels.

5.4.2 Changes to hydrodynamics compared to the Base Case

Figure 5-17 shows the maximum inundation throughout the model domain during the modelling period January – February 2019 (during sustained dry weather). The inundation extent is mostly limited to the Tuckean Nature Reserve area between Stibbards Creek and Tucki Canal, although there is also some overbank flow to the east of Hendersons Drain and to the south of Stibbards Creek, particularly in Scenario 3c (two sluice gates open 500 mm). The increased inundation depths in Scenario 3c are a direct reflection of the additional volume of tidal inflows (and therefore greater water level variation) as a result of the larger sluice gate openings, as shown in Table 5-4. The tidal inflows and outflows will result in greater flushing of the floodplain, with improved water quality.

Figure 5-21 to Figure 5-24 show the changes in water levels upstream of the barrage and at the edge of the Tuckean Nature Reserve on Stibbards Creek, Tucki Canal and Hendersons Drain. In the Base Case, water levels rise and fall as catchment base flows backup behind the floodgates before the tide starts to fall and the floodplain drains back to low tide (under hydrostatic pressure head). With the sluice gates open, the backing up of catchment base flows still occurs, but limited tidal inflows occur. The high tide water levels increase by approximately 10 cm, 20 cm and 30 cm for Scenario 3a, 3b and 3c, respectively (relative to the Base Case), and this propagates upstream throughout Stibbards Creek, Hendersons Drain and Tucki Canal. However, these figures also show that the outflow conveyance capacity of the barrage is still sufficient to drain the floodplain back to the same level observed in the Base Case, even with two (2) sluice gates open 500 mm (Scenario 3c). This is significant as it means that the low tide level in the Tuckean Broadwater remains the dominate water level control throughout the floodplain (during periods of dry weather). The implication of this finding is that prior to the onset of rainfall (such as the small rainfall event on the 22nd and 23rd of February), if the sluice gates are closed on at least two tidal cycles (24 hours) before the runoff began flowing into the floodplain, there would be minimal changes in water levels compared with if the sluice gates had never been opened (for each of the three sluice gate scenarios considered).

Figure 5-18 shows the impact of spring and neap tides on water levels upstream of the barrage for all three (3) sluice gate scenarios. The lower low-tide levels that occur during neap tides are evident in the water levels upstream of the barrage. While tidal inflow volumes are larger during spring tides (by up to approximately 20%), the lower low-tide levels result in water levels typically remaining lower during spring tides upstream of the barrage.

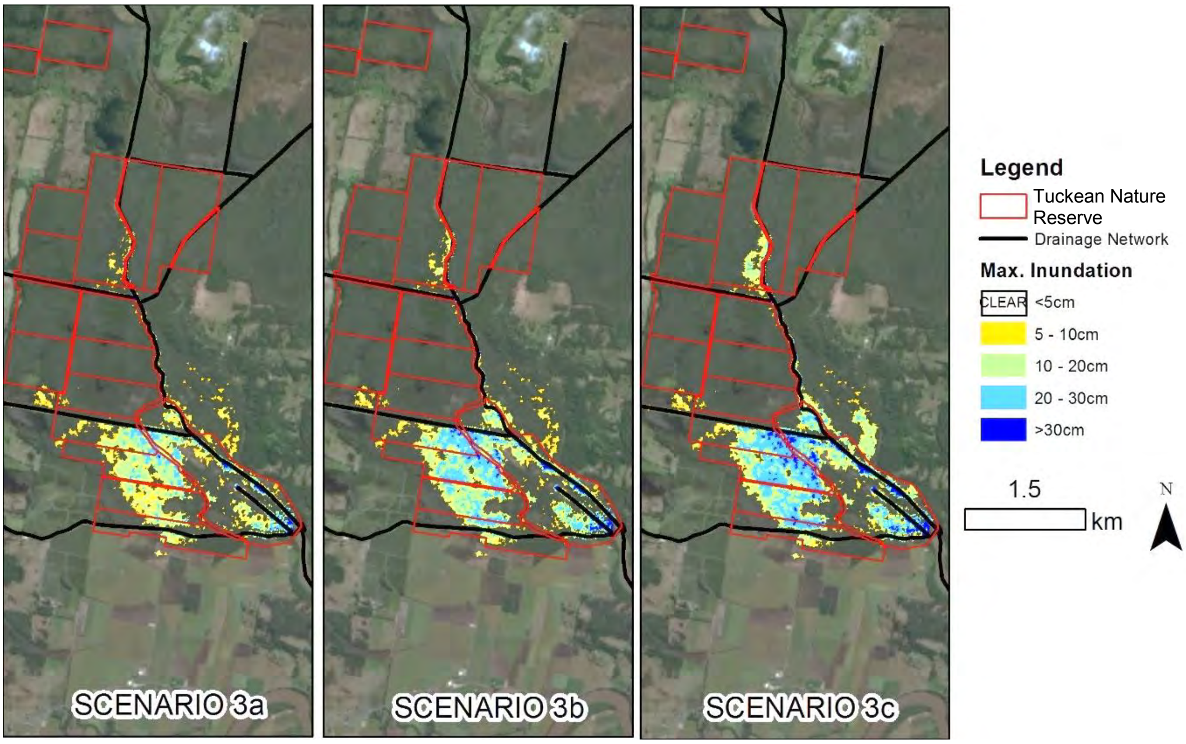

Figure 5-17: Maximum inundation for Scenario 3 (Jan - Feb 2019)

(Note: Scenario 3a – 1 gate open 150 mm, Scenario 3b – 1 gate open 500 mm, Scenario 3c – 2 gates open 500 mm)

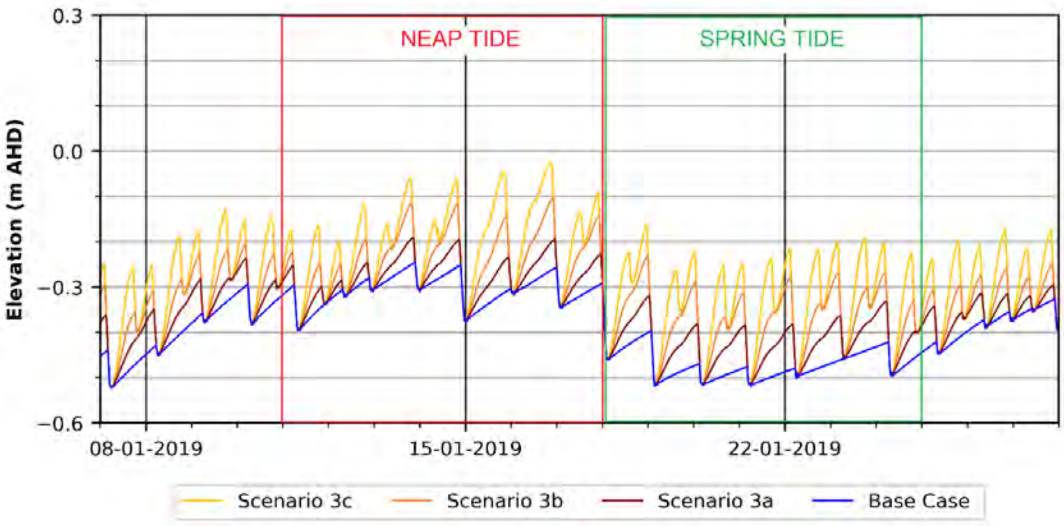

Figure 5-18: Impact of spring and neap tides upstream of the barrage

5.4.3 Salinity throughout the floodplain

Figure 5-19 shows the maximum salinity throughout the model area for each of the model runs in Scenario 3. Salinity on the floodplain typically remains less than 30% of the salinity of the Tuckean Broadwater in Scenario 3a, whereas salinity is typically higher than 50% in both Scenario 3b and 3c. Only in Scenario 3c is there any saltwater overbank on any private property, to the east of Hendersons Drain. This area is heavily vegetated, similar to the Tuckean Nature Reserve, and does not appear to be used for agriculture.

In-channel salinity is also shown upstream of the barrage and at the edge of the Tuckean Nature Reserve on Stibbards Creek, Tucki Canal and Hendersons Drain (at Meerschaum Vale Drain) in Figure 5-21 to Figure 5-24 (locations shown in Figure 5-4). The salinity moving up Hendersons Drain is also shown in Figure 5-20. At the confluence of Hendersons Drain and Meerschaum Vale Drain, salinity is less than 5% of the Tuckean Broadwater in all three (3) scenarios. Salt is unlikely to impact properties upstream of Tuckean Nature Reserve along Hendersons Drain. Figure 5-23 shows that maximum salinity at Tucki Canal (at the edge of the Tuckean Nature Reserve) is approximately 10%, 15% and 20% for Scenario 3a, 3b and 3c, respectively. The groundwater connectivity in this region is limited due to the presence of dense clays (Brodie, 2007) and the catchment draining towards Tucki Canal is large and will rapidly flush salt from the system during a rainfall event. Due to low hydraulic conductivity and generally high levee banks, the impact of this salinity is likely to be limited along Tucki Canal.

Along Stibbards Creek, the salinity may increase due to the close proximity to the barrage. South of the downstream section of Stibbards Creek is largely privately owned and is predominately used for sugar cane. While the low hydraulic conductivity dense clays also exist in this area, a layer of sandy clay overlies this strata, over approximate -0.4 m AHD, based on WRL's field investigation. The sandy clay is expected to have a moderate to high hydraulic conductivity, based on the observations elsewhere on the floodplain by Brodie (2007), which may result in substantial groundwater connectivity between the drains and the floodplain. Salinity in this area may need to be monitored to prevent adverse effects to the private property south of Stibbards Creek if the management of the sluice gates was to change. Alternatively, the sluice gates could be upgraded to SmartGates which can be programmed to be opened and closed based on real time monitoring (either of water levels or water quality). Additional modelling could be undertaken to determine the effectiveness of SmartGates in managing risks along Stibbards Creek and the wider Tuckean floodplain.

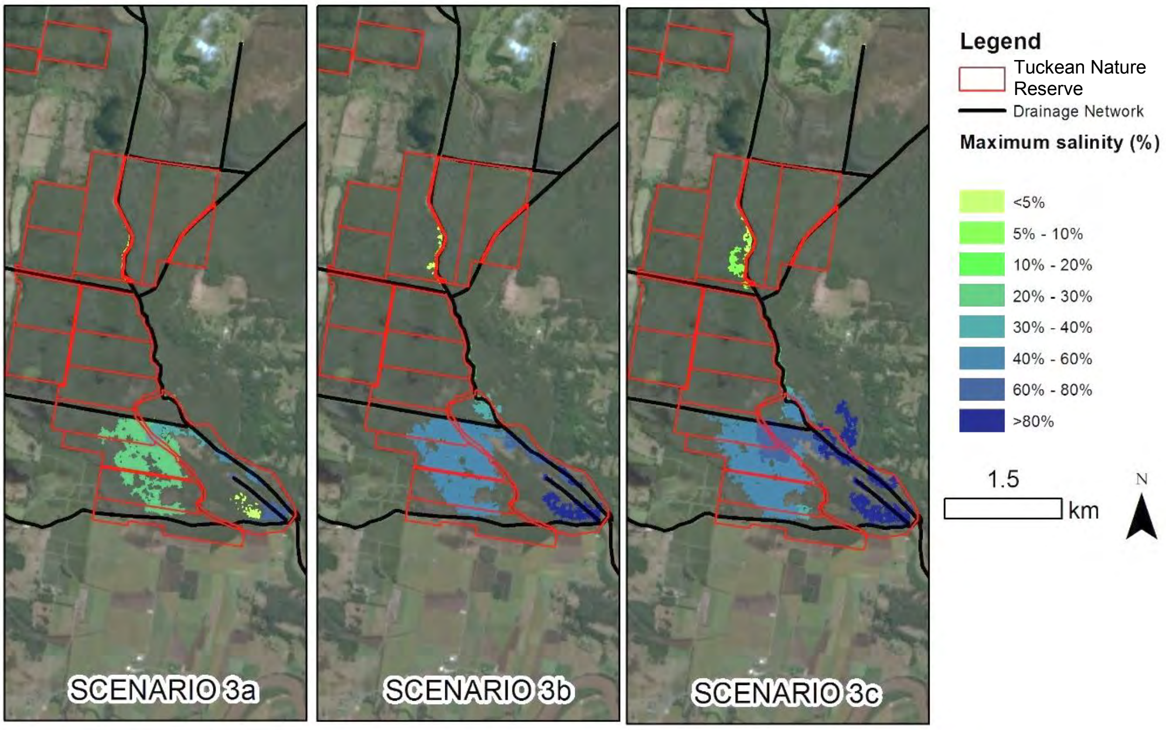

Figure 5-19: Maximum salinity throughout the model domain for Scenario 3a, 3b and 3c

(Note: Scenario 3a – 1 gate open 150 mm, Scenario 3b – 1 gate open 500 mm, Scenario 3c – 2 gates open 500 mm).

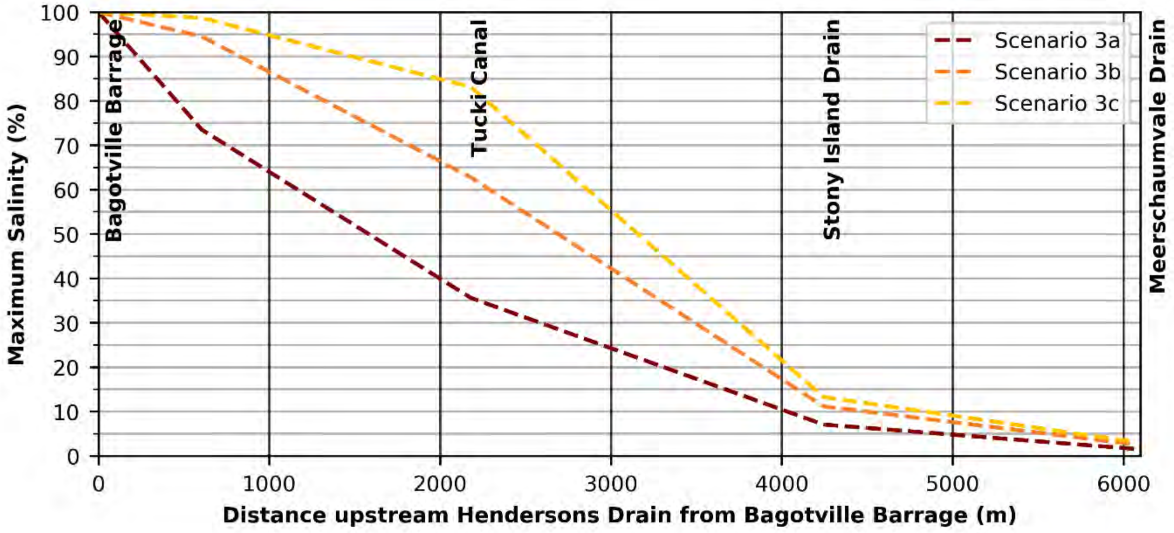

Figure 5-20: Salinity throughout Hendersons Drain in Scenario 3 models

5.4.4 Summary of implications of Scenario 3

Based on the results of the numerical modelling, the implications of opening the sluice gates are summarised in Table 5-5. This only considers changes to opening the sluice gates during selected dry weather periods. It is assumed that the sluice gates would remain closed during any significant catchment inflows and rainfall events. Indicative costs are also included, based on Table 4-1.

Table 5-5: Summary of implications for Scenario 3

Consideration	Implication
Floodplain inundation	At present, the Tuckean Nature Reserve remains relatively dry during periods of minimal catchment inflows. By allowing some tidal inflows, the Tuckean Nature Reserve may get inundated during dry periods. The extent of the inundation varies depending on the sluice gate management, as shown in Figure 5-17. A small area of privately-owned floodplain to the east of Hendersons Drain will be impacted by tidal flows.
In-channel drainage after rainfall events	It is assumed that the sluice gates will be closed prior to rainfall. Providing the gates are shut at least 24 hours before catchment flows begin to enable drainage of surface waters, there should be negligible changes to peak nuisance flood levels or drainage.
Diffusive acid transport	While there have been no changes to drainage cross-sections to reduce diffusive acid transport, higher salinity in the drains will promote neutralisation of the acidic waters due to naturally occurring bicarbonates in marine water. This neutralisation will only improve water quality during dry periods (after floods, salinity in the Broadwater is low, and there will

Consideration	Implication
	be limited neutralisation capacity). The neutralisation capacity will increase with the greater tidal inflows and salinity that results from opening the sluice gates further.
Groundwater levels	Increasing the tidal inundation of the Tuckean Nature Reserve and surrounding areas will elevate the ground water table in this area and the surrounding floodplain during dry periods. Higher surface water levels in the north-east corner of the floodplain (e.g. Jumbo Drain) may also slightly increase groundwater levels in this area. The increase in groundwater levels is greater the more the sluice gates are open (i.e. the more tidal flushing).
Advective acid transport	Advective acid transport will be reduced due to higher average water levels and a reduced hydraulic gradient between surface water and groundwater. The reduction in advective acid transport is proportional to the increase in water levels, and therefore also a function of the amount the sluice gates are open.
Salinity	Salinity in the lower sections of Hendersons Drain, Stibbards Drain and Tucki Canal will increase through the controlled tidal inflows allowed by the sluice gates. Floodplain inundation is predominately limited to the Tuckean Nature Reserve for the sluice gate options tested. The more the gates are opened, the further the salinity is transported throughout the drainage network. However, even with 2 gates open 500 mm, salinity remains low upstream of the confluence on Hendersons Drain and Meerschaum Vale Drain.
Implementation constraints	Salinity in the drainage network can be transported through groundwater connectivity. This is known to be of concern around the downstream sections of Stibbards Creek, where in-channel salinity is expected to be high and higher hydraulic conductivity soils are known to exist. Further field investigation of soil types may be required to ensure that this is not an issue elsewhere in the floodplain and additional monitoring may be required. Alternatively, the sluice gates could be upgraded to SmartGates which can be programmed to be opened and closed based on real time monitoring (either of water levels or water quality). Additional modelling could be undertaken to determine the effectiveness of SmartGates in managing risks along Stibbards Creek and the wider Tuckean floodplain. Changes in management of the Bagotville Barrage should only be implemented in consultation with landholders.

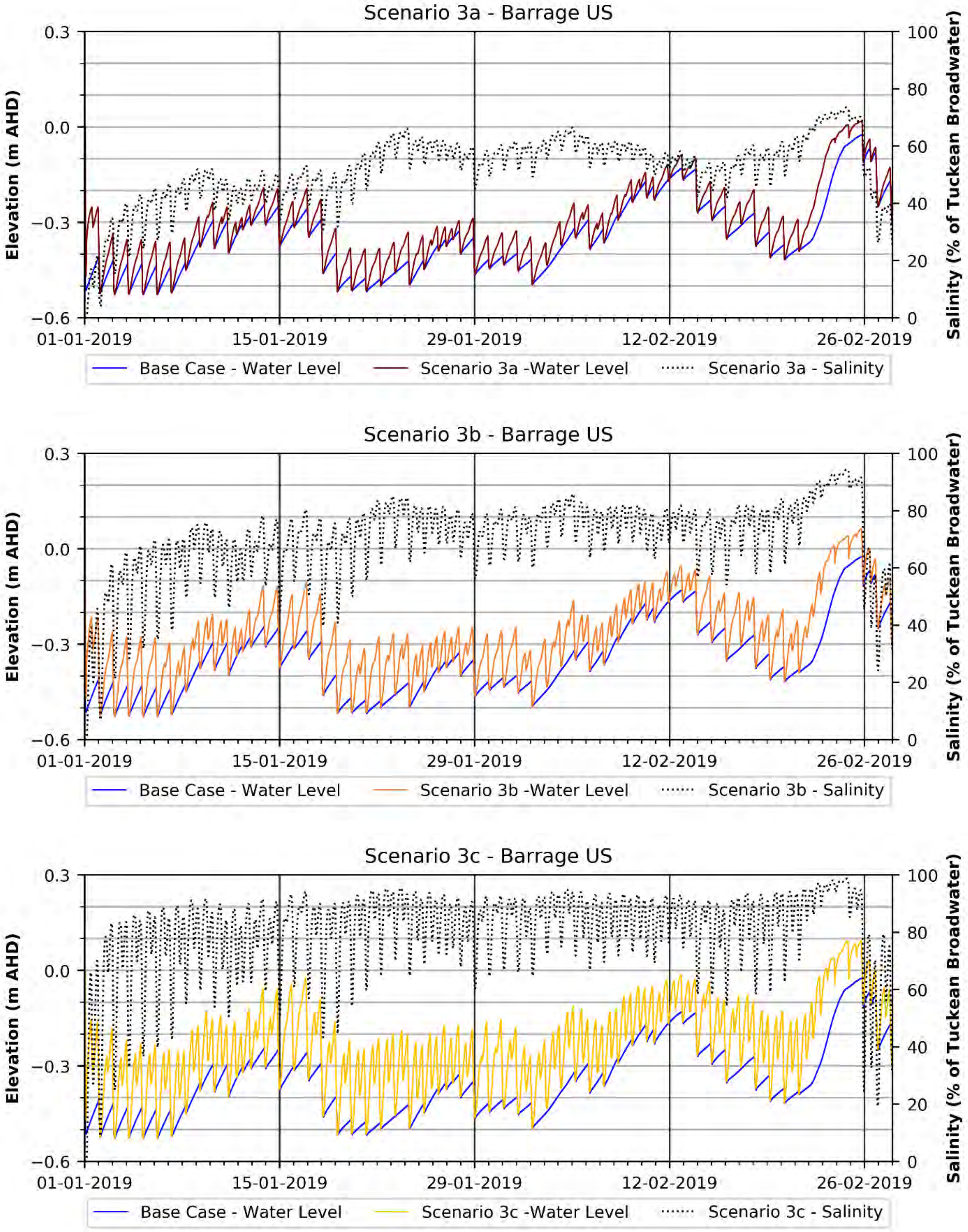

Figure 5-21: Impact of Scenario 3a, 3b and 3c (top to bottom) upstream of the barrage

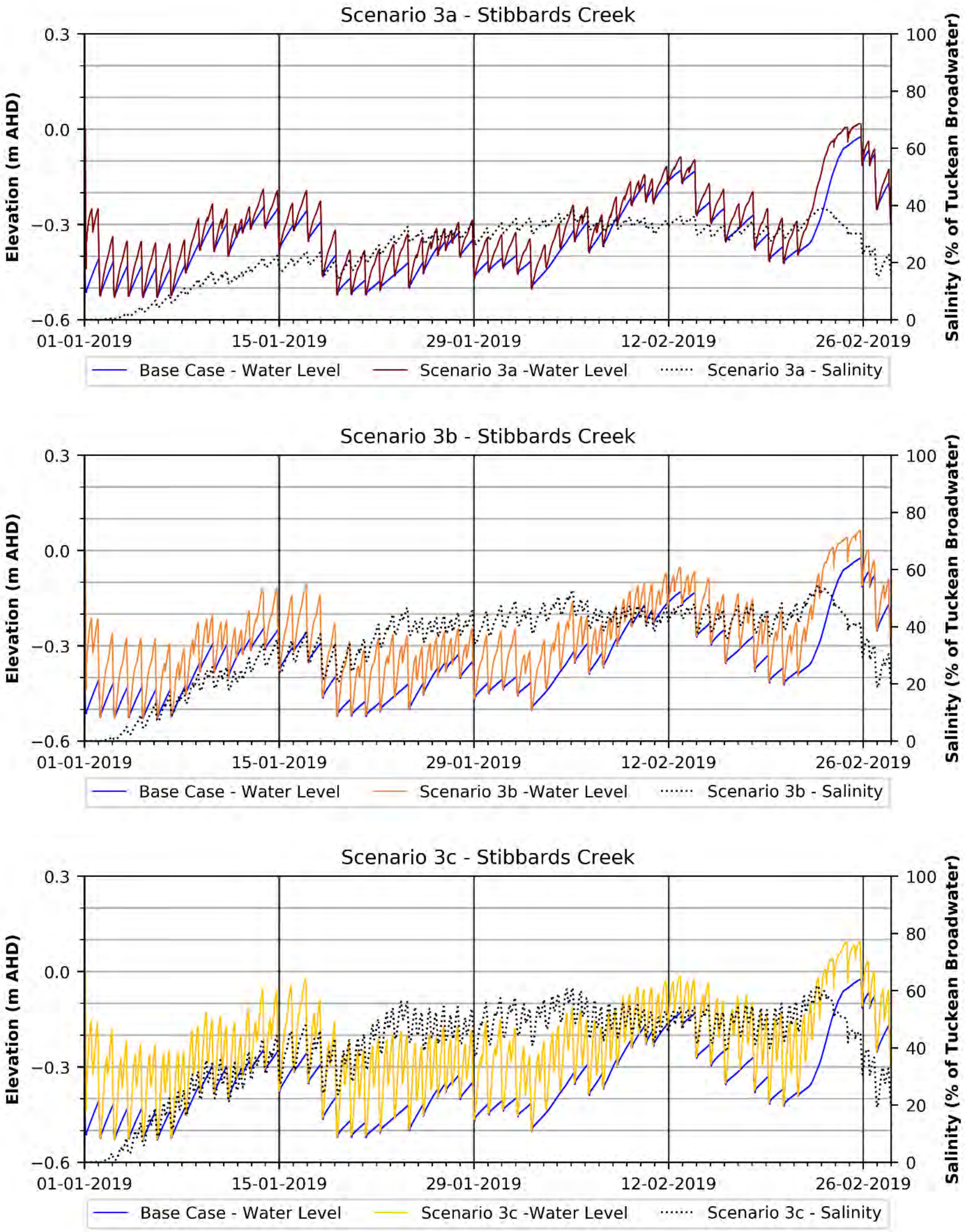

Figure 5-22: Impact of Scenario 3a, 3b and 3c (top to bottom) at Stibbards Creek at the end of the Tuckean Nature Reserve

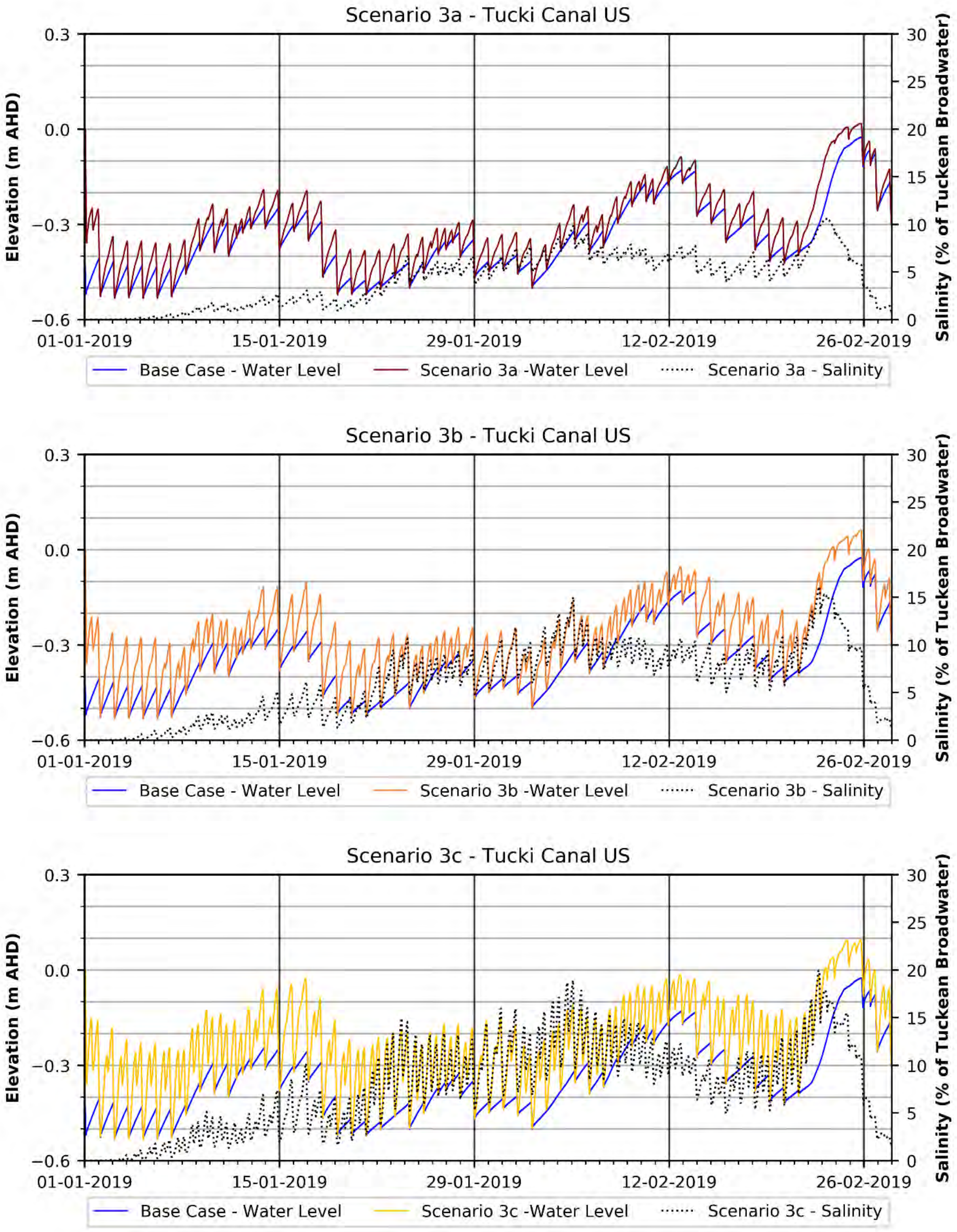

Figure 5-23: Impact of Scenario 3a, 3b and 3c (top to bottom) at Tucki Canal at the end of the Tuckean Nature Reserve

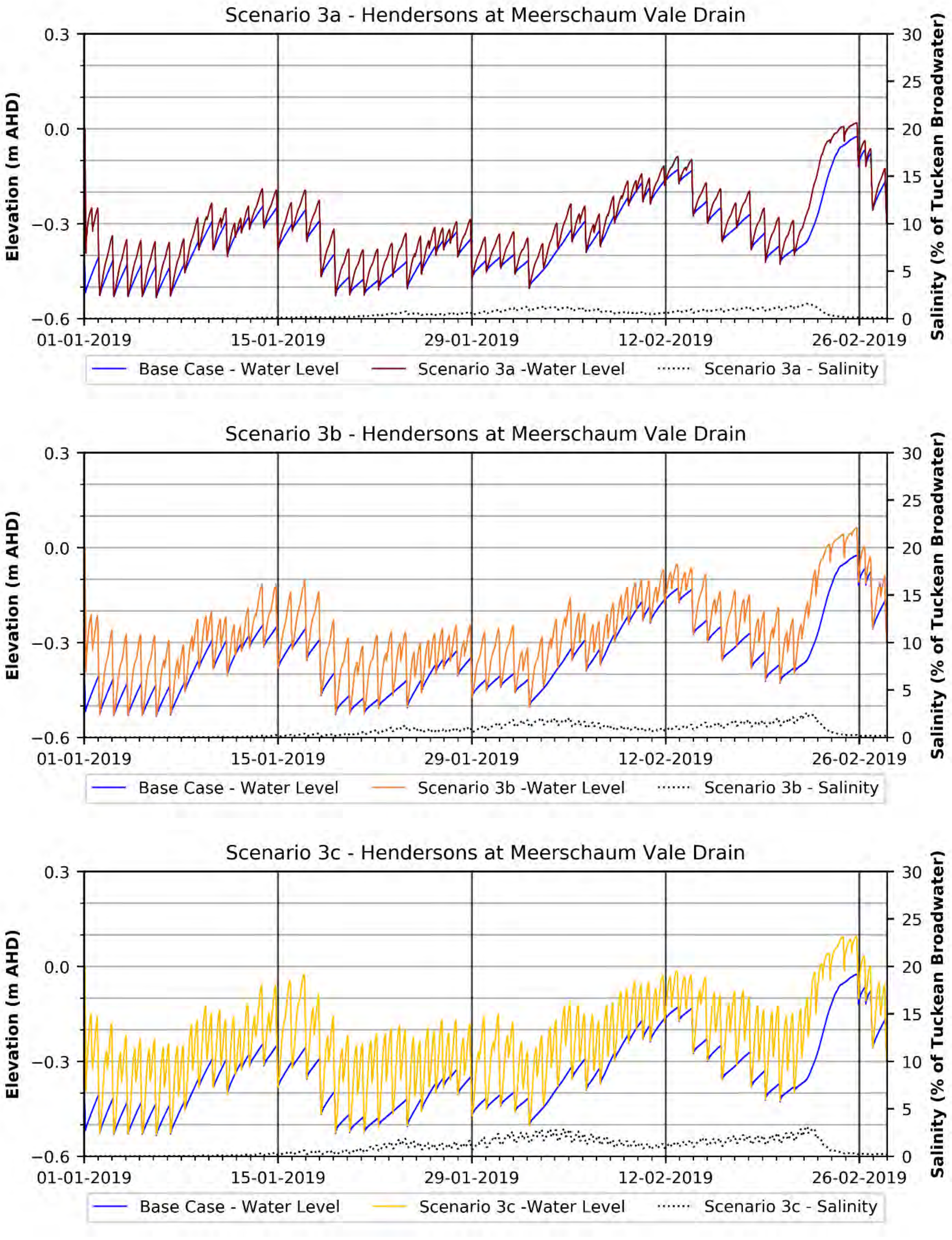

Figure 5-24: Impact of Scenario 3a, 3b and 3c (top to bottom) at Hendersons Drain at the confluence of Meerschaum Vale Drain

5.5 Scenario 4 – Opening the barrage floodgate flaps

5.5.1 Description

There are eight (8) 3 m x 3.5 m one-way flood gates on the Bagotville Barrage that allow flows to discharge into the Richmond River, but prevent water from the Richmond River flowing upstream. This scenario investigates the impact of opening the floodgate flaps on the Bagotville Barrage. By hinging open the gate flaps, but leaving the structure intact, this option allows the reintroduction of tidal flows into the swamp during desirable periods, while still allowing for the opportunity to close the gate flaps when water levels are elevated in the Richmond River to prevent backwater flooding (as shown in Figure 5-25). This scenario has been included in the modelling to understand the maximum tidal extent that could occur through manipulating the existing infrastructure. Note that large-scale changes in the management of the gates are not being considered in the short term and would not be implemented without landholder and stakeholder consent.

In the modelling scenario, the gate flaps remained hinged open throughout the modelling period (1/10/2018 – 28/2/2019), simulating both wet and dry condition effects. While the 'gate open' configuration allows for the floodgates to be closed during wet weather events, it is important to understand the management implications and consequences of the gates remaining open throughout a prolonged period.

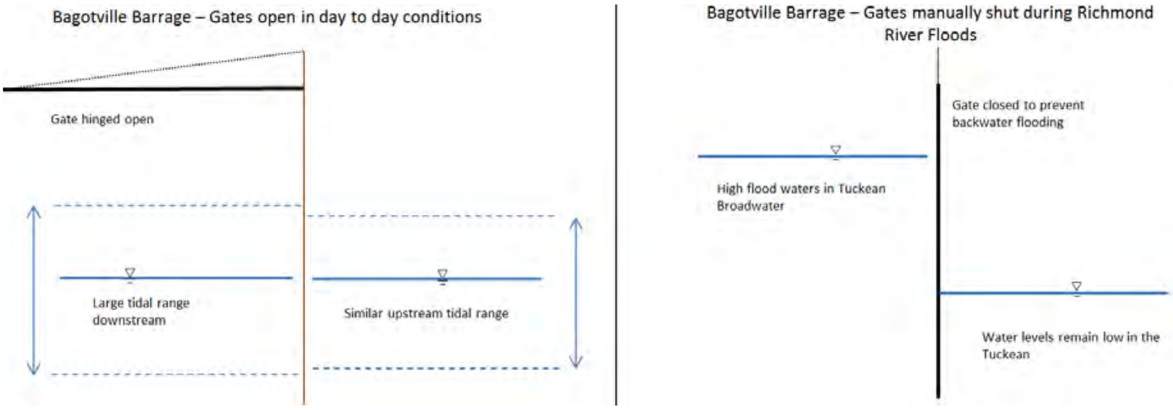

Figure 5-25: Bagotville Barrage gates hinged open to allow normal tides, but still preventing backwater flooding

As there are tidal inflows from the Tuckean Broadwater into Hendersons Drain in this scenario, salinity has been modelled. The salinity boundary of the model was assigned a constant concentration of 100, and results are presented as a percentage of the salinity in the Broadwater. This scenario ran for the modelling period 1/10/2018 to 28/2/2019, thereby covering both wet and dry conditions.

5.5.2 Changes to hydrodynamics compared to the Base Case

Scenario 4 considers changes to the management of the sluice gates at the downstream boundary of the Tuckean floodplain. This has the potential to cause large scale changes in drainage, salt transport and floodplain inundation throughout the study area.

Figure 5-28 shows the changes in 2D mean and maximum inundation across the floodplain. By leaving the barrage floodgate flaps open, a substantial area of the lower swamp remains inundated almost permanently. While this area is largely contained within the Tuckean Nature Reserve boundaries, there are also some low-lying privately-owned areas south of Stony Island Drain that would experience significant changes in inundation. The primary areas impacted include:

- Inundation of a large portion of the Tuckean Nature Reserve;
- Approximately 60 ha around Tucki Canal inundated immediately upstream of the Tuckean Nature Reserve boundary (predominately used for grazing);
- Low lying area south of Stibbards Creek (predominately used for sugar cane) inundated; and
- Low lying area east of Hendersons Drain (privately owned but appears densely vegetated) inundated.

The hydroperiod has been calculated through the model domain to help understand the implications of inundation of these areas. Hydroperiod is a measure of the percentage of time that an area is wet – for example, a hydroperiod of 50% indicates that there is water on the floodplain 50% of the time (note that hydroperiod does not consider water depth). The hydroperiod for the floodplain based on the model results is shown in Figure 5-26. The low-lying areas (<0.4 m AHD) of the floodplain downstream of Meerschaum Vale Drain remain wet over 80% of the time with the barrage gates open. The areas which are currently used for agriculture (near both Stibbards Creek and Tucki Canal) are unlikely to be able to tolerate the increased inundation without significant changes to land management. Scenario 6 includes modifications that could be considered to mitigate these impacts.

Water levels within the channels would be changed substantially as a result of opening the gates. Areas immediately upstream of the barrage become tidal (Figure 5-32) and reach up to 0.6 m AHD during extended dry periods. The tide is attenuated upstream of the barrage in both Stibbards and Hendersons Drain, although the tidal signal is still evident in Jumbo Drain, more than 8 km upstream of the barrage. While opening the floodgates does not significantly increase peak water levels during the rainfall event (shown in Figure 5-28 and Figure 5-29), the low tide levels upstream of Tucki Canal remain high for up to two (2) weeks after the peak of the event. Drainage immediately after the peak water level (first 24 – 48 hours) remains similar despite the changes to the floodgates. Importantly these results suggest that 'bathtub' modelling results, such as standard GIS type results, are not representative of onsite conditions.

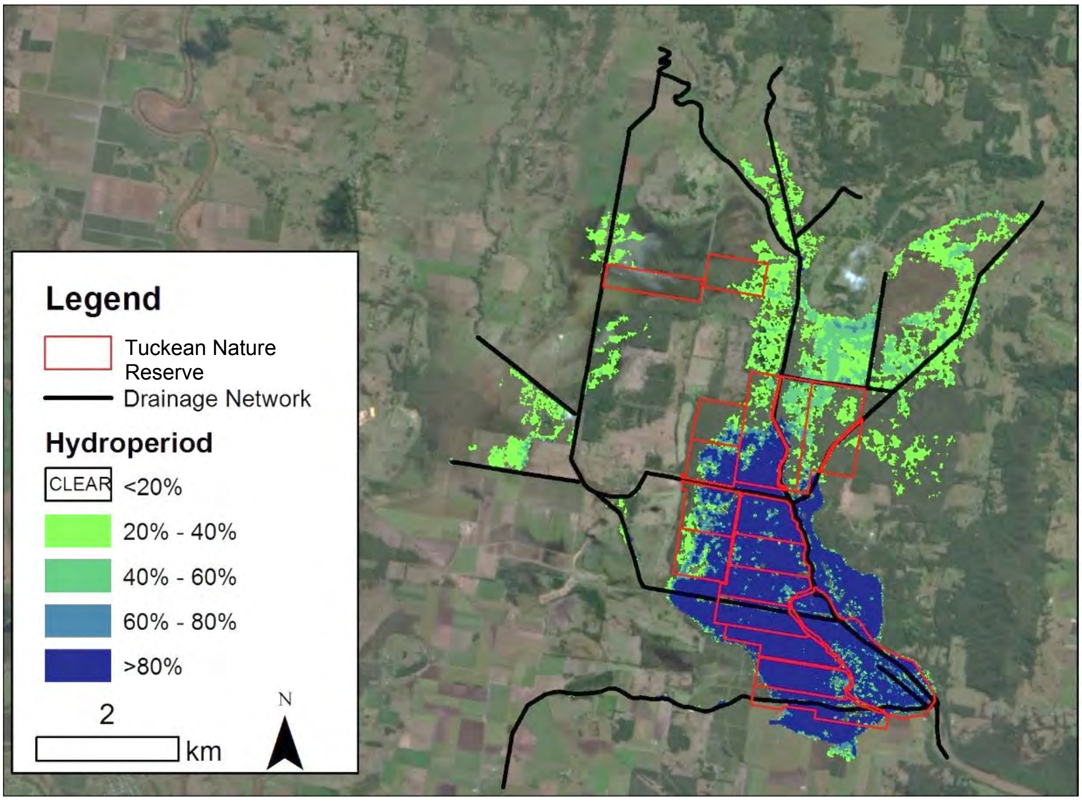

Figure 5-26: Scenario 4 - hydroperiod

5.5.3 Salinity throughout the floodplain

Figure 5-29 shows the mean and maximum salinity (as a percentage of the salinity downstream of the barrage) throughout the model domain. Salinity is also shown in the 1D model results presented at each location in Figure 5-30 to Figure 5-33.

During large freshwater catchment events (Figure 5-30 and Figure 5-31), salt is quickly flushed from the system and overbank flow throughout the floodplain is fresh. There is a bigger risk of saltwater inundation of the floodplain when there is a small rainfall event, just large enough to allow overbank flow and after an extended dry period, similar to what occurred in the 2018/2019 summer period (see rainfall data in Figure 5-27). The impact of this event is shown in Figure 5-30 and Figure 5-31. The catchment event is not sufficient to dilute the water in the upstream drains (such as Jumbo Drain in Figure 5-31) before the overbank flow occurs. This results in floodplain inundation across the low-lying area (<0.5 m AHD) around Jumbo Drain and Meerschaum Vale Drain with a concentration of 4 – 10 % of the salinity in the Tuckean Broadwater. As the Broadwater can reach salinity levels of approximately 60% of seawater (based on 3 years of monitoring by Rous County Council), this may result in impacts on pasture that currently exists on the floodplain in this area.

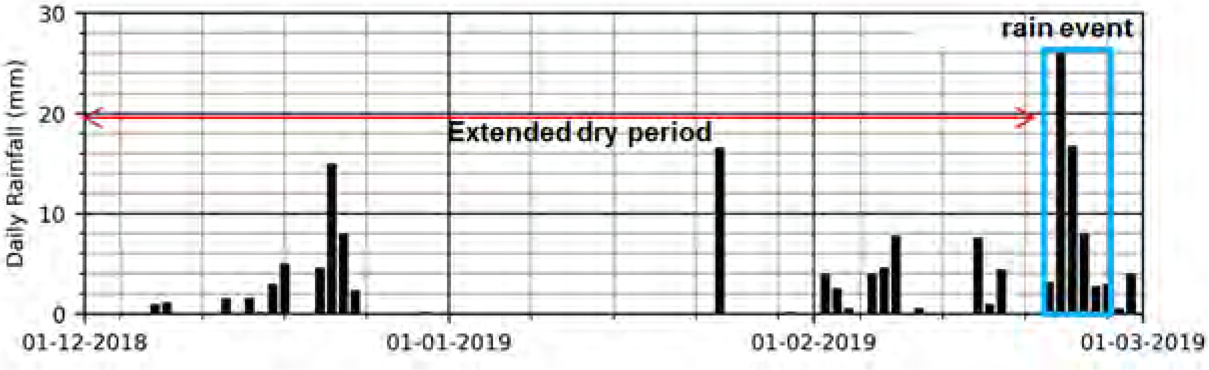

Figure 5-27: Rainfall at BOM rainfall station at Meerschaum Vale (Station ID: 058171)

During dry periods, salinity within the Tuckean Nature Reserve and along the inundated privately-owned properties that flank Stibbards Creek, Tucki Canal and Hendersons Drain is similar to the salinity in the Tuckean Broadwater. Regular salt inundation of these areas would influence the ecology of these areas. Without other interventions, there may be an initial dieback of the salt-intolerant plant species and a gradual recruitment of salt tolerant vegetation, such as mangroves or saltmarsh.

5.5.4 Summary of implications of Scenario 4

Based on the results of the numerical modelling, the implications of opening the floodgate flaps is summarised in Table 5-6. Indicative costs are also included, based on Table 4-1.

Table 5-6: Summary of implications for Scenario 4

Consideration	Implication
Floodplain inundation	Tidal inundation covers a significant portion of the Tuckean Nature Reserve area, as well as over some privately-owned land around Tucki Canal, Stibbards Creek and east of Hendersons Drain. These areas are inundated over 80% of the time.
In-channel drainage after rainfall events	Peak water levels throughout the floodplain increase marginally as a result of opening the barrage. Drainage immediately after the rainfall event (first 24 – 48 hours) is not greatly impacted, however the drainage for the fortnight after the rainfall event is slower.
Diffusive acid transport	While there are no changes to the drainage cross-sections to reduce diffusive acid transport, high salinity in the drains will promote neutralisation of the acidic waters because of naturally occurring bicarbonates in marine water. This neutralisation will largely only improve water quality during dry periods. After floods, salinity in the Broadwater is low, there will be limited neutralisation capacity and acid discharges from the north-eastern corner of the floodplain will continue to impact water quality.
Groundwater levels	The near-permanent inundation of the Tuckean Nature Reserve and surrounding areas will hold up the ground water table in this area and the surrounding floodplain. Higher surface water levels throughout the floodplain, but particularly in the north-east corner of the floodplain (e.g. Jumbo Drain) will also increase groundwater levels in this area.
Advective acid transport	Advective acid transport will be reduced due to higher average groundwater levels and a reduced hydraulic gradient between surface water and groundwater. This reduction in advective acid transport will be particularly significant in the Tuckean Nature Reserve, where groundwater levels are likely to remain at or near the surface during most periods.
Salinity	Hinging open the gates will allow tidal inundation throughout the Tuckean Nature Reserve and privately-owned areas around Tucki Canal, Stibbards Creek and east of Hendersons Drain. During extended dry periods, salinity in Meerschaum Vale and Jumbo Drains may increase to up to 10% of the salinity in the Tuckean Broadwater. If a small catchment event occurs after an extended dry period, salt-affected water can flow overbank in the north-east corner of the floodplain. High salinity in the drains will improve the natural acid neutralisation capacity and decrease acid discharge into the estuary, particularly during small events when salinity is not fully flushed from the drainage network.

Consideration	Implication
Implementation constraints	Hinging open the Bagotville Barrage floodgates will allow saltwater to inundate significant areas of the Tuckean floodplain, including private properties. Large changes in the ecosystems that occur on the impacted areas of the floodplain would have to be planned for and would also require substantial changes in land management practises in some privately-owned properties. Changes in management of the Bagotville Barrage should only be implemented in consultation with landholders.

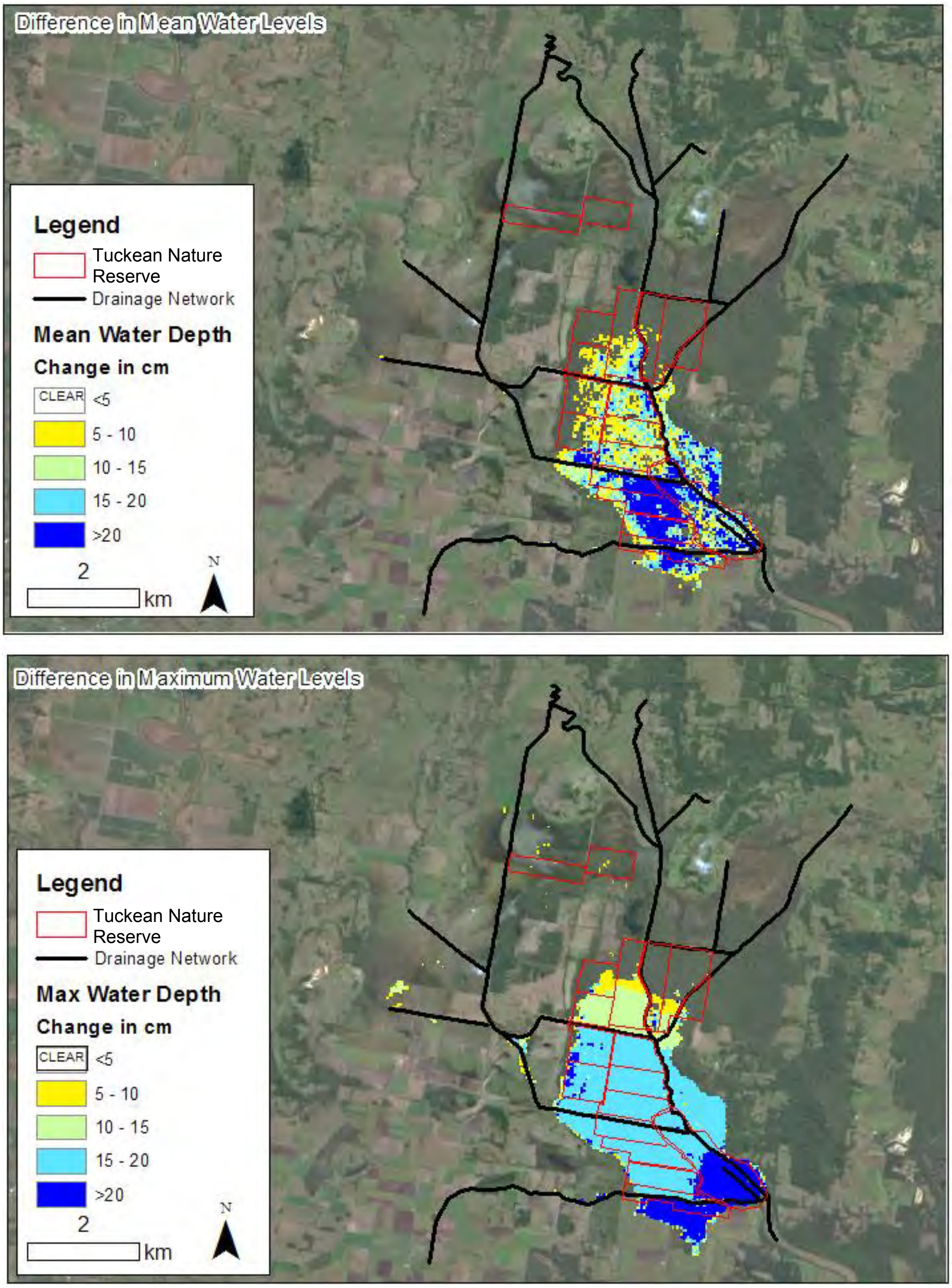

Figure 5-28: Scenario 4 - differences in mean (top) and maximum water depth on the floodplain, compared to the Base Case

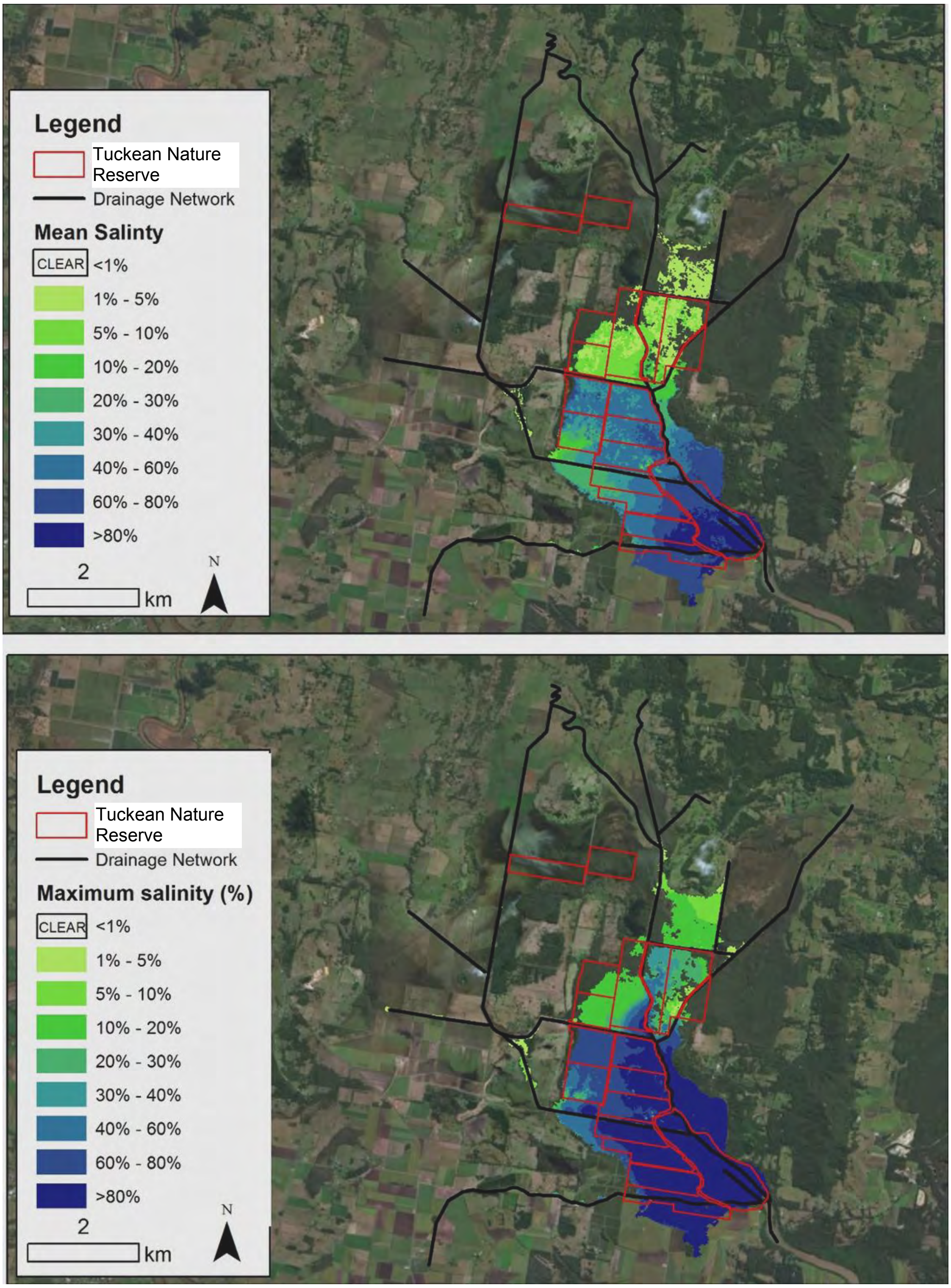

Figure 5-29: Scenario 4 - mean (top) and maximum water salinity on the floodplain, as a percentage of Tuckean Broadwater salinity

Note that areas that have a maximum or mean salinity below 1% are not coloured in these figures, and may still be inundated occasionally.

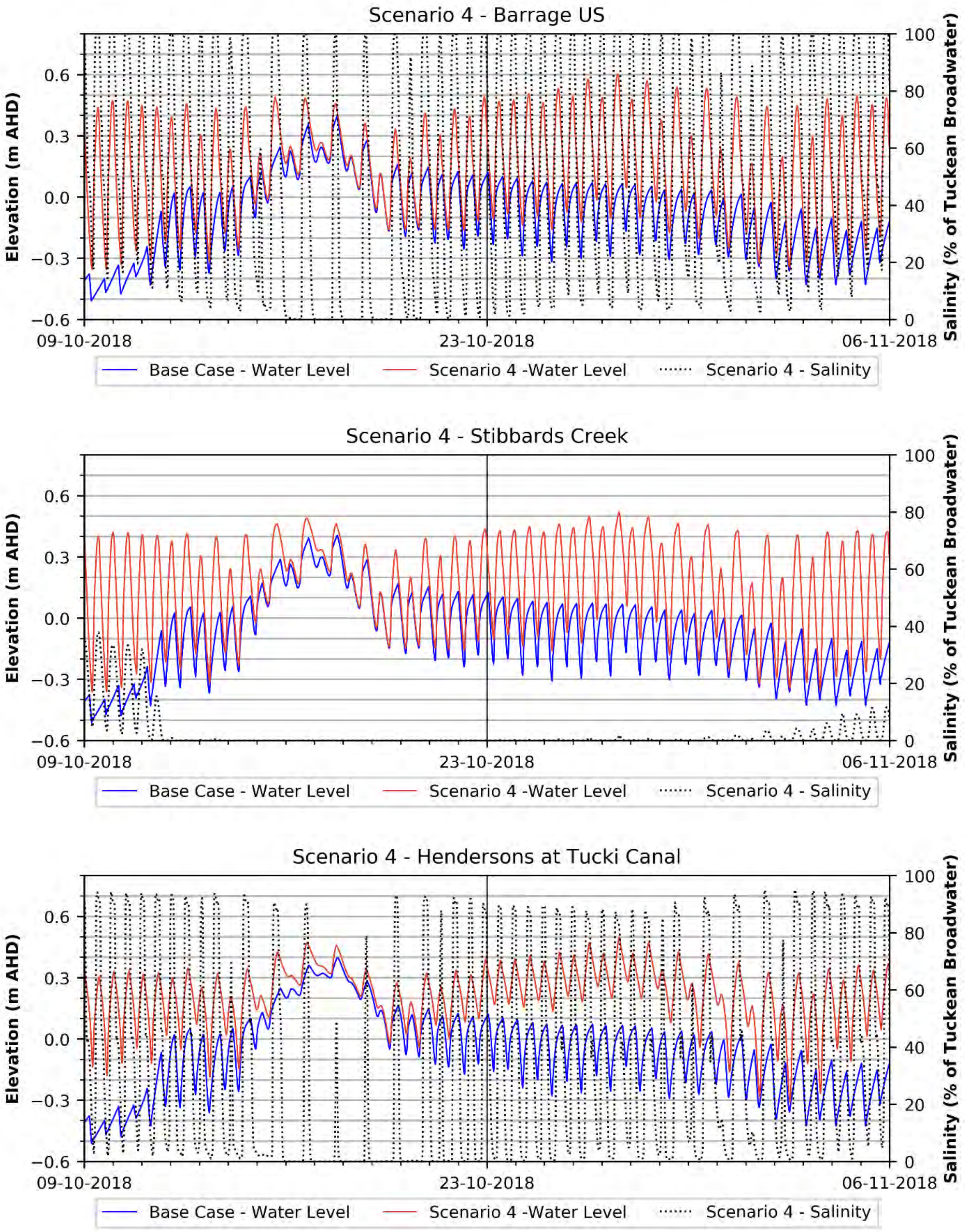

Figure 5-30: Scenario 4 - wet period drainage and salinity

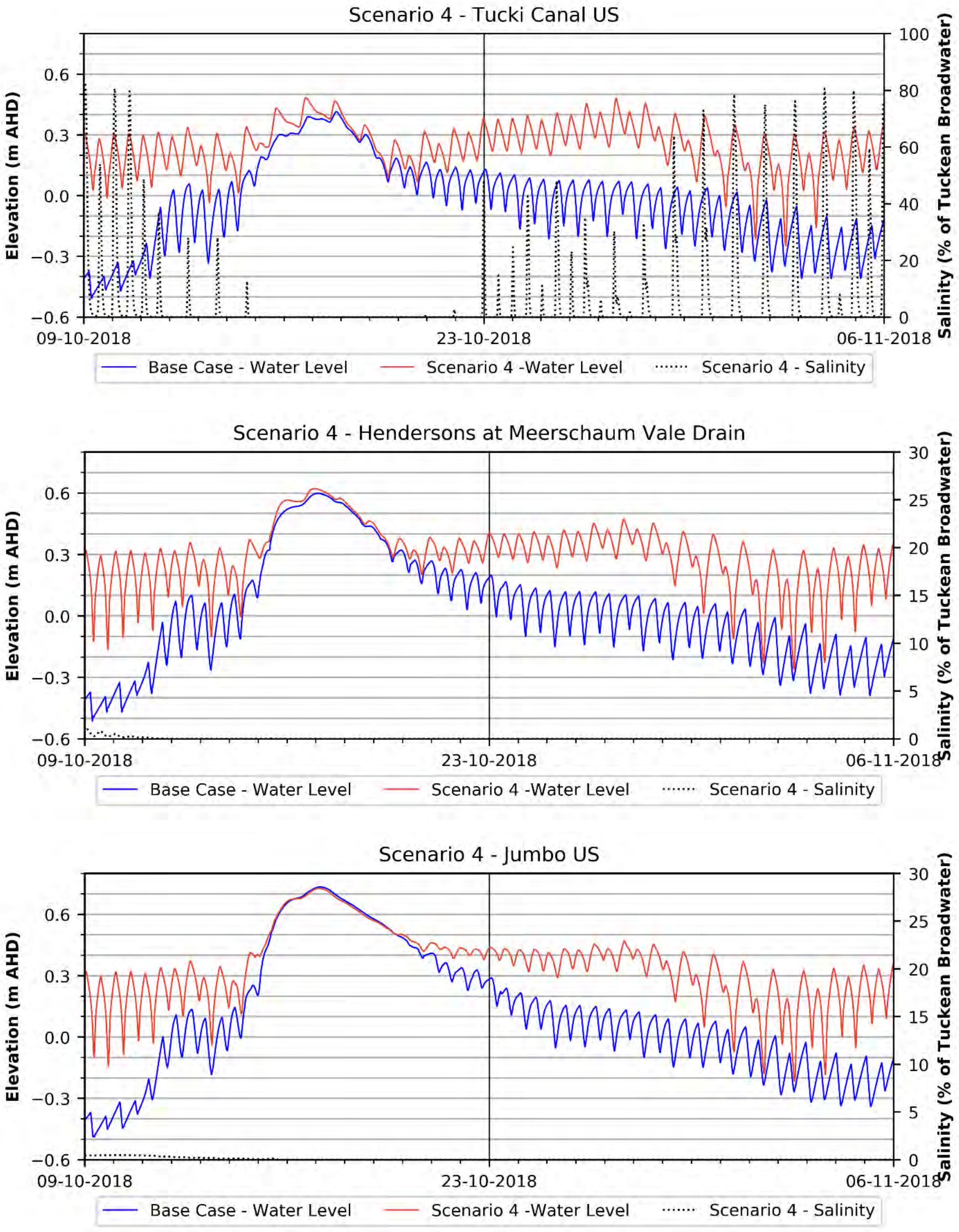

Figure 5-31: Scenario 4 - wet period drainage and salinity

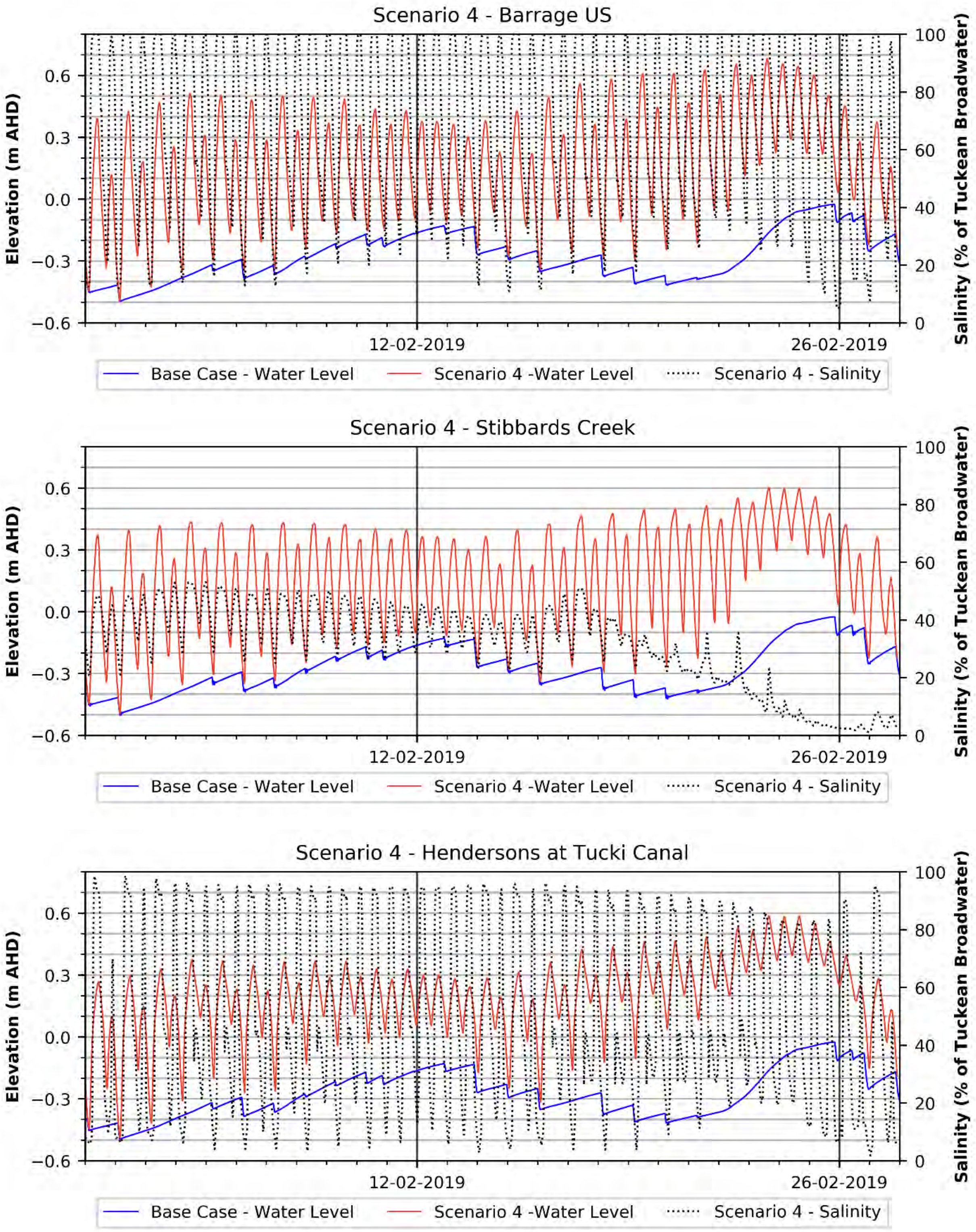

Figure 5-32: Scenario 4 - dry period drainage and salinity

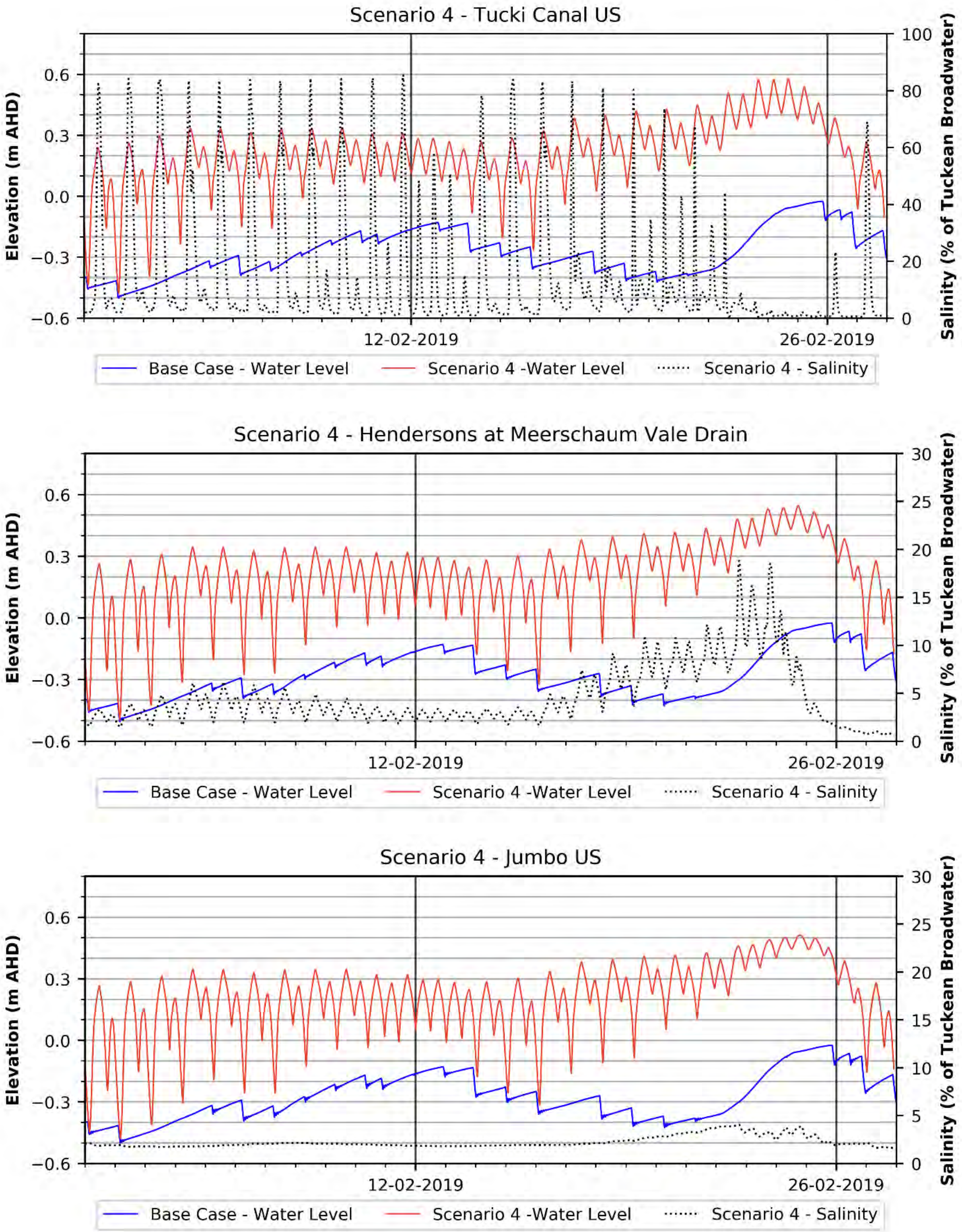

Figure 5-33: Scenario 4 – dry period drainage and salinity

5.6 Scenario 5 – Reflooding near Slatteries Drain

5.6.1 Description

Scenario 5 applies the modified drainage network developed for Scenario 1 (major reshaping of Meerschaum Vale, Jumbo and Slatteries Drains) to assess reflooding options. In this scenario, small to medium catchment flows from the Slatteries catchment are diverted onto the floodplain to encourage increased floodplain residence times of the low-lying land immediately west of Slatteries Drain (primarily focusing on the area between Slatteries Drain, Meerschaum Vale Drain and Jumbo Drain). This land was assessed for remediation as field data indicated it was highly acidic and a substantial source of acidic by-products.

Figure 5-34 shows the modifications to the model (beyond those described in Scenario 1) for this scenario. A 1D channel was added to the west of Slatteries Drain, with an invert of 0.6 m AHD (upstream) to 0.5 m AHD (downstream) before spilling on to the floodplain. In addition, the 2D topography was depressed to form a channel that diverts flow towards the lower section of the floodplain. Finally, a weir was placed on Slatteries Drain downstream of the new channel, with an invert of 0.7 m AHD. The overarching aim was to redirect low flows onto the floodplain, while maintaining flood conveyance through Slatteries Drain.

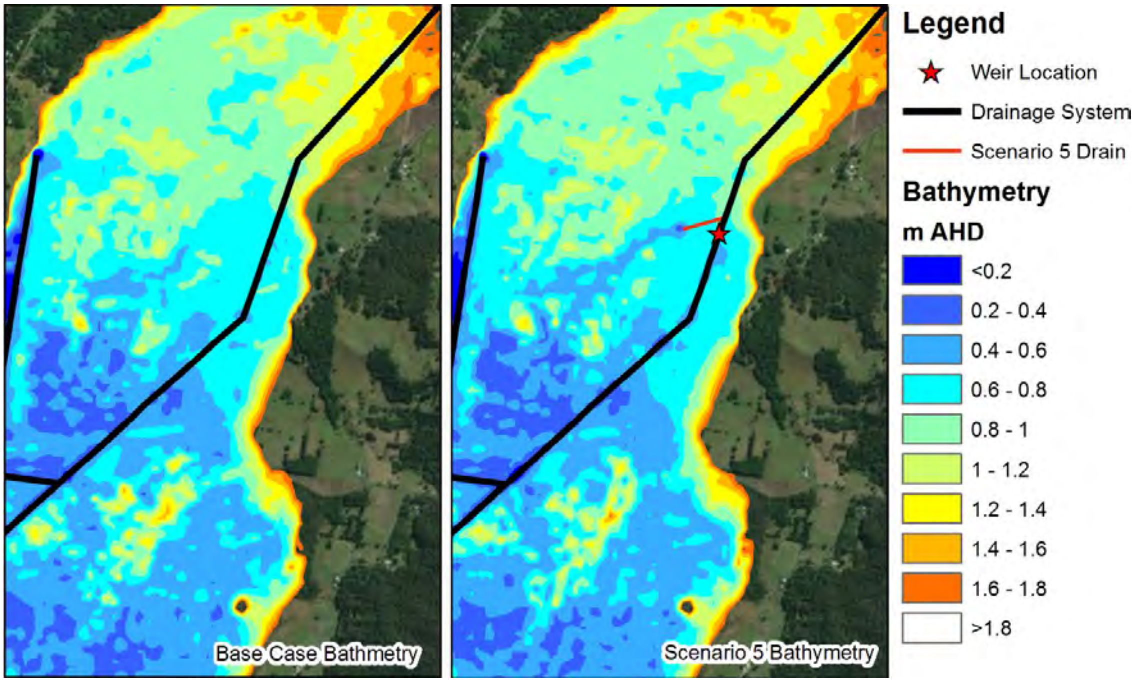

Figure 5-34: Modifications for Scenario 5
(Left – original bathymetry, Right – Scenario 5 bathymetry, with new channel in floodplain)

Field data has shown that the north-eastern section of the Tuckean floodplain has shallow ASS present near the ground surface. By encouraging small to medium catchment flows on to the floodplain, the length of time that this high priority section of the floodplain remains inundated will increase significantly. Reflooding the ASS affected area will limit further oxidisation and prevent advective acid transport that affects the surface water quality in the drains. This scenario will change floodplain inundation and would likely require land to be acquired from existing landholders and/or current land practices to be discontinued.

The barrage was assumed to be closed with no sluice gates open. As such, salinity was not modelled.

5.6.2 Changes in hydrodynamics from the Base Case

The Scenario 5 results indicate a change in drainage in the north-east corner of the Tuckean floodplain. Figure 5-36 shows that both the mean and maximum inundation changes as a result of this scenario. As per the purpose of this scenario, there is an area of approximately 25 ha (500 m by 500 m) that is typically under 10 – 20 cm of water west of Slatteries Drain. Mean inundation beyond the targeted area west of Slatteries Drain was not significantly impacted by the proposed changes to the drainage network. However, there are changes to the maximum inundation, also shown in Figure 5-36, beyond the targeted 25 ha area. Immediately upstream of the weir, maximum inundation depths are up to 20 cm higher as a result of the changes to the drainage network. Additional small changes in inundation between Jumbo Drain and Slatteries Drain are also identified, due to the increased water levels in the drains immediately upstream of the weir structure.

As noted, Scenario 5 involves the same re-shaping of drains as per Scenario 1. Both Figure 5-37 and Figure 5-38 show that the differences between drainage in Scenario 5 and Scenario 1 are minor, except at Slatteries US. As there is an additional structure (weir at 0.7 m AHD) in Slatteries Drain, the water levels upstream of the structure are significantly higher. This allows the water that would have otherwise flowed downstream to be re-directed to the floodplain. Figure 5-37 shows that this slightly increases peak water levels at Slatteries US and slows down the drainage immediately after the rain event. Water levels during dry periods, shown in Figure 5-38, remain almost half a metre higher than the Base Case due to the weir structure.

Figure 5-35 shows the discharge through the new drain (shown in red in Figure 5-34). Discharge through this drain is typically greater than 0.1 m^3/s, allowing water onto the floodplain during most periods. However, in the period from the 20/1/2019 to the 20/2/2019, when rainfall was minimal, there is negligible discharge onto the floodplain. This indicates the floodplain would still dry out during periods of extended droughts through evaporation and groundwater leakage.

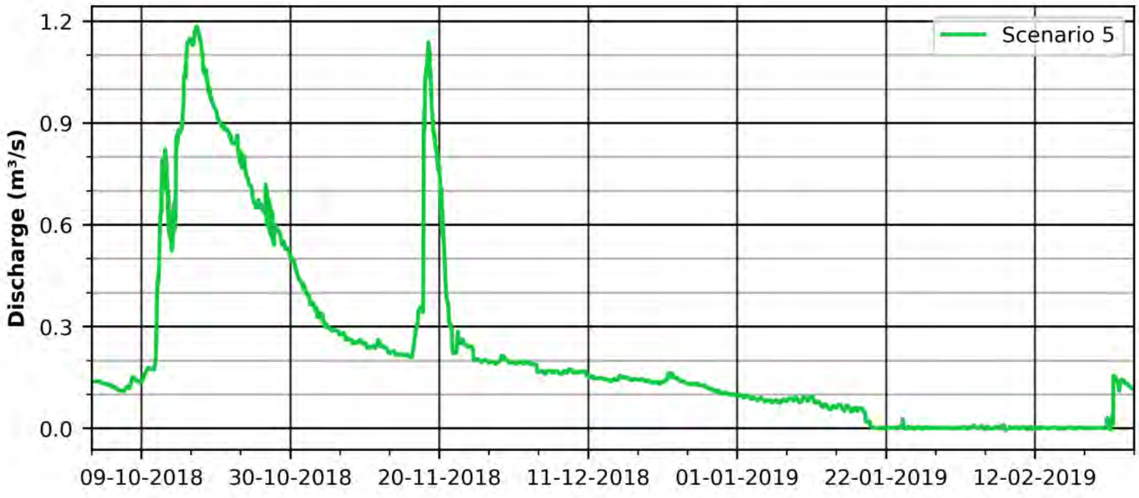

Figure 5-35: Discharge on to the floodplain throughout modelling period

5.6.3 Summary of implications for Scenario 5

Based on the results of the numerical modelling, the implications of reshaping the drainage network and actively re-flooding selected areas of the floodplain are summarised in Table 5-7. Indicative costs are also included, based on Table 4-1.

Table 5-7: Summary of implications for Scenario 5

Consideration	Implication
Floodplain inundation	A 25 hectare area of the floodplain near the confluence of Meerschaum Vale and Slatteries Drain would be inundated most of the time, with typical water depths of 0.1 – 0.2 m. However, this area would dry out during extended dry periods. Some minor increases in maximum floodplain inundation levels are likely near the weir structure.
In-channel drainage after rainfall events	Drainage times will increase within the drainage network as a result of shallowed drains as per the results of Scenario 1. In addition, water levels will increase upstream of the additional weir structure, and drainage time in the upstream sections of Slatteries Drain will also increase.

Consideration	Implication
Diffusive acid transport	Diffusive acid transport will be reduced as the drains no longer intersect the deeper acid sulfate soils existing on the floodplain, as per the summary for Scenario 1.
Groundwater levels	Encouraging inundation of the floodplain will result in increased groundwater levels in the area. Also, by increasing drainage times after a rainfall event, the hydraulic gradient between the surface water and groundwater table will be reduced, resulting in less groundwater drawdown. This, combined with higher mean and minimum surface water levels will increase the average groundwater levels in the north-east corner of the floodplain.
Advective acid transport	A reduced hydraulic gradient between the surface water and groundwater will decrease advective acid transport from the surrounding floodplain, particularly from the 25 ha of area that is actively re-flooded. Increasing minimum water levels and near-permanent inundation of some areas will also prevent further oxidation of ASS at low levels.
Salinity	No changes to salinity are expected.
Construction constraints	This scenario will require the construction of an additional drain and some reshaping of the floodplain in the vicinity of the drain. The results also show that a significant floodplain area will be inundated, which would likely require the acquisition of property and/or alternative land management practices. In addition, swaled drains typically have a larger footprint than the narrower, deeper drains than they replace. This work would require agreement from the private landholders that live adjacent to the relevant drains. To construct the drains actual acid sulfate soils will have to be disturbed, which would require an acid sulfate soil plan to be developed. In some areas, swaling will also require some outside fill to be obtained from off-site.

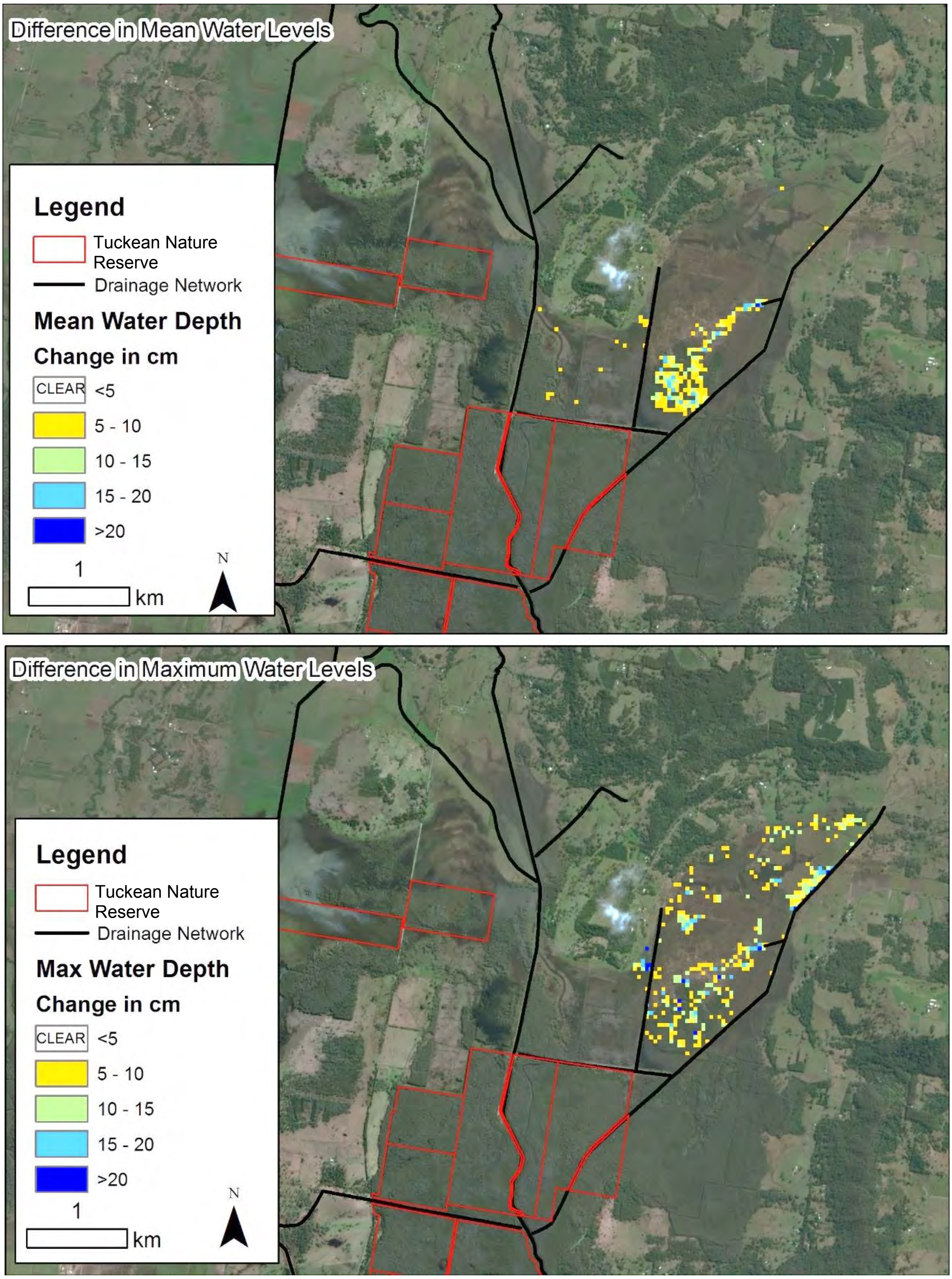

Figure 5-36: Scenario 5 - differences in mean (top) and maximum water depth on the floodplain, compared to the Base Case

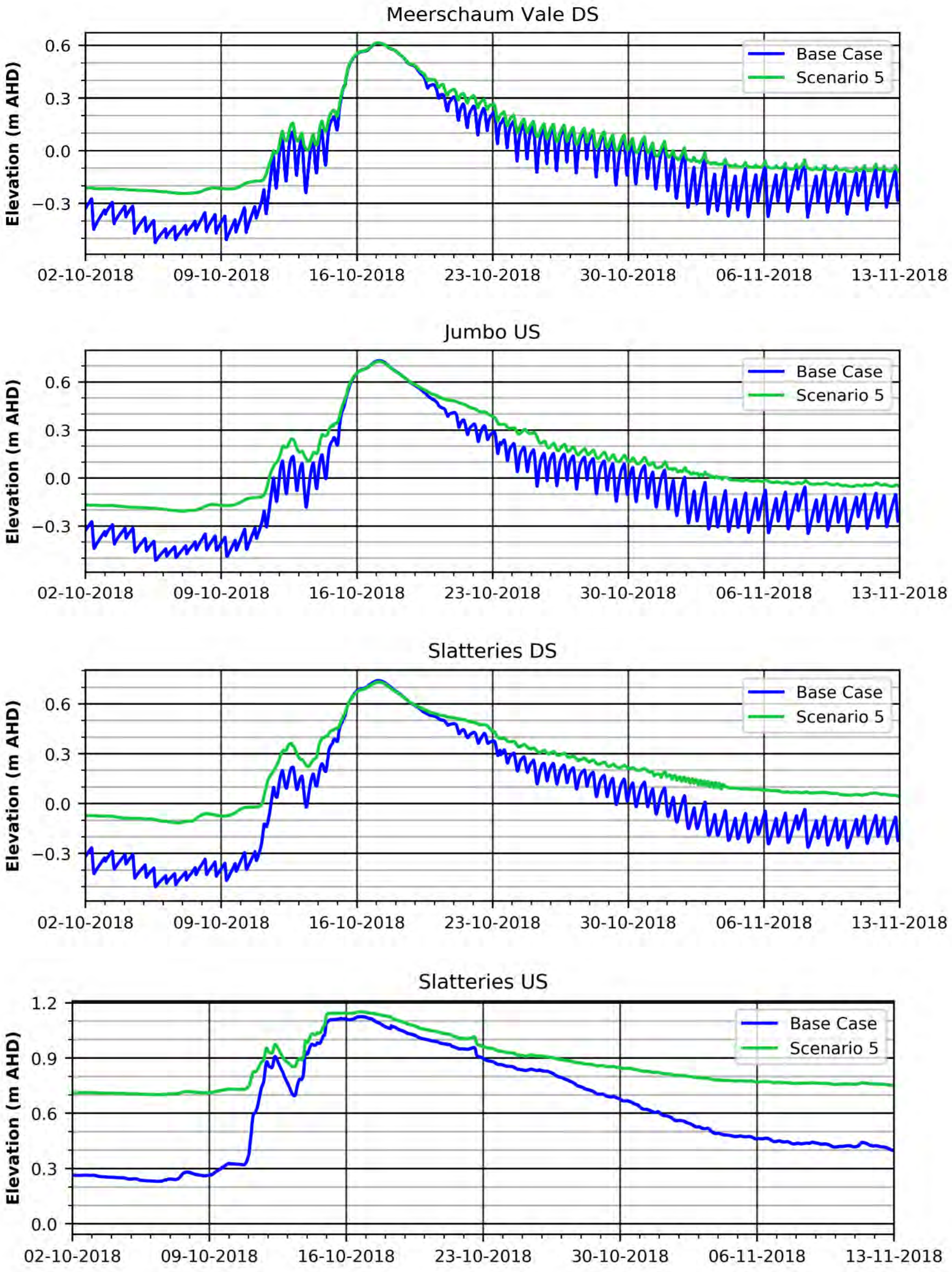

Figure 5-37: Scenario 5 - wet period drainage at key locations

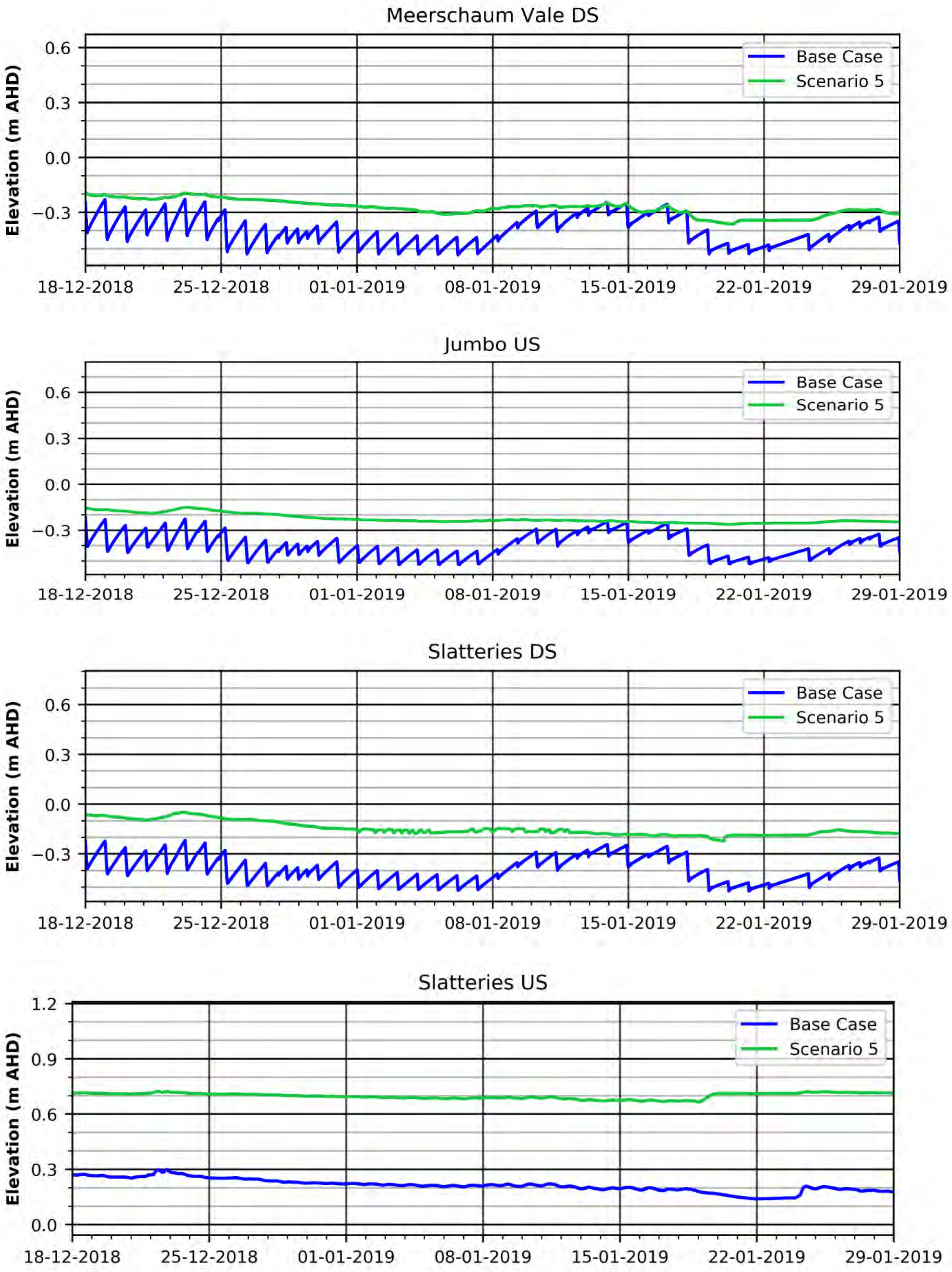

Figure 5-38: Scenario 5 – dry period drainage at key locations

5.7 Scenario 6 – Open the barrage floodgate flaps and installing upstream flood control structures

5.7.1 Description

Scenario 4 considers a strategy where the barrage floodgates are hinged open, but there are no upstream structures put in place to reduce the impact of the tides upstream of the Tuckean Nature Reserve boundary (to contain the tidal inundation within the Tuckean Nature Reserve). To refine this option, Scenario 6 assesses the impact of installing four (4) new one-way tidal control structures at the boundary of the Tuckean Nature Reserve on Stibbards Creek, Tucki Canal, Stony Island Drain and Hendersons Drain (locations shown in Figure 5-39). The modelled dimensions of the structures are provided in Table 5-8. Note that these dimensions could be refined if on-ground works were to occur, however the results are indicative of the potential impacts of similar structures.

It is likely that additional drain levees may be required to stop tidal inundation bypassing the additional structures. The result provided below includes a description of where any additional levees may be required.

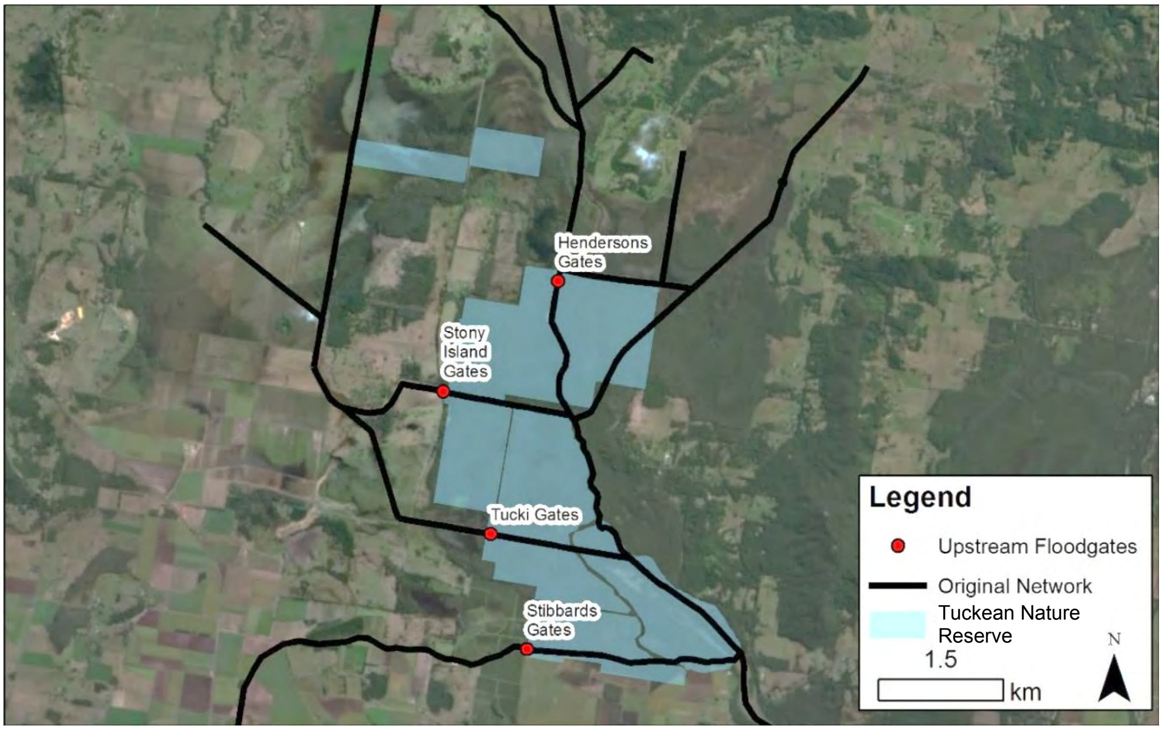

Figure 5-39: Location of new tidal control structures for Scenario 6

Table 5-8: Dimensions of new floodgate structures

Location	No. Box Culverts	Width (m)	Height (m)	Invert (m AHD)
Stibbards Gates	4	3	2	-0.8
Tucki Gates	5	3	2.5	-1.2
Stony Island*	1	3.4	1.9	-0.76
Hendersons Gates	6	3	2.5	-1.1

* Installing flap gate on existing culvert.

As there are tidal inflows from the Tuckean Broadwater into Hendersons Drain in this scenario, salinity has been modelled. The salinity boundary of the model was assigned a constant concentration of 100, and results are presented as a percentage of the salinity in the Broadwater. The modelled salinity concentration is thereby a percentage of the Broadwater boundary condition.

5.7.2 Changes to hydrodynamics compared to the Base Case and Scenario 4

As this scenario involves hinging open the barrage gates, as in Scenario 4, but with additional structures to mitigate upstream impacts, the hydrodynamic results for Scenario 6 have been compared to both the Base Case and Scenario 4.

Figure 5-46 shows that there is a significant difference in floodplain inundation in Scenario 6 when compared to the Base Case. However, by comparing Figure 5-46 and Figure 5-28, it can be seen that there is limited difference in floodplain inundation between this scenario and Scenario 4. Additionally, the new proposed upstream floodgates do not prevent floodplain inundation on the private properties west of the Tuckean Nature Reserve on Tucki Canal, south of the Tuckean Nature Reserve on Stibbards Creek and east of Hendersons Drain. Additional levees and bunding would be required to prevent inundation on these properties.

Figure 5-48 and Figure 5-49 show that in-drain water levels during a large rain event in early October do not vary significantly between Scenario 6 and Scenario 4 -(water levels in the Tuckean Broadwater are the primary control throughout this period). However, Figure 5-50 and Figure 5-51 highlight that this is not the case during extended dry periods. Water levels upstream of the new floodgates (Stibbards Creek, Tucki Canal US, Hendersons at Meerschaum Vale Drain and Jumbo US) behave differently than in Scenario 4. At Stibbards Creek, which has the most significant levees to prevent over-bank flow near the structure and the smallest inflow catchment, water levels drain to the low tide level upstream of the barrage as per normal floodgate hydraulics.

At the other three upstream locations (Tucki Canal, Stony Island Drain and Hendersons Drain), water levels in the drains are generally lower than Scenario 4, however in-drain water levels are still routinely up to 0.8 m higher than in the Base Case. This indicates that there is significant over-bank flow occurring, allowing water flowing around the new structures and bypassing the floodgates. This is also supported by Figure 5-46 and salinity modelling, which is discussed further in Section 5.7.3. Mitigation options are discussed further in Section 5.7.5.

5.7.3 Changes to salinity compared to the Base Case and Scenario 4

Figure 5-47 shows that the salinity propagation is similar in Scenario 6 to Scenario 4. Areas downstream of the new floodgates are inundated with high salinity water during normal tidal cycles, including most of the Tuckean Nature Reserve and the privately-owned properties south of Stibbards Creek and east of Hendersons Drain. Saltwater inundation on the floodplain is also evident along the banks of Tucki Canal west of the Tuckean Nature Reserve boundary.

Figure 5-50 and Figure 5-51 depict the potential salinity throughout the drainage network in Scenario 6. The new floodgates in Tucki Canal and Stibbards Creek prohibit tidal flows in the channel upstream of the structures. However, salinity in Jumbo Drain still reaches up to 10% of the salinity in the Tuckean Broadwater.

There are two (2) ways for the tidal waters to enter this upstream section of the floodplain:

1. Through the relic part of Slatteries Drain, which directly connects Slatteries Drain to Hendersons Drain through the Tuckean Nature Reserve. This is connected to the upstream section of Slatteries Drain by two (2) 60 cm culverts that appeared largely blocked at the time of the survey (June 2018) however the culverts have been included in the model.
2. Floodplain flows through low sections in the Meerschaum Vale Drain (left bank as highlighted in Figure 5-40), allowing tidal flushing from the Tuckean Nature Reserve into Meerschaum Vale Drain upstream of the new floodgates.

5.7.4 Mitigation strategies to limit tidal flow around new floodgates

There are four (4) distinct areas, outside the Tuckean Nature Reserve, which experience an increase in inundation and/or salinity, despite the installation of the upstream structures. These include:

- South of Stibbards Creek (currently used for sugar cane);
- West of the Tuckean Nature Reserve, near Tucki Canal (currently used for grazing);

- East of Hendersons Drain, downstream of Stony Island Drain (privately owned, and appears densely vegetated); and
- North-eastern quadrant of the floodplain, around Meerschaum Vale, Jumbo and Slatteries Drains.

Possible mitigation strategies for each area are discussed below.

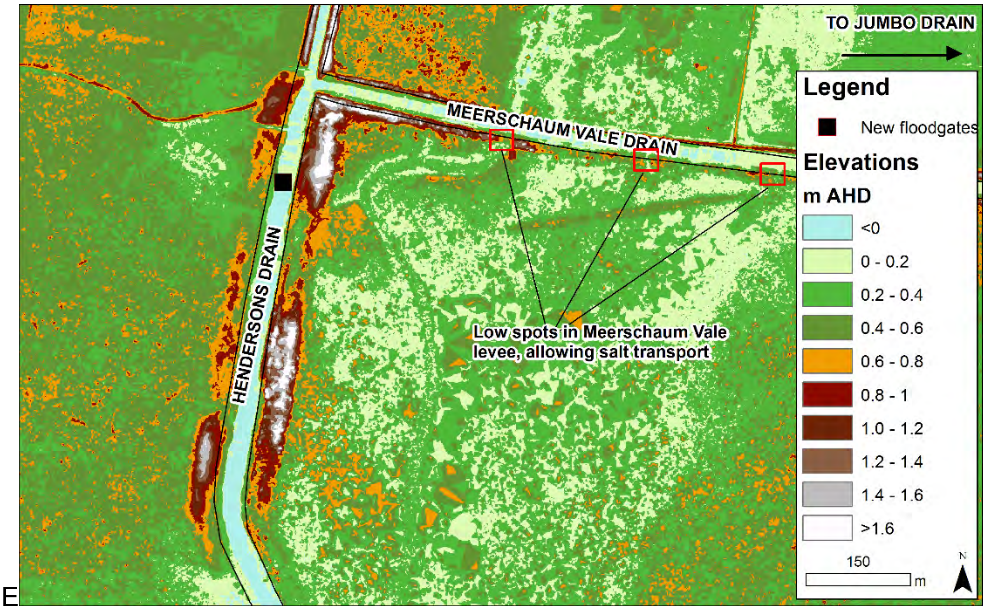

Figure 5-40: Low points in the Meerschaum Vale Drain levee

Stibbards Creek

The downstream section of Stibbards Creek (downstream of the new floodgate) has low-lying drain levee banks that do not prevent over bank flow during high water levels. With the barrage gates shut, this is only an issue during freshwater flows when the water levels in the drainage system rise above low tide levels. However, if the barrage gates were open, high tide water levels flow overbank on most tides. To prevent this overbank flow the levee height along the right (southern) bank of Stibbards Creek would have to be increased. Based on water level modelling during dry periods (see Figure 5-50), a minimum levee height of approximately 0.7 m AHD would be required.

Figure 5-41 shows the existing levee heights, based on the ground-truthed DEM developed for this project (see Appendix B, Section B.2.3 for more details on the DEM). There are two distinct areas that require additional levee raising. Within 600 m of the Bagotville Barrage, the levee of the existing levee is low (approximately 0 m AHD), allowing a significant amount of overbank flow. An additional 400 m of levee (approximately 1.5 km upstream from the barrage) would have to be raised by approximately 20 cm to prevent overbank flow under this scenario.

This mitigation strategy does not consider groundwater flow through the levee banks. While WRL (2019) showed that there was an extremely low hydraulic conductivity in the clay layer that lies at approximate -0.4 m AHD, it is expected that groundwater flow would occur in the higher sandy layer (which is expected to have a high hydraulic conductivity, based on the work of Brodie, 2007). Further investigations would be required to ensure that salinity through groundwater exchange would not impact landholders south of Stibbards Creek and it is possible that the groundwater conductivity in this area would impact adjacent private land. Alternatively, the lowest lying land in the area could be purchased, or the landholder compensated for the loss in agricultural productivity.

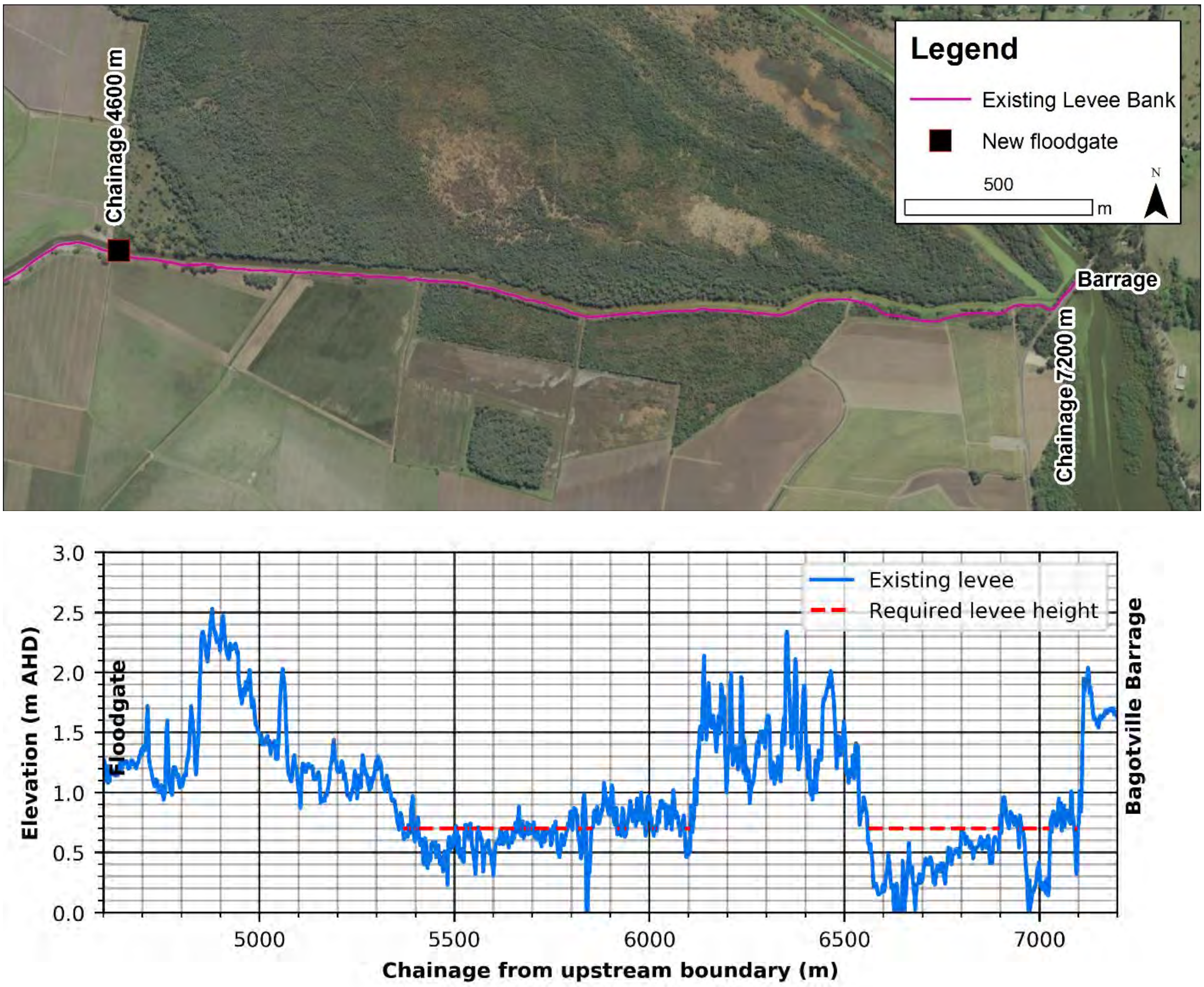

Figure 5-41: (Top) Stibbards Creek right bank levee. (Bottom) Existing and required drain levee bank height

Tucki Canal

The private properties immediately to the west of the Tuckean Nature Reserve along the banks of Tucki Canal are low lying with some areas below 0 m AHD. Despite the new floodgate structure on Tucki Canal, this land is well connected to the adjacent land in the Tuckean Nature Reserve and tidal flows over the floodplain inundate the privately-owned land. To mitigate these impacts, two (2) remedial actions would have to be undertaken:

- 'Blow outs' (low points) on the levees upstream of the new floodgate would need to be infilled to a height of at least 0.6 m AHD (see Figure 5-42 for examples of levee blowouts). Small, one-way floodgates could be installed in the levee to maintain floodplain drainage; and
- A bund with a minimum crest height of 0.6 m AHD would be required along the low-lying boundary of the Tuckean Nature Reserve (see Figure 5-42 for bund location). Based on the existing ground elevation (shown in Figure 5-43), the average ground elevation along this boundary is approximately 0.15 m AHD. It is estimated that approximately 3,500 m^3 of fill would be required to construct this bund (based on a crest width of 1 m and bank slope of 1V:2H).

Alternatively, the area impacted could be purchased or the landholder compensated for the loss in agricultural productivity.

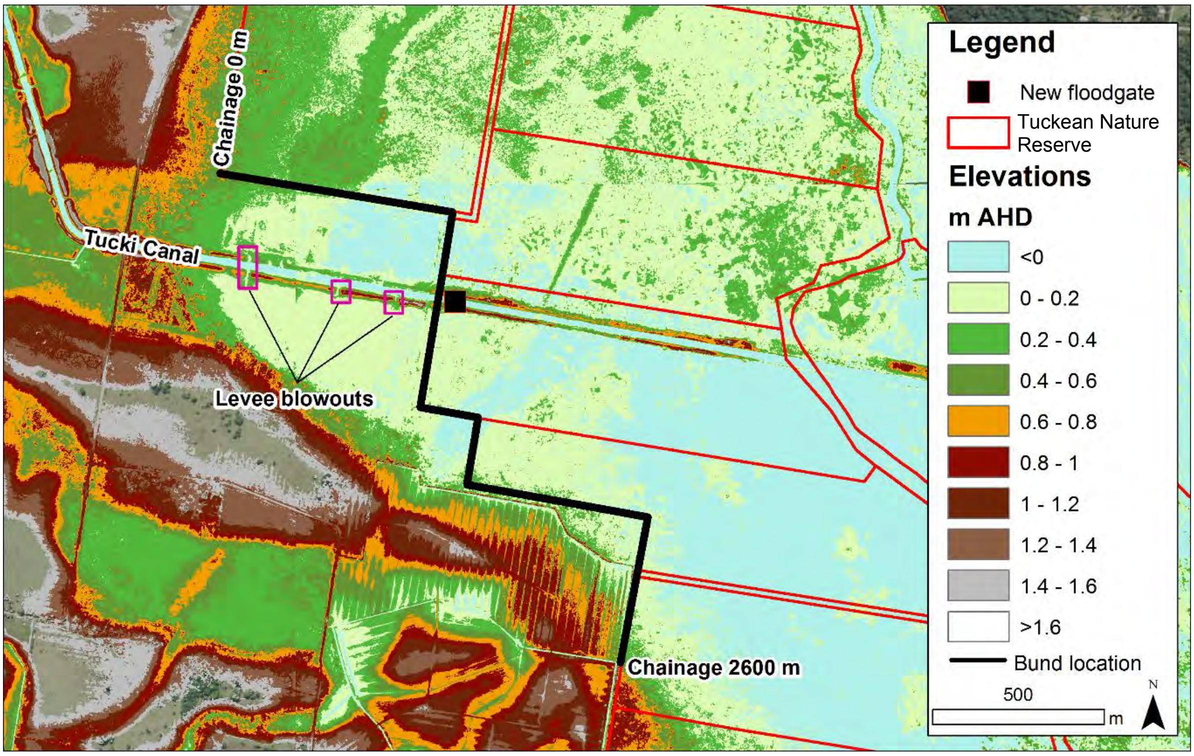

Figure 5-42: Levee and bund requirements for Tucki Canal

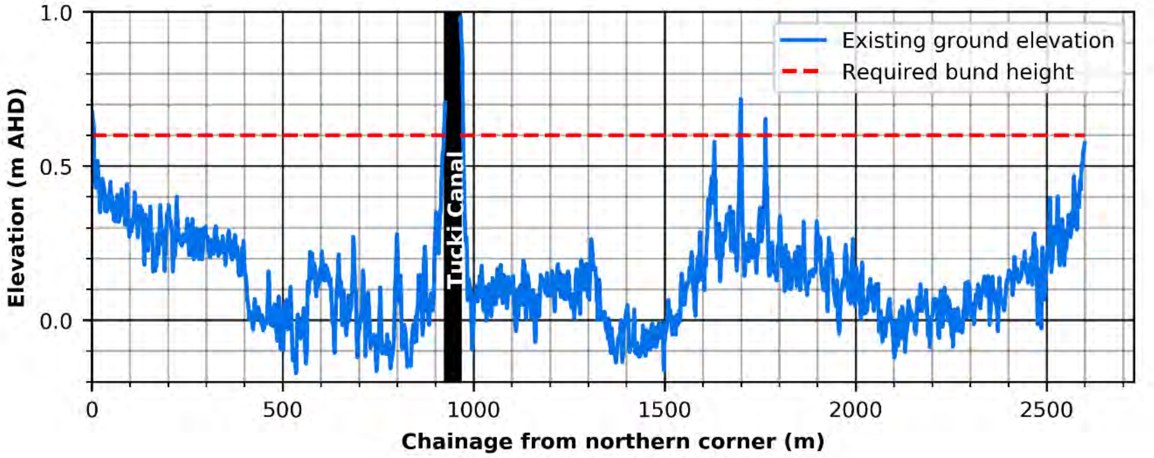

Figure 5-43: Required bund height at Tucki Canal

North-eastern section of the floodplain

Salt infiltration into Meerschaum Vale and Jumbo Drains may impact agriculture in this section of the floodplain. Two (2) potential mitigation measures could be implemented to prevent salt transport in this area:

- Infilling the culvert connecting the main section of Slatteries Drain (at the confluence with Meerschaum Vale Drain) and the relic section of the drain through the Tuckean Nature Reserve to the south. This connection was observed to be poor during field investigations in June 2018. The majority of flows are conveyed through Meerschaum Vale Drain and disconnecting this drain from the northern part of the floodplain is unlikely to change flood conveyance; and
- As shown below Figure 5-44, there are low sections in the southern levee of Meerschaum Vale Drain that allow water from the Tuckean Nature Reserve to flow overbank into the drain when water levels are particularly high. Based on modelled water levels in the Tuckean Nature Reserve, the levee along the southern bank of Meerschaum Vale Drain would have to be raised to a minimum height of 0.5 m AHD to prevent downstream flows bypassing the new floodgate structures. Based on Figure 5-44, it is estimated that approximately 130 m of the levee would have to be raised between 10 – 40 cm.

While there may continue to be groundwater inflow from the Tuckean Nature Reserve into Meerschaum Vale drain, the clays that occur in this area generally have a low hydraulic conductivity (discussed further in Appendix B). This, combined with the relatively low salinity in the Tuckean Nature Reserve south of Meerschaum Vale Drain, is likely to limit the groundwater transport of salinity into the north-east corner of the floodplain.

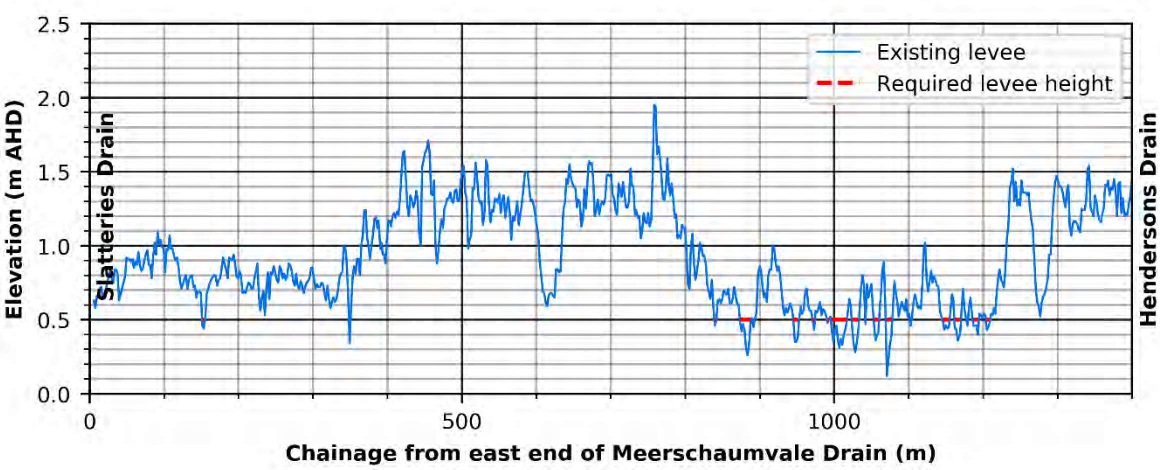

Figure 5-44: Existing and required levee elevation along the southern bank of Meerschaum Vale Drain

East of Hendersons Drain

There is approximately 100 ha of private land east of Hendersons Drain that lies below 0.2 m AHD (shown in Figure 5-45) which would be inundated more than 80% of the time if the Bagotville Barrage floodgates were hinged open to allow tidal flows. This low-lying land is bordered by steep hills to the east. While this land is privately owned, aerial images show that the land is densely vegetated and already often waterlogged.

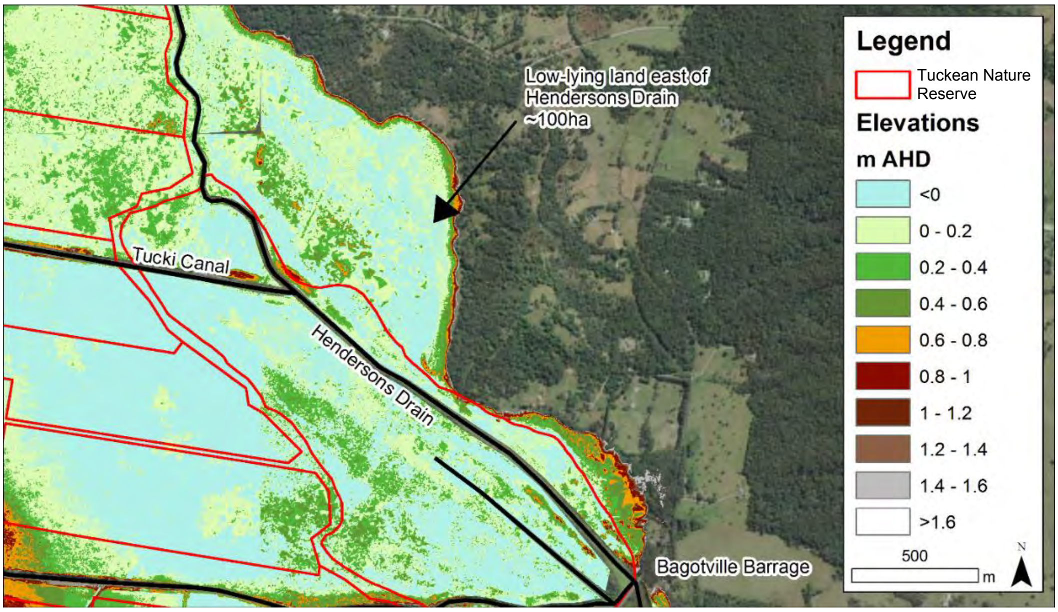

Figure 5-45: 100 ha of low-lying land east of Hendersons Drain

Given the area that lies below mean sea level (0 m AHD), levees to protect this area from tidal inundation are unlikely to be practical. Implementing this option would require the consent from landholders or this land to be acquired (and possibly sub-divided from higher sections of the property).

5.7.5 Summary of implications of Scenario 6

Based on the results of the numerical modelling, the implications of opening the barrage floodgates and installing new upstream floodgate structures are summarised in Table 5-9. Indicative costs are also included, based on Table 4-1.

Table 5-9: Summary of implications for Scenario 6

Consideration	Implication
Floodplain inundation	Tidal inundation covers a significant portion of the Tuckean Nature Reserve area, as well as over some privately-owned land around Tucki Canal, Stibbards Creek and east of Hendersons Drain. These areas are inundated over 80% of the time. The privately-owned land along Stibbards Creek and Tucki Canal could be partially protected through additional earthworks.
In-channel drainage after rainfall events	Peak wet weather water levels throughout the floodplain increase marginally as a result of opening the barrage. Drainage immediately after the modelled October 2018 rainfall event (first 24 – 48 hours) is not greatly impacted, however the drainage for the fortnight after the rainfall event is slower throughout the entire floodplain.
Diffusive acid transport	While there are no changes to the drainage cross-sections to reduce diffusive acid transport, high salinity in the drains downstream of the new floodgates will promote neutralisation of the acidic waters because of naturally occurring bicarbonates in marine water. This neutralisation will largely only improve water quality during dry periods. After floods, salinity in the Broadwater is low, there will be limited neutralisation capacity and acid discharges from the north-eastern corner of the floodplain will continue to impact water quality. There would be no change to diffusive acid transport upstream of the new floodgates.
Groundwater levels	The near-permanent inundation of the Tuckean Nature Reserve and surrounding areas will hold up the ground water table in this area and the surrounding floodplain. Higher water levels in the north-east corner of the floodplain (e.g. Jumbo Drain) will also increase groundwater levels,

Consideration	Implication
	although the increases in groundwater levels would be smaller than Scenario 4.
Advective acid transport	Advective acid transport will be reduced due to higher average water levels and a reduced hydraulic gradient between surface water and groundwater. The north eastern Slatteries section of the floodplain (which is one of the largest acid contributors) would continue to discharge acid into the surface waters.
Salinity	Salinity downstream of each of the new floodgates would routinely be similar to the Tuckean Broadwater (up to about 60% of seawater). This would significantly improve the acid neutralisation capacity of the lower floodplain and decrease acid discharges into the wider Richmond River. However, if additional mitigation measures are implemented (see Section 5.7.4) salinity transport beyond the boundaries of the Tuckean Nature Reserve would be limited.
Implementation constraints	A number of impact mitigation measures would be required to prevent adverse effects for private landholders adjacent to the Tuckean Nature Reserve, including; land acquisition, improving levees, and installation of approximately 2.5 km of bunding. A detailed discussion of these measures is provided in Section 5.7.4. Even with these measures, groundwater transport of saline water may still be an issue, especially for those properties south of Stibbards Creek. Areas within the Tuckean Nature Reserve would undergo a significant change in ecology as a result of increased inundation times and increased salinity. Changes in management of the Bagotville Barrage could only be implemented in consultation with landholders.

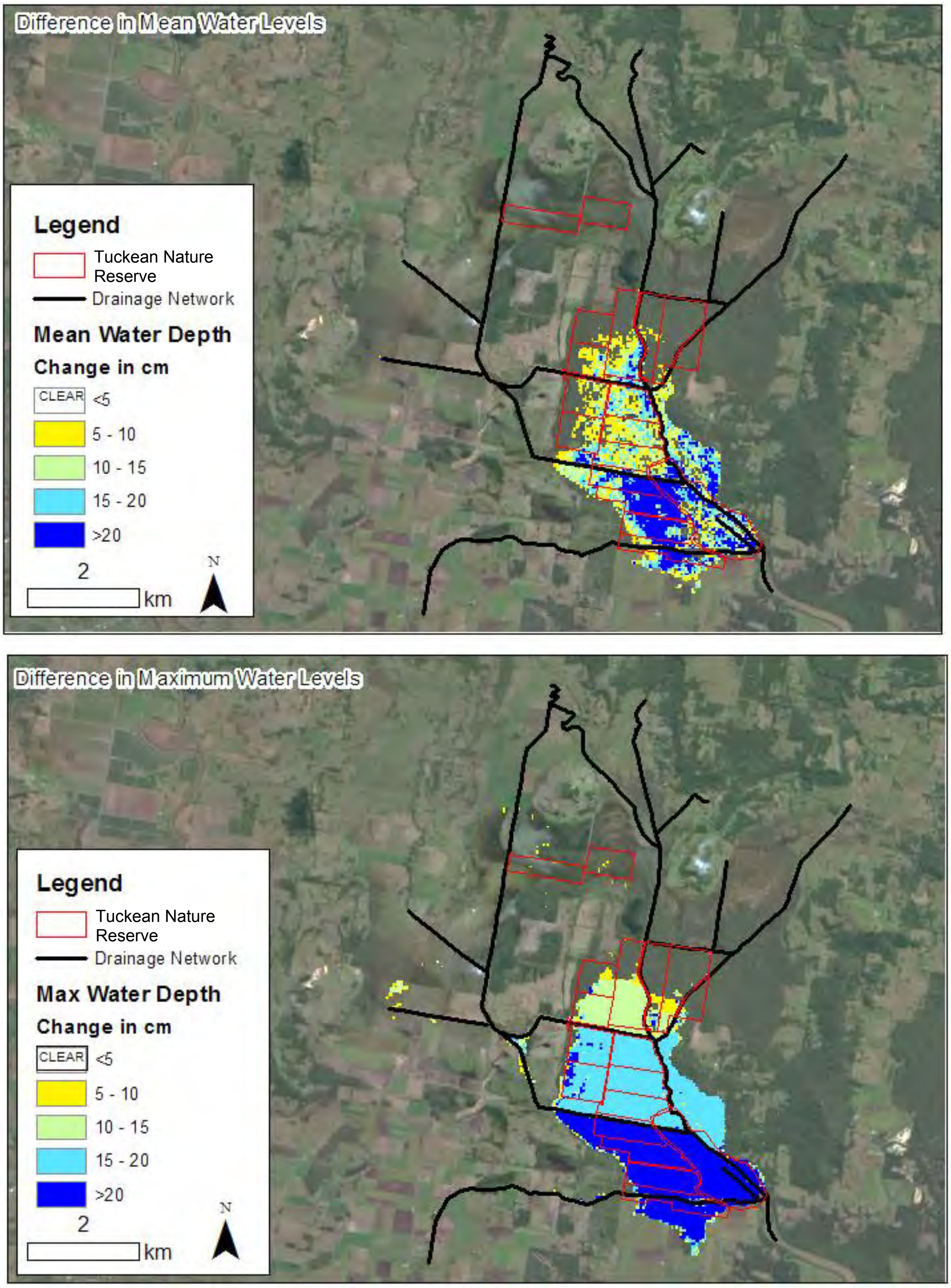

Figure 5-46: Scenario 6 - differences in mean (top) and maximum water depth on the floodplain, compared to the Base Case

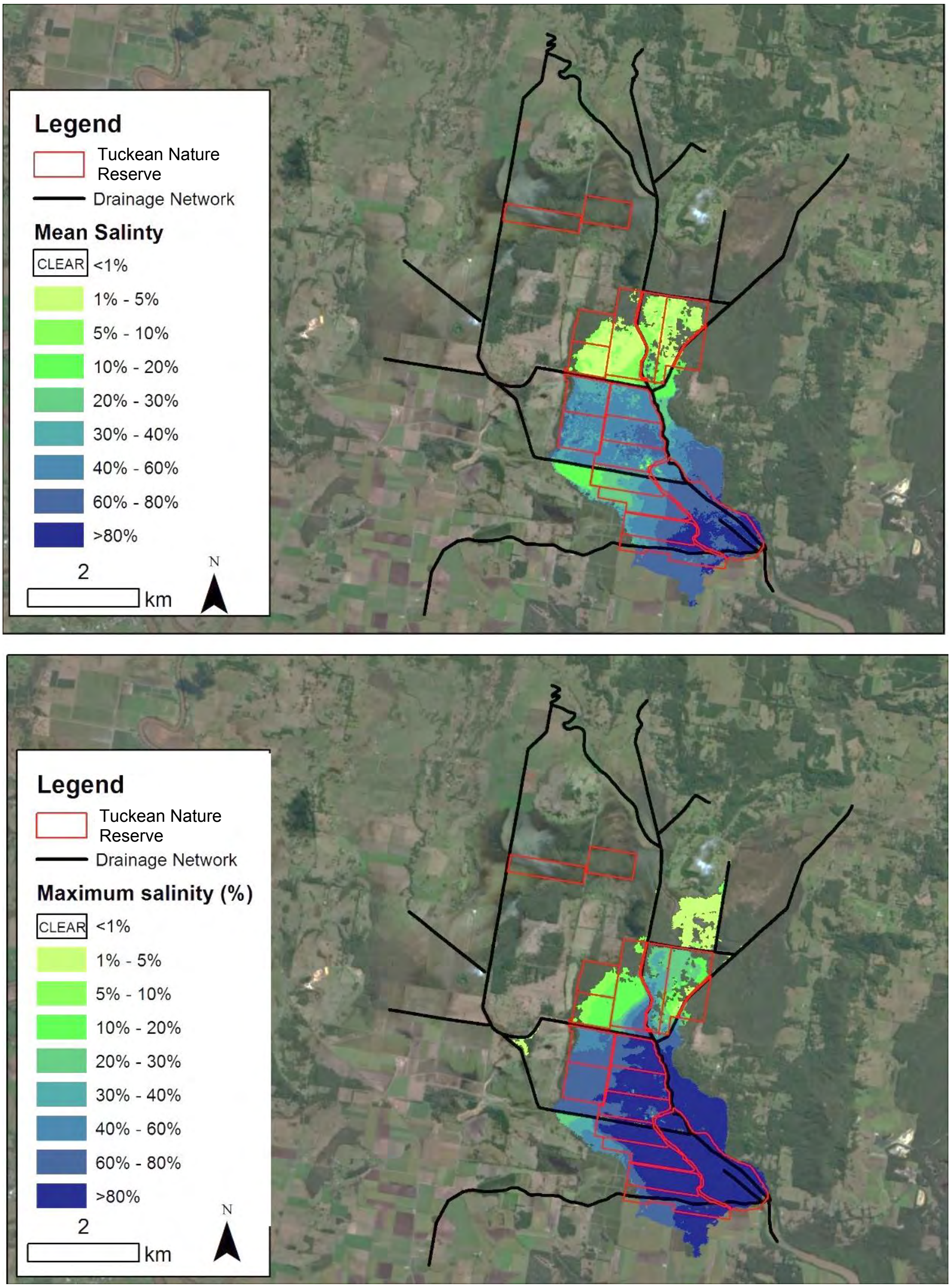

Figure 5-47: Scenario 6 - mean (top) and maximum water salinity on the floodplain, as a percentage of Tuckean Broadwater salinity

Note that areas that have a maximum or mean salinity below 1% are not coloured in these figures, and may still be inundated occasionally

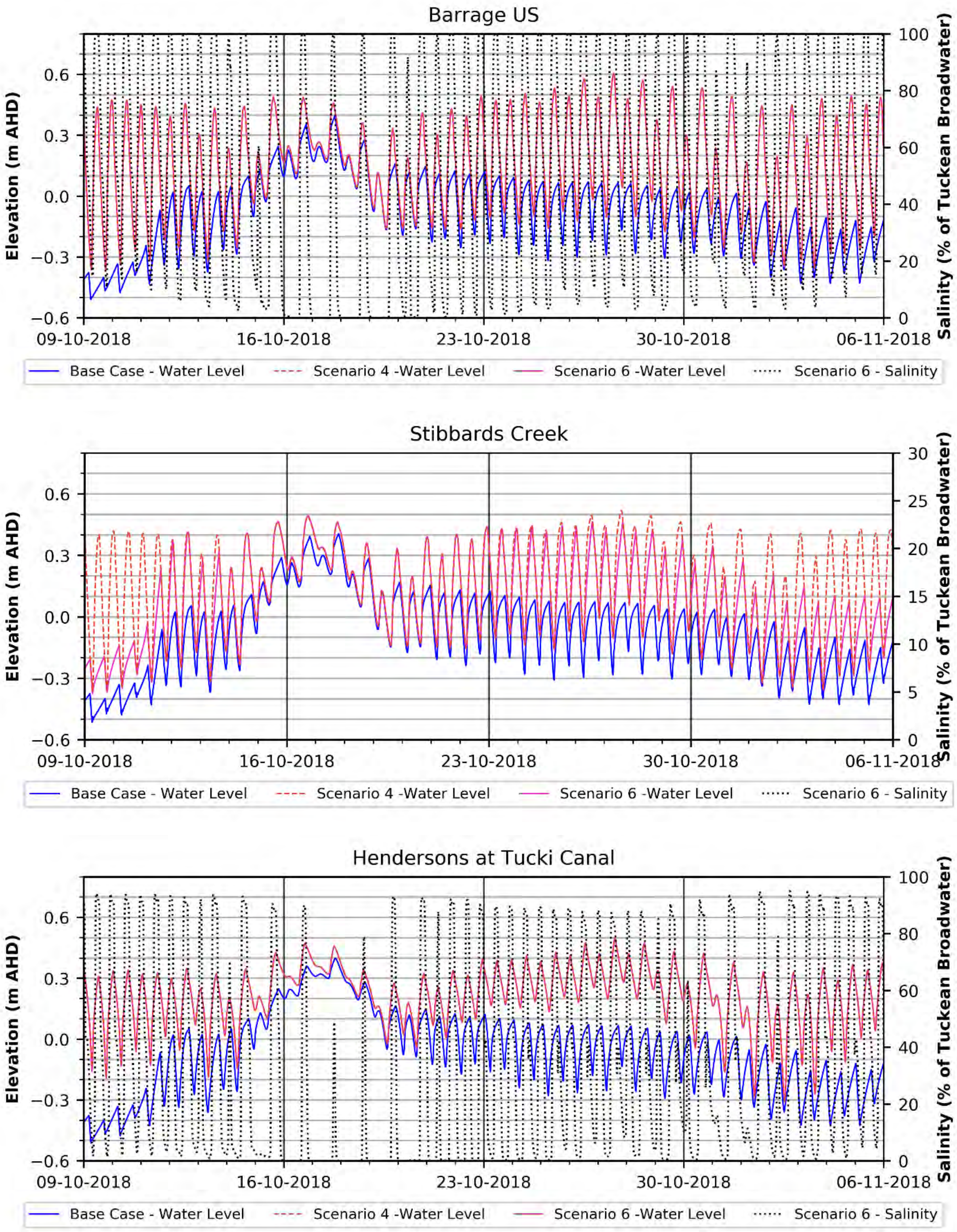

Figure 5-48: Scenario 6 - wet period drainage and salinity

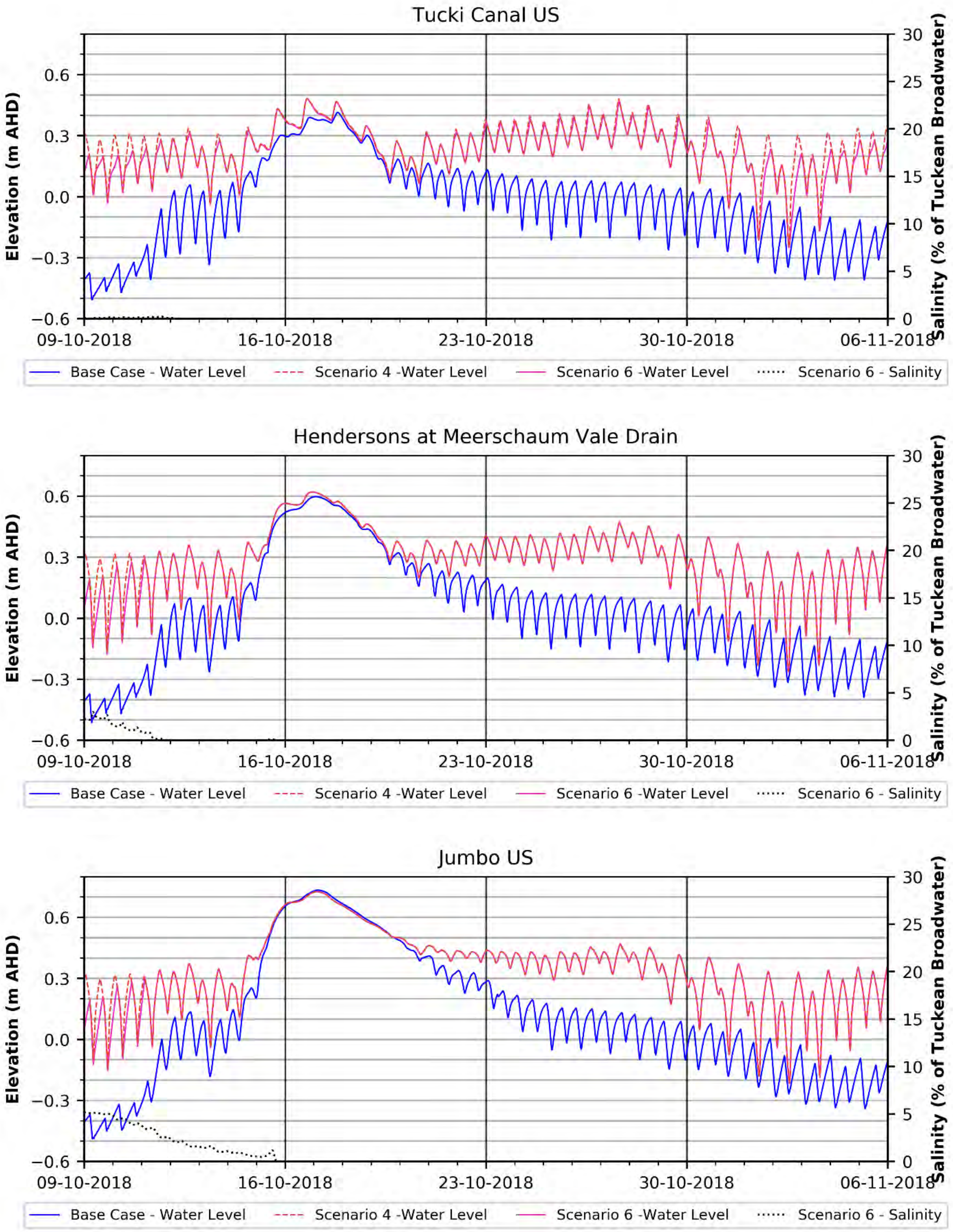

Figure 5-49: Scenario 6 - wet period drainage and salinity

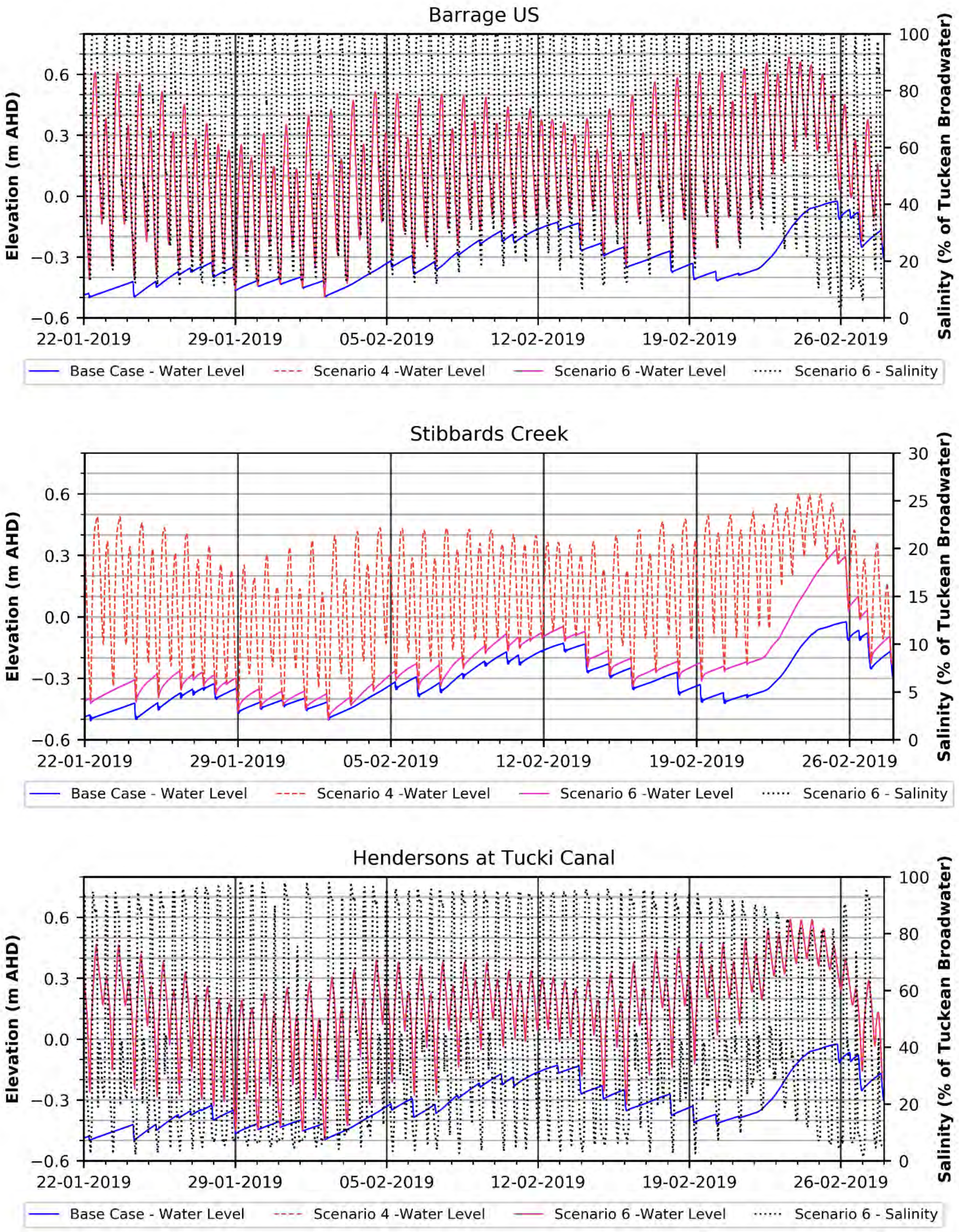

Figure 5-50: Scenario 6 - dry period drainage and salinity

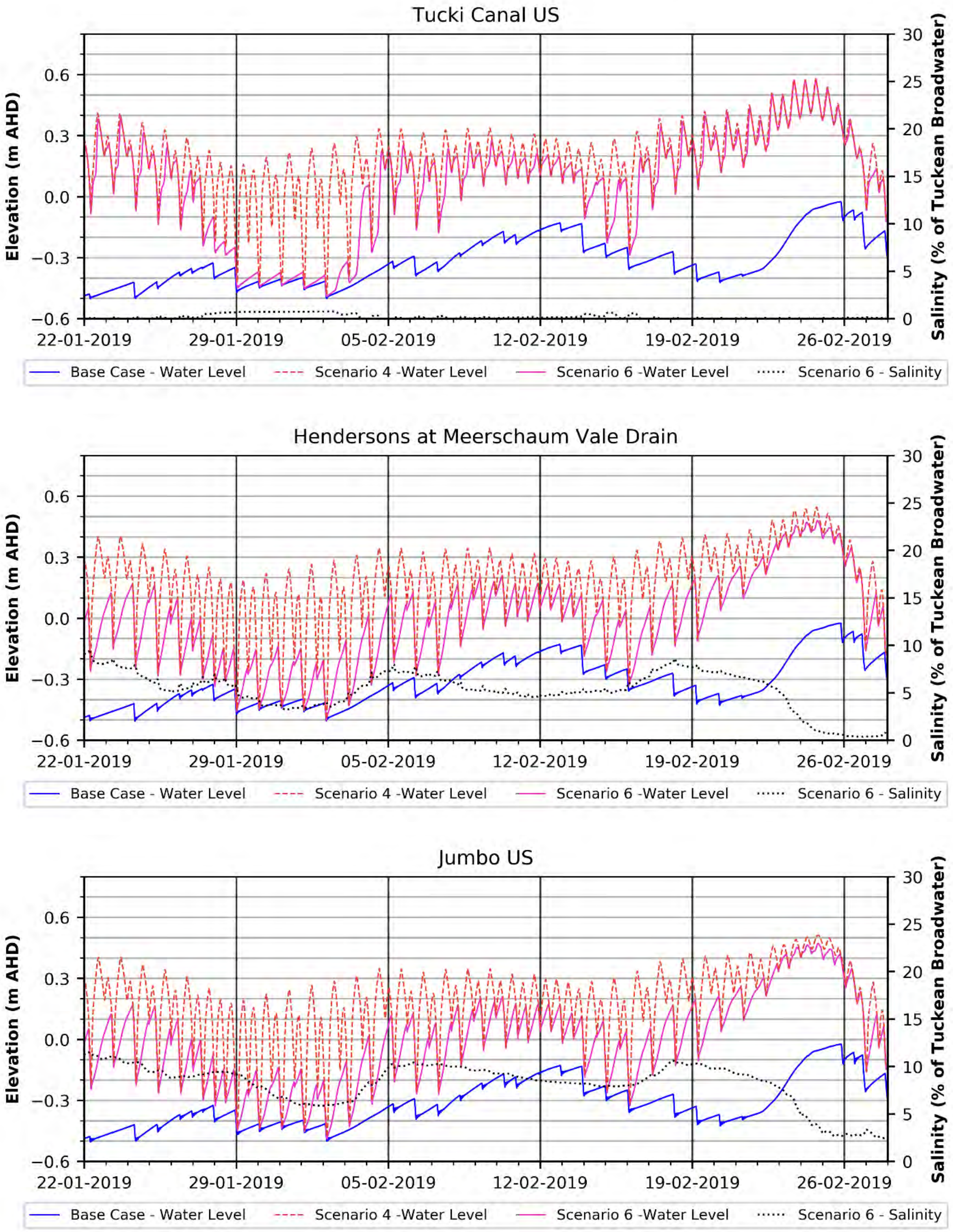

Figure 5-51: Scenario 6 – dry period drainage and salinity

6 Qualitative Costs and Benefits

6.1 Preamble

The magnitude of the costs and benefits associated with the six (6) management scenarios presented in this report varies substantially. There are potentially high costs associated with implementing some of the remediation scenarios investigated for the Tuckean Swamp. While benefits of the remediation are largely environmental, there is an increasing body of research that shows that the ecosystem services from improved water quality and remediated wetland areas have a real economic benefit (both direct and indirect) that should be considered.

This section provides a summary of the relative costs and benefits associated with each scenario. This is not an attempt to put an actual dollar value to the costs and benefits for each scenario, but rather to emphasise the types and sources of costs involved and the potential magnitude of the relative benefits of each scenario

It is important to recognise that not all management options are mutually exclusive. Specifically, any one of the three (3) freshwater management scenarios (Scenario 1, 2 and 5) could be combined with any one of the saltwater management scenarios (Scenario 3, 4 and 6) to improve overall outcomes. However, for the purpose of this report and for modelling, each scenario has been considered separately.

6.2 Relative Costs

The costs associated with each of the modelled scenarios vary greatly. Some options include higher upfront costs including substantial on-ground works and property acquisition/land use changes, while others may incur on-going management and maintenance costs for the foreseeable future. Detailed costings of all the aspects of each scenario have not been undertaken. Instead, the relative magnitude of the expenditure associated with each option has been assessed with respect to a number of commonly occurred costs associated with floodplain remediation. The scope of the costs considered is outlined in Table 6-1.

For each of the costs outlined in Table 6-1, a qualitative rating (minimal change, very low, low, moderate, high and very high) was assigned to each scenario, summarised in Table 6-2. The qualitative rating is relative in magnitude and cannot be compared between costs (e.g. a very high cost of on-ground works may not be the same as a very high cost of impact management). The purpose of this table is to highlight which scenarios may present low cost options overall.

A semi-quantitative measurement of total comparative cost has been provided in Figure 6-1. This figure is not intended to show the actual dollar expenditure of each scenario, but to emphasise the different orders of magnitude of costs associated with different options. Note that the total costs include both upfront costs and on-going costs (including lost agricultural productivity) for a management horizon of 30 years. The order of magnitude of costs has been determined based on model results, previous experience at other restoration sites and an estimate of the amount of time and equipment required.

Table 6-1: Scope of costs considered

Cost	Description
Community consultation and engagement	Community consultation and engagement includes conversations with landholder and stakeholder groups (such as the Tuckean Landholder Association), as well as individual negotiations for property acquisition as required for each scenario.
Asset management	Costs associated with asset management include long term management of floodgates (including opening and closing sluice gates) and drain clearing. Asset management costs have been considered where they are in excess of estimated costs of the existing management of the site.
Public/Crown Land management (NPWS)	Any increase or change in the management of public or crown land (including land owned by NPWS) has been considered in the cost.
Acquisition/compensation (incl. negotiation)	Acquisition or compensation for loss of productive land has been considered based broadly on the values available from the NSW Valuer General's website.
Environmental assessment	Where applicable, the cost of an environmental assessment (EIS or REF) has been considered.
Social costs and land use changes	Where there is land that is acquired and can no longer be used for agricultural production, the annual loss in productivity from that land has been considered.
Habitat changes	Costs associated with changing habitat (e.g. from paperbark to estuarine wetland) has been assessed based on water level and salinity modelling for each scenario.
Technical assessment/design	Each option would require further technical assessment and design prior to implementation and the associated cost has been considered.
On-ground works and implementation (including sub-contractors and access facilitation)	The cost of on-ground works and implementation includes access facilitation, machinery, materials and other tangible up-front costs. It does not include the on-going management of new structures or drains.
Impact Management	Management of any impacts (e.g. salinity or changes to flood storage) will be an on-going cost associated with some of the scenarios. This includes additional monitoring and other minor on-going works that might be required.

Table 6-2: Relative cost matrix for each scenario

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
	Reshaping Slatteries	**Slatteries Weir**	**Sluice Gate Management**	**Open Barrage**	**Reshaping + Reflooding Slatteries**	**Open Barrage + Upstream Structures**
Community consultation	Moderate	Moderate	Moderate	Very High	Moderate	Very High
Asset management	Minimal change	Low	Low	High	Moderate	High
Public/Crown Land management (NPWS)	Minimal change	Minimal change	Very Low	High	Moderate	High
Acquisition/compensation	Low	Minimal change	Minimal change	Very High	High	Moderate
Environmental assessment	Low	Low	Very Low	Very High	High	Very High
Land use changes	Very Low	Minimal change	Minimal change	High	Moderate	Low
Habitat changes	Minimal change	Minimal change	Low	Very High	Moderate	Very High
Technical design	High	Moderate	Moderate	Moderate	Very High	Very High
On-ground works	Very High	High	Very Low	Low	Very High	Very High
Social/Land use changes	Low	Low	Very Low	High	Moderate	High
Impact management	Minimal change	Minimal change	Low	High	Minimal change	Moderate

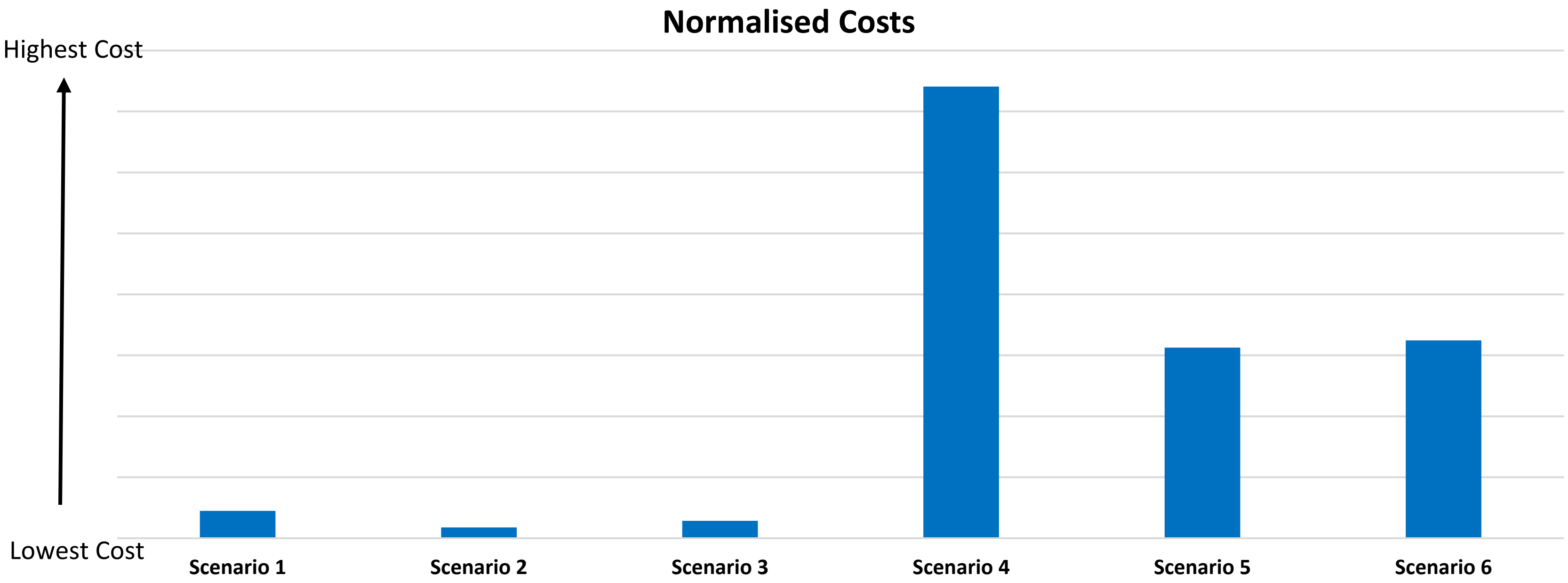

Figure 6-1: Order of magnitude of total costs associated with each option

6.3 Relative Benefits

Environmental resources and natural capital have historically not been consistently included in economic decision making, as they are generally not bought or sold in traditional markets and therefore may be difficult to monetise. However, there is an increasing awareness that natural capital interacts with human environments and provides a positive contribution to human welfare.

The management options investigated for Tuckean Swamp in this study are largely focussed on improving water quality within the floodplain and throughout the wider Richmond River. The benefits associated with these types of remediation works are largely environmental and are commonly referred to as ‘ecosystem services’. Ecosystem services is the term used to refer to the “benefits people obtain from ecosystems” (Millennium Ecosystem Assessment MEA, 2005), including both the direct and indirect contributions of ecosystems to human welfare (Costanza et al., 1997). Ecosystem services include a wide array of benefits, including food production (e.g. improved fisheries production resulting from improved water quality), climate regulation (e.g. carbon sequestration) and recreational use of environmental resources (e.g. recreational fishing or boating).

Similar to the costs, a number of different types of benefits could result from undertaking each remediation scenario at Tuckean Swamp. Table 6-3 summarises the scope of the benefits considered in this study (which may not be exhaustive). At this stage, detailed quantification of the benefits is not practical – further modelling and research would be required to provide a dollar value of the benefits of each scenario. However, a qualitative rating (minimal change, very low, low, moderate, high and very high) was assigned to each scenario, summarised in Table 6-4.

A semi-quantitative measurement of total normalised benefit has been provided in Figure 6-2. This figure is not intended to show the actual dollar benefit of each scenario, but to emphasise the different orders of magnitude of benefits. As the benefits of these scenarios are not easily quantifiable, the following subjective measures have been used to compare the potential benefits:

- Length of drain reducing diffusive acid transport (through shallowing of drains);
- Length of drain reducing advective acid transport (through tidal flushing, weirs or reshaping);
- The pH of surface waters observed in the existing drainage system (noting that pH is a log scale);
- Opportunities for increased fish passage (gate opening) and area of increased fish habitat (area inundated by brackish water);
- Area of grassed floodplain remediated, reducing blackwater potential; and
- Improved bird habitat through increased median inundation extent (fresh or brackish water).

Table 6-3: Scope of benefits considered

Benefit	Description
Acidity	Highly acidic water has been recorded throughout the Tuckean Swamp and the receiving waters of the Tuckean Broadwater over an extended period of time. Benefits of remediation have been considered in respect to acidity during normal (i.e. non flood) periods (for example long term median and mean pH) and acidity immediately following rainfall (for example, minimum pH after a rainfall event).
Metals	The ASS that occur in the Tuckean Swamp region are also related to the release of high concentrations of metals including iron and aluminium. The benefits relating to reduced metal concentrations have been considered during normal (i.e. non flood) periods and immediately falling rainfall.
Dissolved oxygen/blackwater	Blackwater, or water with low dissolved oxygen, events can occur on drained coastal floodplains after flood events when inundation intolerant vegetation dies due to prolonged floodwater retention. Some remediation options may reduce the impact of blackwater discharging from Tuckean Swamp on the wider Richmond River estuary. The benefits relating to dissolved oxygen have been considered during normal (i.e. non flood) periods and immediately following rainfall.
Aquatic connectivity	The installation of one-way floodgates effectively prevents fish passage into many drained coastal floodplains in the NSW. Improved fish passage is considered a benefit of changing the management of floodgates like the Bagotville Barrage.
Fisheries nursery habitat	Coastal backswamps provide important fisheries nursery habitat to aquatic fauna. Installation of floodgates, poor water quality and removal of natural estuarine vegetation (e.g. mangroves and saltmarsh) reduce or eliminate nursery habitat. The benefits of each remediation option with respect to the creation of nursey habitat has been considered.
Terrestrial habitat	Wetlands play an important role as habitat for terrestrial animals, including migratory birds. Encouraging a natural remediation of the Tuckean Swamp could potentially provide suitable habitat for a range of terrestrial animals.
Fisheries production	Tidal wetlands are significant areas for fisheries, with almost 70% of commercially caught fisheries in eastern Australia spending some part of their life cycle in estuaries (Creighton, 2013). Saltmarsh in particular has been shown to be important to fisheries productivity in NSW estuaries (Taylor et al., 2018).
Nutrient reduction	Wetlands have the capacity to remove significant amounts of nutrients (total phosphorus and total nitrogen) from catchment inflows. Wetlands are also associated with sediment retention and stabilisation that would reduce the total suspended solids delivered to the estuary.
Biodiversity protection	Wetland ecosystems are important to biodiversity. Improving estuarine vegetation recruitment, such as saltmarsh and mangroves, provides important support to biodiversity in the region.
Increased groundwater levels	Increase in groundwater and surface water levels, particularly during droughts improve drought resilience on surrounding properties.
Carbon sequestration	Estuarine vegetation, such as saltmarsh, is recognised as an important ecosystem for carbon sequestration (Kelleway et al., 2005), which is important for regulating the climate.

Table 6-4: Relative benefit matrix for each scenario

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
	Reshaping Slatteries	**Slatteries Weir**	**Sluice Gate Management**	**Open Barrage**	**Reshaping + Reflooding Slatteries**	**Open Barrage + Upstream Structures**
Acid (Dry)	Very Low	Very Low	Moderate	High	Low	High
Metals (Dry)	Very Low	Very Low	Moderate	High	Low	High
Dissolved oxygen (Dry)	Minimal change	Minimal change	Low	High	Minimal change	High
Acid (Wet)	Moderate	Moderate	Minimal change	Low	Moderate	Low
Metals (Wet)	Moderate	Moderate	Minimal change	Low	Moderate	Low
Dissolved oxygen (Wet)	Low	Low	Minimal change	Low	Moderate	Low
Aquatic connectivity	Minimal change	Minimal change	Low	High	Minimal change	High
Fisheries nursery habitat	Minimal change	Minimal change	Low	High	Very Low	High
Terrestrial habitat - birds	Minimal change	Minimal change	Minimal change	Moderate	Low	Low
Fisheries production	Minimal change	Minimal change	Very Low	High	Minimal change	High
Nutrient reduction	Minimal change	Minimal change	Minimal change	Low	Low	Low
Increased groundwater levels	Low	Low	Minimal change	Moderate	Low	Moderate
Carbon sequestration	Minimal change	Minimal change	Very Low	High	Low	Moderate

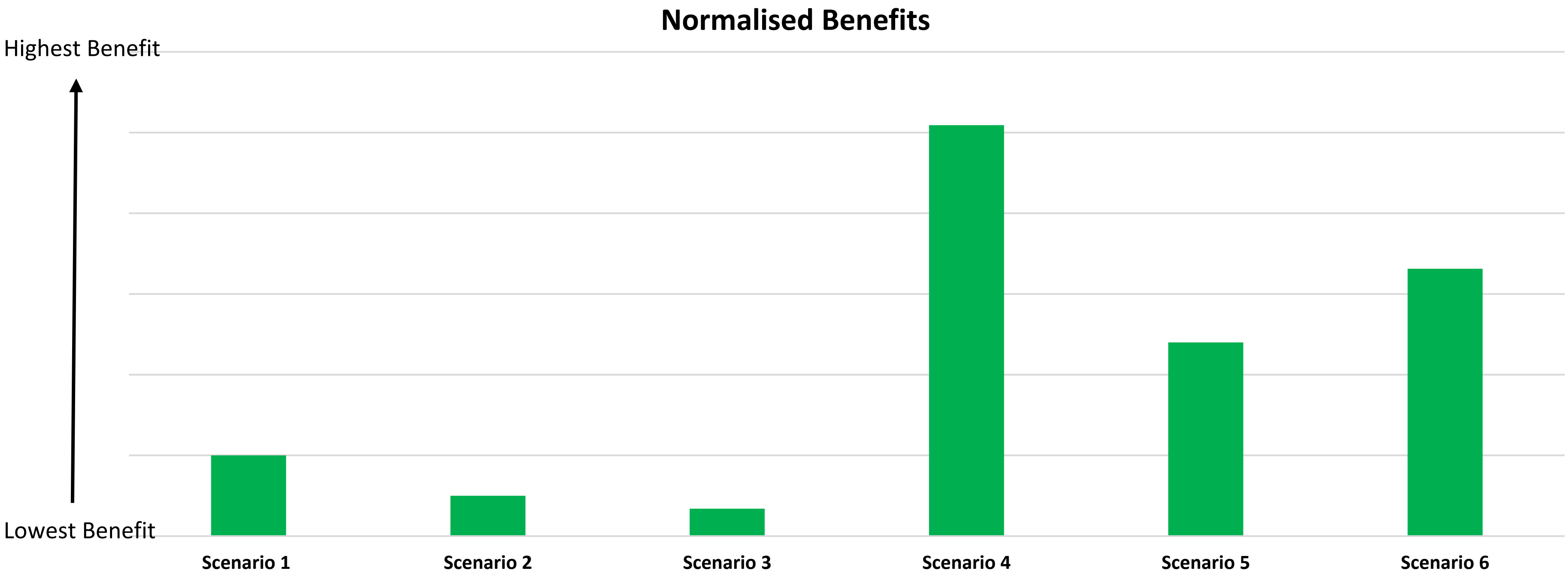

Figure 6-2: Order of magnitude of total benefit associated with each option

7 Summary and Conclusions

The Tuckean floodplain has undergone significant changes since European settlement began in the 1800's. A network of deep, wide drains was dug throughout the floodplain in the early 1900's to assist the movement of floodwaters from the natural swamp land that once existed. As a consequence of this artificial drainage network, tidal waters infiltrated further into the floodplain than had been previously experienced, due to the efficient connection to the Tuckean Broadwater. In 1971, the Bagotville Barrage was completed, which effectively prevented the tidal connection between the greater Richmond River and Tuckean Swamp. While these works improved floodplain drainage, it also had unintended impacts on the hydrodynamics and water quality, including the exposure of large quantities of acid sulfate soils (ASS). It is currently estimated that over 250 Olympic swimming pools of pH 3 water (equivalent pH to lemon juice) are able to be stored behind the barrage at any given moment.

This study developed a detailed hydrodynamic and salinity model of the Tuckean floodplain to test the impact of a range of drainage management options designed to mitigate ASS and improve water quality on the site. The focus of the modelling exercise was to identify the environmental benefits of specific management techniques and to understand the potential impacts to surrounding landholders. Seven (7) management options were modelled, which can be broken down into three (3) categories, summarised in Table 7-1.

Table 7-1: Summary of model scenarios

Category	Model Description
Current	**Base Case** – the model was run to replicate the site as it operates today and provide present day conditions for comparison.
Freshwater management options *Focus on the north-eastern (Slatteries) corner of the floodplain*	**Scenario 1** – Reshaping of major drains in the north-eastern corner of the floodplain (Slatteries, Meerschaum Vale and Jumbo Drains). **Scenario 2** – Weir implementation at the downstream end of Meerschaum Vale Drain. **Scenario 5** – Reshaping of drains (as per Scenario 1) but encouraging small catchment flows onto the floodplain.
Saltwater management options *Focus on the management of the Bagotville Barrage*	**Scenario 3** – Alternative management of Bagotville Barrage sluice gates during dry periods. **Scenario 4** – Opening of the Bagotville Barrage tidal floodgates. **Scenario 6** – Opening of the Bagotville Barrage floodgates and installing new floodgate control structures upstream of the Tuckean Nature Reserve boundary on all the major drains.

The modelling results summarise the effect of each management option on floodplain inundation, drainage times, salinity, groundwater levels and acid transport. Construction and implementation issues have also been highlighted. The modelling results highlighted the following key results:

- With careful design, works could be undertaken on the highest priority north-eastern (Slatteries) corner of the floodplain to reduce acid transport without changing the drainage capacity of the network. However, any changes to the drainage network are likely to result in an increase in the footprint of the drainage system and would require significant construction works; and
- Opening the barrage gates during dry periods would permit a significant volume of tidal water onto the floodplain. Preventing possible impacts to upstream landholders would require substantial works including new upstream floodgates, drain levee banks and constructed bunds. Even with these additional works, groundwater connections between the creek lines and the privately-owned properties may remain an issue, particularly south of Stibbards Creek. However, the existing sluice gates could be managed effectively to promote additional tidal flushing and some limited saline infiltration without significant risk to floodplain properties. This may be achieved via the implementation of automated tidal control gates that are manipulated based on water levels, salinity, dissolved oxygen and/or levels of acidity

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Appendix A – Acid Sulfate Soil Theory

A.1 Preamble

Early experiences with Acid Sulfate Soils (ASS), formerly known as 'cat clays', date back to the 17th century in the Netherlands, and the late-19th century in Australia, but it was not until the early 1970s that acidic clays on coastal floodplains were causing problems worldwide. Since then the various manifestations and impacts of ASS has been extensively researched and are consequently well known, both overseas and in Australia. This section introduces the pertinent aspects of ASS theory, including its formation, mobilisation, and the various land and water impacts.

A.2 What are Acid Sulfate Soils?

Acid Sulfate Soils is the common name given to soils and sediments containing iron sulfides, the most common being pyrite (FeS_2) (DERM, 2009). ASS are chemically inert whilst in reducing (anaerobic) conditions, including when situated below the water table, and are known as potential acid sulfate soils (PASS). When PASS are exposed to atmospheric oxygen due to climatic, hydrological, or geological changes, oxidation occurs. The oxidised layer produces sulfuric acid and is termed an actual acid sulfate soil (AASS).

A.2.1 Formation

ASS are predominantly located within five (5) metres of the surface and are found extensively on Australia's coastline (DERM, 2009). Pyrite is formed in reducing environments where there is a supply of easily obtained decomposed organic matter, sulfate, iron and reducing bacteria (Figure A-1). The deposition of these sands and muds occurs in low-lying coastal zones characterised by low energy environments, such as estuaries and coastal lakes. ASS that are of concern on Australia's coastal floodplains were formed during the last 10,000 years (i.e. the Holocene epoch).

DERM (2009) stipulates that the formation of pyrite requires:

- A supply of sulfur (usually from seawater);
- Anaerobic (oxygen-free) conditions;
- A supply of energy for bacteria (usually decomposing organic matter);
- A system to remove reaction products (e.g. tidal flushing of the system);
- A source of iron (most often from terrestrial sediments); and
- Temperatures greater than 10ºC.

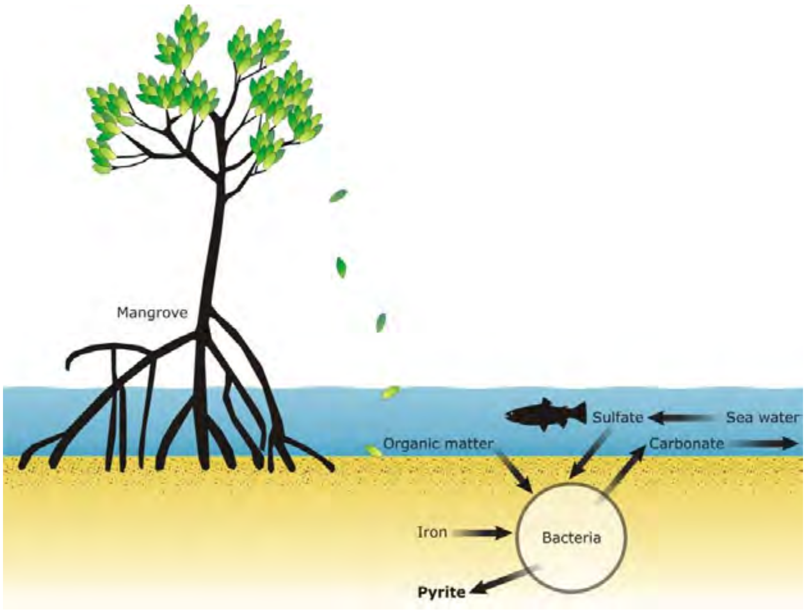


Figure A-1: Pyrite Formation (NRM, 2011)

A.2.2 Acidification

The pH scale (Figure A-2) is used to grade acidity and is a measure of the hydrogen ion (H^+) concentration. The pH scale is logarithmic, ranging from 0 (strongly acidic) to 14 (strongly alkaline). Due to the logarithmic scale, a soil with a pH of 4 is 10 times more acidic than a soil with a pH of 5, and 1,000 times more acidic than a soil with a pH of 7 (NRM, 2011).

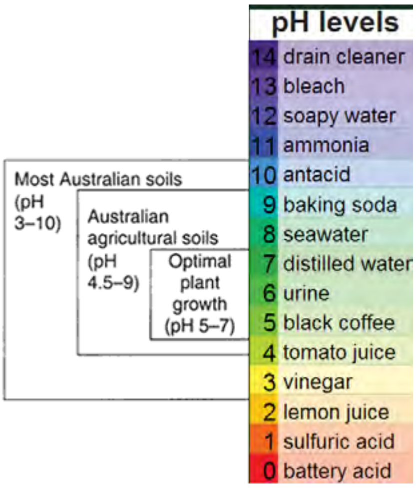


Figure A-2: pH Scale (NRM, 2011)

Potential Acid Sulfate Soils (PASS) are oxidised to form Actual Acid Sulfate Soils (AASS) by clearing of coastal land for agriculture, resulting in extensive drainage and a lower groundwater table, introducing gaseous oxygen into the soil matrix. When pyrite is exposed to atmospheric oxygen, the iron sulfides react to form sulfuric acid and numerous iron cations (e.g. Fe^{2+} and Fe^{3+}). The acid generated can break down the fine clay particles in the soil profile, causing the release of metals, including aluminium (Al^{2+}). Generated acid is often mobilised from the soil matrix by rainfall raising the groundwater table, resulting in discharge into the drainage network or other receiving waters (Figure A-3). Depending on the pyrite content of the soil, acidity levels can fall below a pH of 4.5. At a pH of 4.5, iron and aluminium concentrations become soluble and can greatly exceed environmentally acceptable levels.

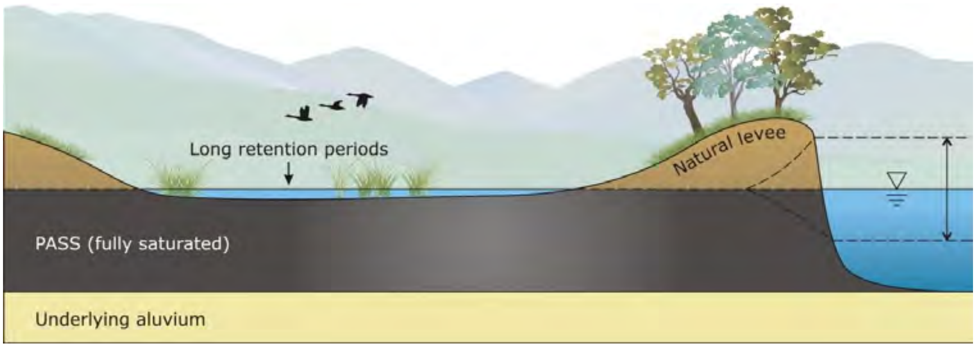
The soil structure of coastal floodplains is typically comprised of five (5) distinct zones of varying thickness. On the surface, an organic peat layer exists comprised largely of roots and decomposing matter. This layer transforms into an alluvial/clay zone. An AASS layer commonly exists below this and can be identified by the presence of orange/yellow mottling caused by the oxidation of pyrite. This soil layer often overlies a PASS layer characterised by dark grey, saturated estuarine mud. The PASS layer often has a pH near neutral, as pyritic material in the soil is unoxidised. The PASS layer is underlain by non-acidic sub-soil.

A.3 Groundwater drainage

The construction of deep drainage channels on floodplains acts to drain the low-lying backswamp and wetland areas, to allow for agricultural production. However, on coastal floodplains, drainage channels also allow tidal water to potentially inundate pasture and groundwater. As such, one-way floodgates are commonly installed to reduce tidal inundation of backswamp areas. The tidal floodgates restrict saline intrusion and may provide livestock with a source of drinking water (Figure A-4).

In areas affected by ASS, the combination of deep drainage channels and one-way floodgates increases ASS oxidation, creates acid reservoirs, and restricts potential buffering (or neutralisation) of acid by tidal waters. Floodgates and drainage structures are usually designed to maintain drain levels at the low tide mark to drain backswamp areas and reduce pasture water logging (Glamore, 2003). Since the pyritic layer is normally at the mid to high tide level, by maintaining drain water elevations lower than the pyritic layer, such as the low tide elevation, one-way floodgates increase the hydraulic gradient between the drain water and the surrounding acidic groundwater (Glamore, 2003).

Undisturbed Environment



Drained Paddock

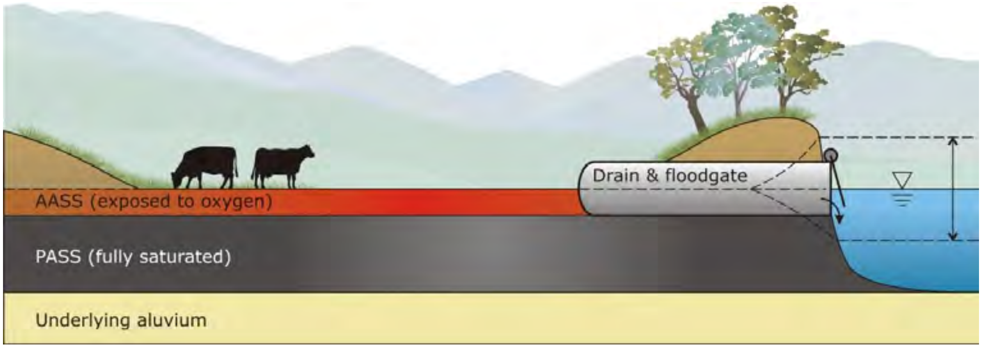
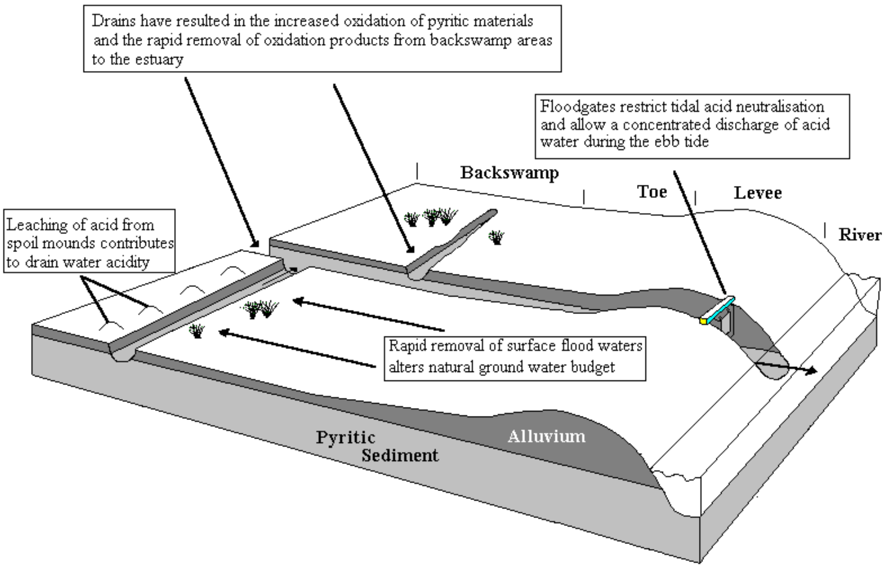


Figure A-3: Soil acidification by lowering of groundwater levels


Drains have resulted in the increased oxidation of pyritic materials and the rapid removal of oxidation products from backswamp areas to the estuary

Floodgates restrict tidal acid neutralisation and allow a concentrated discharge of acid water during the ebb tide

Leaching of acid from spoil mounds contributes to drain water acidity

Rapid removal of surface flood waters alters natural ground water budget

-

Figure A-4: : Schematic of a backswamp drainage and floodgate network (Naylor et al., 1995)

The difference in the hydraulic gradient between the groundwater table and surface water in the drain, caused by the one-way tidal floodgates, promotes the lowering of the groundwater and transport of oxygen into sulfidic soil material and the leaching of acid into the drain (Blunden and Indraratna, 2000). This is particularly evident following large rainfall events when receiving surface water levels quickly recede, whilst groundwater levels remain elevated, and floodgates effectively drain surface waters from the floodplain causing low drain water levels (Glamore and Indraratna, 2001). This strong surface to groundwater level gradient promotes the efficient drainage of stored groundwater.

The depth of a drain (or drain invert) in relation to the acidic layer influences the potential risk of acid discharge. A deeply incised drain with a low invert constructed in a shallow AASS layer has a high risk, or potential, for acidic discharge. Conversely, a shallow drain constructed in the same shallow AASS layer floodplain would have a lower risk of acid discharge.

The ease at which groundwater flows through the soil and into a drain also influences the risk of acid discharge. Soil with a low potential groundwater flow rate, or low hydraulic conductivity, will export less acid compared to a soil with a high groundwater flow rate. This effectively relates back to the porosity of the soil. Generally, gravel is more porous than sand, which is more porous than clay. The higher the porosity, the greater potential for rapid acid discharge into a drain.

A.4 Acid discharge

In a similar manner to geographical/geomorphological descriptions of estuaries internationally, Australian estuaries have been classified by Digby (1999). Digby (1999) describes an Australian estuary classification regime based on climate and hydrology. In Australia, most estuaries (approximately 70%) fall within the wet and dry tropical/subtropical category. These estuarine systems are dominated by episodic short-lived large freshwater inputs during summer, and very little or no flow during winter. Under high flows, saltwater may be flushed out of these estuaries completely. Many of these estuaries have a high tidal range, so following a flushing event, a salt-wedge intrudes along the estuary bottom, and the estuary progresses from a highly stratified salt-wedge estuary to a partially mixed estuary, to a vertically homogeneous estuary.

An understanding of estuarine systems in NSW under various climatic conditions has important implications for the cause and effect of acid discharges from coastal floodplains. While the water in drains on ASS-affected coastal floodplains can be highly acidic on a day-to-day basis, large plumes of acidic discharge are not typically recorded within estuaries during dry conditions. Conversely, large quantities of acid are often discharged following significant rainfall events. This typically occurs in the 5 to 14 days following the peak of a flood event. During other periods, the risk of widespread acid contamination to the estuary is reduced.

Figure A-5 depicts a period of strong tidal flushing, limited acid flux (concentration x discharge) and thereby, high tidal buffering. The acid buffering capacity of an estuary is directly proportional to the volume of buffering agents within the system (Rayner et al., 2015). In areas with limited upstream inflows of buffering agents, the primary buffering agents are sourced from the diffusion of marine constituents. During dry climatic conditions (little or no flow), bicarbonate-rich seawater diffuses upstream from the tidal ocean boundary creating a salinity gradient throughout the estuary resulting in low acid risk conditions.

Figure A-6 depicts a period during or immediately following a flood event, whereby coastal floodplains are inundated with fresh floodwaters. As the floodwaters recede, large volumes of freshwater drain from the floodplain into the estuary. This process, in conjunction with large freshwater flows in the main river channel, reduces estuarine salinity. During these periods, acid is quickly flushed from the estuary and/or is highly diluted.

Figure A-7 depicts a period after floodwaters have receded and tidal levels slowly re-establish. During this period, floodplain pastures are saturated and groundwater levels remain elevated, resulting in a steep gradient between drain water levels and the surrounding groundwater. This process mobilises acid from the soil towards drainage channels and receiving waters (Figure A-8). As the natural buffering capacity of the estuary has been removed by the fresh floodwaters, acidic plumes comprised of low pH water and soluble metal in high concentration remain in the open estuary.

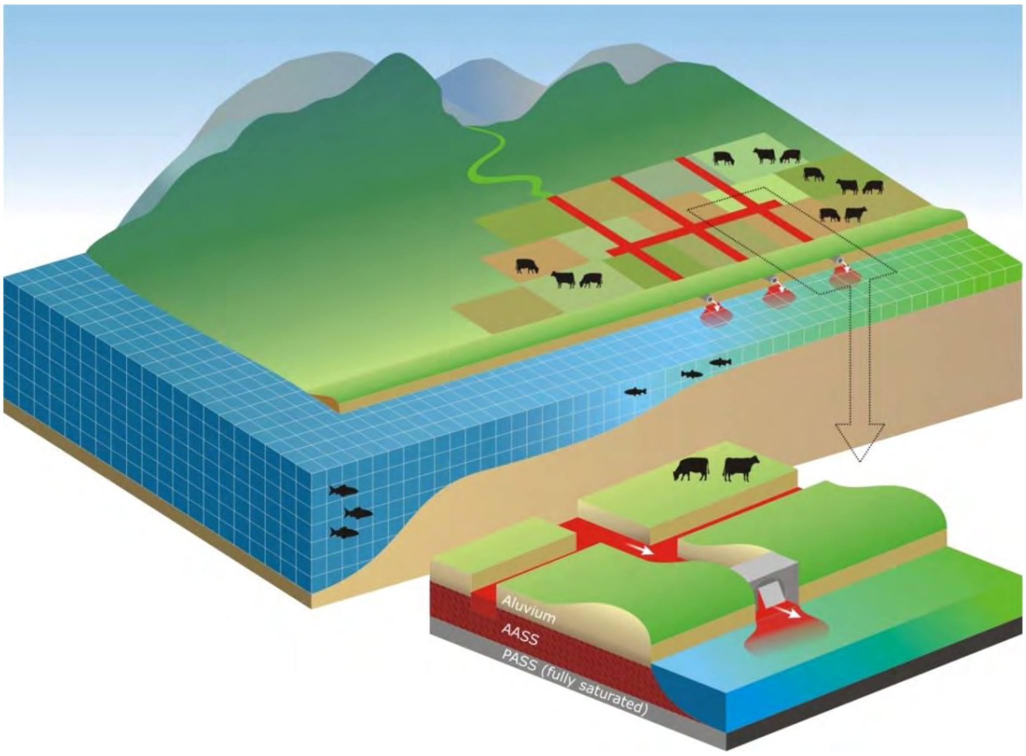


Figure A-5: Period of tidal buffering and low acid risk

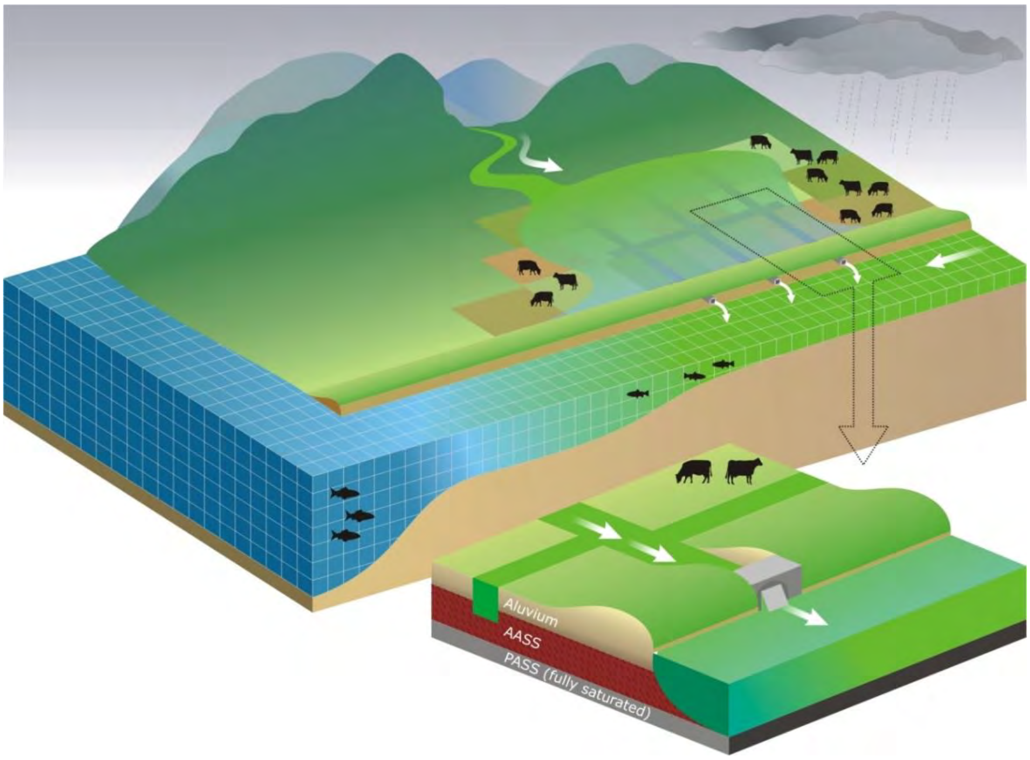


Figure A-6: Flow dilution period as a result of a large rainfall event

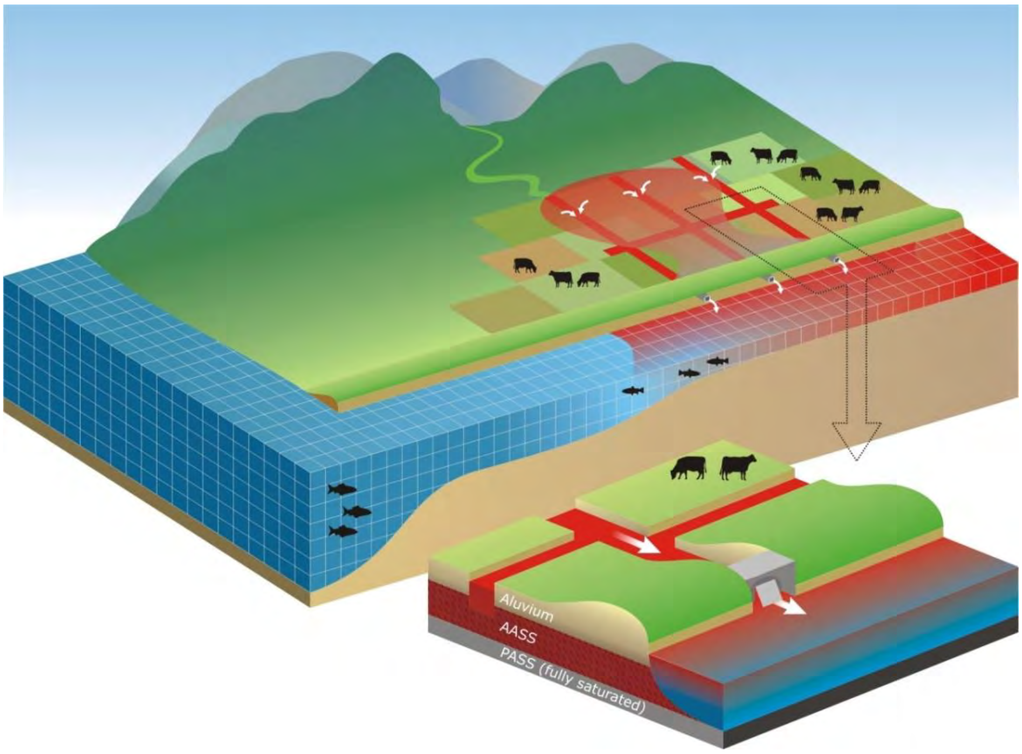


Figure A-7: Period of acid impact following rainfall event

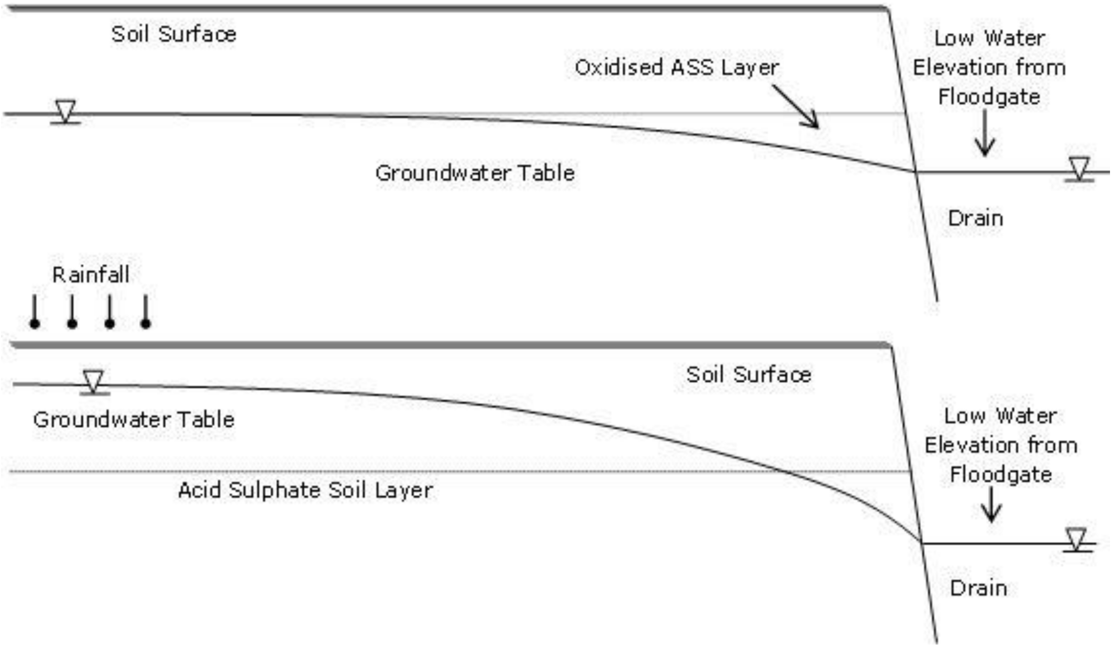


Figure A-8: Influence of one-way floodgates on groundwater elevation under normal (top) and flood (bottom) conditions (Glamore, 2003)

A.5 Environmental impacts

Pyrite oxidation causes adverse environmental, ecological, and economic effects worldwide. Soil acidification can lead to a deficiency in essential plant nutrients and plant base minerals such as calcium, magnesium, and potassium, while at the same time, toxic concentrations of metals such as, aluminium, iron, and other heavy metals may occur. Furthermore, the release of acidic plumes, containing aluminium and iron flocculants, is well-known to cause widespread environmental pollution in tidal estuaries resulting in large scale fish kills and negatively impacts oyster health (Dove and Sammut, 2007).

In 2008, the NSW Department of Planning, Industry and Environment (formerly the NSW Department of Environment and Climate Change (DECC, 2008)) identified numerous environmental impacts of acid discharge including:

- Habitat degradation;
- Fish kills;
- Outbreaks of fish disease;
- Reduced resources for aquatic food;
- Reduced ability of fish to migrate;
- Reduced recruitment of fish;
- Changes to communities of water plants;
- Weed invasion by acid-tolerant plants;
- Subsidence and structural corrosion of engineering structures; and
- Indirect degradation of water quality.

Aasø (2000) notes further chronic impacts, such as:

- Loss of spawning sites and recruitment failure in both estuarine and fresh-water species;
- Habitat degradation and fragmentation from acid plumes, thermochemical, stratification of waters and the smothering of benthos from iron oxy-hydroxide flocculation;
- Altered population demographics within species;
- Simplified estuarine biodiversity with invasions of acid-tolerant exotics and loss of native species; and
- Reduction in dissolved nutrients and organic matter entering the estuarine food web.

Appendix B – Data collection and field investigations

B.1 Preamble

This section provides an overview of the data that was utilised and collected for this study. It includes a summary of the data collected in the three (3) field campaigns completed by WRL engineers over a period of approximately 12 months, including 16 days on the floodplain. The aim of these investigations was to collect sufficient data to develop and verify a numerical model that can be used to assess drainage options around the swamp. The data collected as part of this study, in particularly the spatial coverage of bathymetric and topographic surveys, was limited in some areas due to issues associated with gaining access to the floodplain on private property.

B.2 Topography

B.2.1 LiDAR

Aerial surveys using LiDAR (Light Detection and Ranging) technology provide topographic data over widespread areas. LiDAR data from 2010 (at a 1 m horizontal resolution) was sourced from the ELVIS database (http://elevation.fsdf.org.au/). LiDAR surveys are taken using an airborne laser scanner providing a vertical accuracy of ±0.15 m and a horizontal accuracy of ±0.3 m. LiDAR surveys are an efficient technique to obtain broad-acre topographic data, providing significant special coverage in comparison to conventional, labour-intensive ground surveys. However, the remote sensing approach can be hindered by dense vegetation and water on the ground surface. For example, the ground surface in areas featuring dense stands of grasses or phragmites are misrepresented, with the elevation of the top of the vegetation measured rather than the ground surface. As such, care must be taken when utilising LiDAR survey datasets in swamp and wetland environments.

B.2.2 Ground surveys

Prior to utilising the LiDAR data as the basis of floodplain elevation data in this study, extensive topographic data was collected to verify the accuracy of the data. Topography collection was undertaken within the Tuckean Nature Reserve, as well as private land where possible using a Trimble RTK GPS with an accuracy of ±0.05 m. Surveyed elevations are shown in Figure B-1. As the technology relies on a line of sight to GPS satellites, survey was limited in areas of high, dense tree coverage. As much of the Tuckean Nature Reserve is vegetated by dense packed paperback trees (Figure B-2) clearings in the vegetation were identified from aerial imagery and accessed by foot. While the topography data within the reserve is relatively limited, this area of the swamp has a very low gradient and the available data is adequate for assessing the LiDAR data.

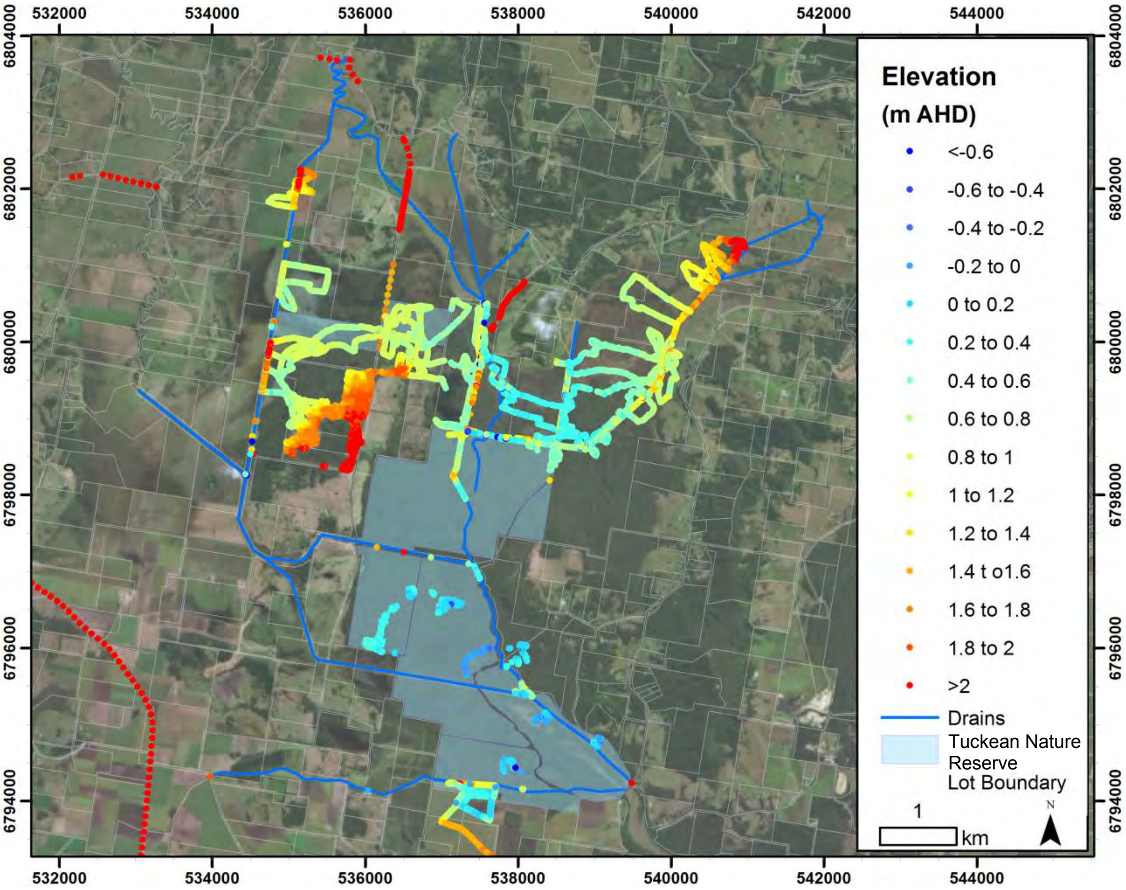


Figure B-1: Surveyed elevations across the Tuckean floodplain

B.2.3 Ground-truthed LiDAR

Comparison of measured surface elevations to LiDAR elevation at every survey point is provided in Figure B-3. This shows a general overestimation of land elevations across the floodplain by the LiDAR, particularly at low elevations. This was likely due to open water areas, ground cover and dense vegetation at the time of the LiDAR flight. Based on the survey data, the LiDAR data was adjusted to better represent the surveyed elevations. As only limited areas of the floodplain were accessible for the survey, ground-truthing was extrapolated to the whole domain based on the linear regression shown in Figure B-3.

Using the ground-truthed LiDAR data, a Digital Elevation Model (DEM) was developed using GIS techniques. The final DEM, used in the model bathymetry, is shown in Figure B-4.

Figure B-2: Dense paperback growth within the Tuckean Nature Reserve

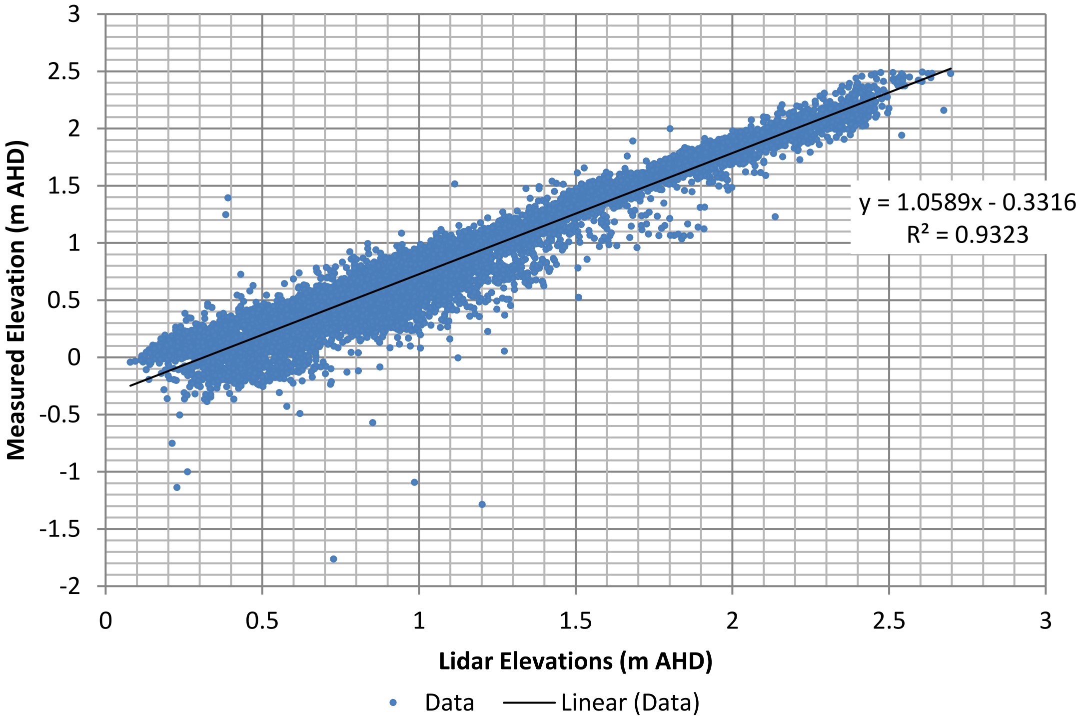


Figure B-3: Comparison of LiDAR to measured elevations

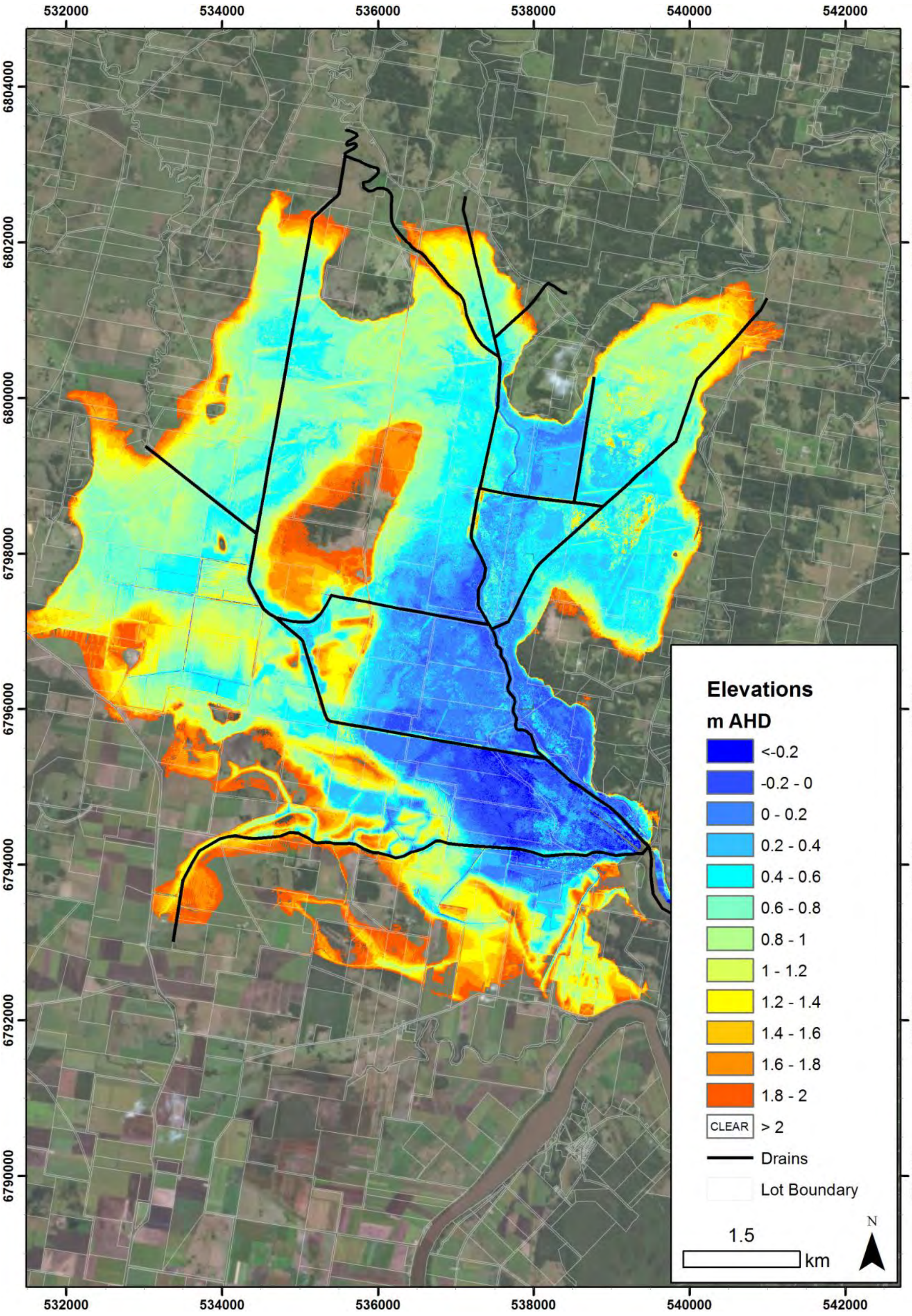


Figure B-4: Corrected DEM of Tuckean Swamp

B.3 Structure surveys

A range of flood mitigation drains and hydraulic structures are located throughout the Tuckean Swamp floodplain to allow drainage of flood waters in wet periods and to prevent backwater flooding from the Richmond River. In the case of the Bagotville Barrage, the floodgate structure also prevents saline intrusion into the upstream waterways. A total of 38 structures, ranging from bridges, to large culverts, to flood-gated culverts were identified and surveyed across the floodplain. Typically, a survey of these structures will include information on the invert (bottom) elevation and the dimensions (length, height, diameter etc). All surveying was measured using a high accuracy Trimble RTK GPS unit. Figure B-5 shows the Bagotville Barrage, the largest of the structures in the Tuckean region. The location of each of the surveyed structures is provided in Figure B-6 and a summary of the survey data is provided in Table B-1. This is not an exhaustive list of all significant structures throughout the floodplain and is limited to those surveyed during the 2018 field investigations.

Figure B-5: Bagotville Barrage – downstream control structure of Tuckean Swamp (looking upstream)

Table B-1: Summary of surveyed structures

ID	Creek/Drain	Type	Easting (GDA94M GA56)	Northing (GDA94M GA56)	Diameter (m)	Width (m)	Height (m)	Length (m)	Upstream Invert (m AHD)	Downstream Invert (m AHD)
1	Stony Island Drain at Tuckean Island Road	Single Box Culvert	535896	6797382	-	3.4	1.9	6.5	-0.76	-
2	Yellow Creek at Marom Creek Road	Two Box Culverts	542131	6801779	-	3.1	1	10	3.42	-
3	Yellow Creek Drain 1 at Marom Creek Road	Box Culvert (Three)	542076	6801787	-	0.4	1.2	9.75	3.85	3.89
4	Yellow Creek Drain 2 at Marom Creek Road	Two Box Culvert	541948	6801810	-	1.5	1.2	7.5	3.72	3.77
5	Gum Creek at Marom Creek Road	Three Box Culverts	541790	6801825	-	2.4	1.2	1.3	4.06	4.19
6	Rock Weir on Gum Creek	Rock Weir	541769	6801844	-	-	-	-	5.25	-
7	Rippen Drain at Marom Creek Road	Two Pipes with 2.5 m Concrete Apron	538144	6801443	1.5	-	-	12.5	3.09	2.81
8	Culvert Crossing on Marom Creek Road	Single Pipe	537667	6801775	1.05	-	-	-	-	7.92
9	Culvert Crossing on Marom Creek Road, East of Youngmans Rd	Single Pipe	537374	6802507	1.7	-	-	12.3	4.92	4.87
10	Youngmans Creek at Marom Road	Three Box Culverts (45 degree to road)	537177	6802705	-	2.5	2.3	15.5	2.78	3.15
11	Creek at LGA Border	Two Box Culverts	536865	6802795	-	2.7	1.2	12.2	3.48	3.42
12	Meerschaum Bridge	Bridge	535735	6803731	-	-	-	-	-	-
13	Robsons Bridge	Bridge	533229	6802038	-	-	-	-	-	-
14	Marom Creek at Tuckean Island Road	Three Box Culverts	536519	6801881	-	1.8	1.25	7.3	0.46	0.50
15	Tuckean Nature Reserve North - Northern Drain	Four Box Culverts	536284	6800544	-	1.8	1.25	7.5	0.38	0.25
16	Tuckean Nature Reserve North -Middle Drain	Two Pipes	536220	6800119	0.6	-	-	-	0.38	0.35
17	Tuckean Nature Reserve North -Southern Drain	Four Box Culverts	536175	6799859	-	1.8	1.25	7.3	0.26	0.15
18	Stibbards Creek from Tuckean Nature Reserve	Single Pipe (Open)	537470	6794237	1.5	-	-	-	-	-0.59
19	Stibbards Creek from South	Single Pipe	538846	6794148	1.5	-	-	-	-0.72	-0.72
20	Stibbards Creek RRCC3840	Single Pipe	539281	6794122	0.55	-	-	-	-	-0.17
21	Tucki Canal Bridge	Bridge	535507	6795824	-	-	-	-	-	1.53 (Obvert)

ID	Creek/Drain	Type	Easting (GDA94M GA56)	Northing (GDA94M GA56)	Diameter (m)	Width (m)	Height (m)	Length (m)	Upstream Invert (m AHD)	Downstream Invert (m AHD)
22	Bagotville Barrage	Eight Flap Gate Culverts	539489	6794232	-	3.05	3.53	8	-1.76	-1.73
		Three Sluice Gates (Gates 2,3,4)	539489	6794232	-	1.0	1.0			-0.64
23	Sunshine Farm West Stibbards Creek	Box Culvert with Flapgate	537369	6794214	-	2.15	2.09	7	-0.854	-1.04
24	Sunshine Farm East Stibbards Creek	Single Pipe with Flapgate	537706	6794200	1.2	-	-	-	-0.805	-0.88
25	Sunshine Farm East Minor	Single Pipe	537696	6794184	0.3	-	-	-	-	-0.41
26	Sunshine Farm West	Single Pipe	537194	6793969	1.2	-	-	-	-	-1.01
27	Sunshine Farm West Upstream Minor	Single Pipe	537206	6793965	0.3	-	-	-	-	-0.32
28	Stibbards Creek	Three Box Culverts	533055	6792872	-	1.8	1.25		0.274	-
29	Minor Drain into Hendersons Drain	Single Pipe	537492	6799741	0.6	-	-	-	-	-0.38
30	Marom Creek into Meerschaum Vale Drain	Single Pipe	537602	6798787	1	-	-	-	-	-0.53
31	Floodplain Drain into Meerschaumvale	Single Pipe	538243	6798707	0.4	-	-	-	-	-0.22
32	Slatteries Drain into Tuckean Nature Reserve	Blocked Two (?) Pipes	538880	6798598	0.6	-	-	-	-	-0.34
33	Minor Drain into Slatteries Drain	Single Pipe	538944	6798649	0.6	-	-	-	-	-0.11
34	Minor Drain into Slatteries Drain	Single Pipe	539229	6798896	0.4	-	-	-	-	0.42
35	Minor Drain into Slatteries Drain	Single Pipe	539365	6799019	0.4	-	-	-	-	0.47
36	Minor Drain into Slatteries Drain	Single Pipe	539383	6799043	0.4	-	-	-	-	0.30
37	Minor Drain into Slatteries Drain	Two Pipes	539684	6799311	0.5	-	-	-	0.218	0.20
38	Minor Drain into Slatteries Drain	Single Pipe	539840	6799446	0.5	-	-	-	-	0.45

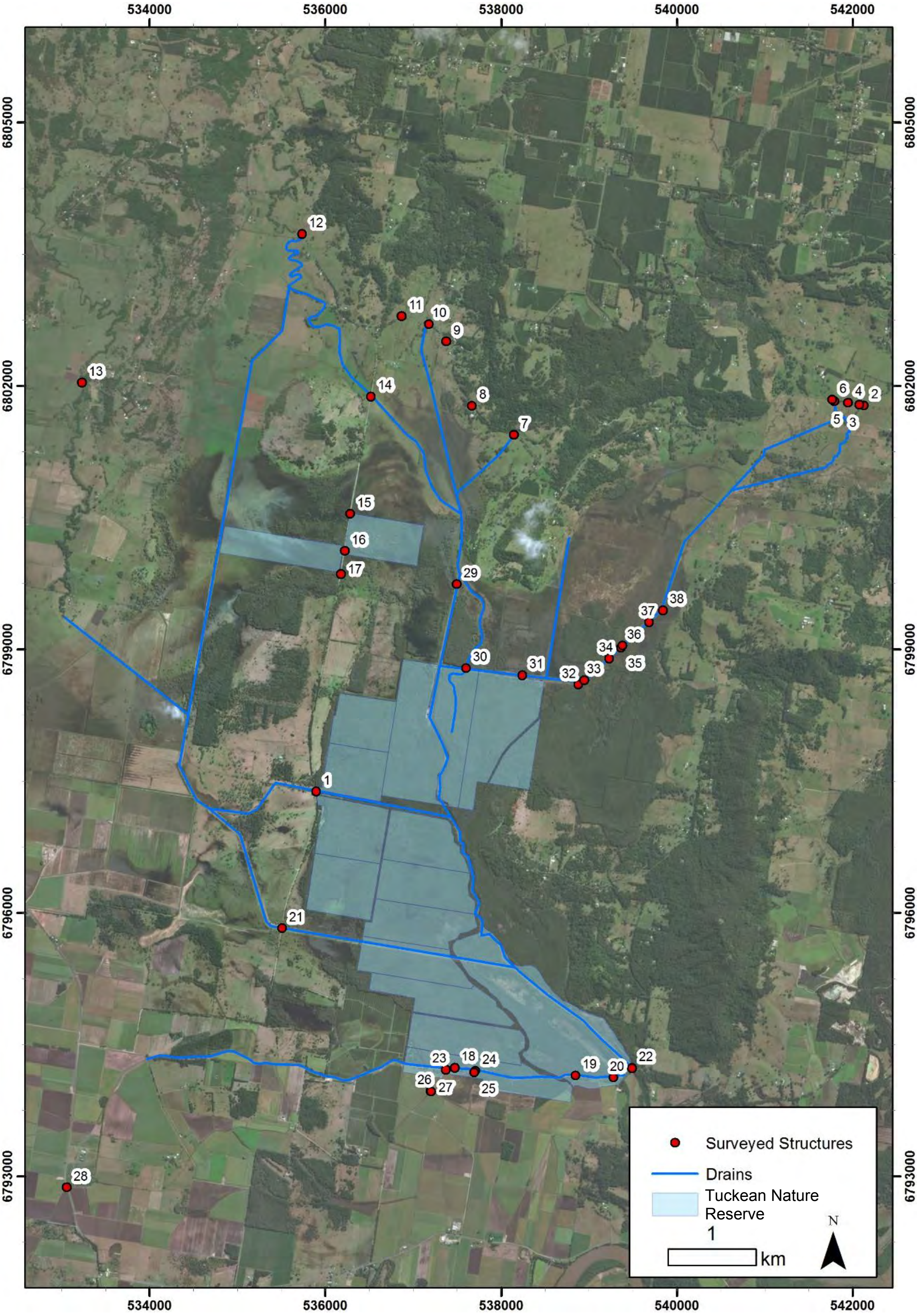


Figure B-6: Locations of surveyed structures

B.4 Bathymetric surveys of major drains

The bathymetry (i.e. cross sections) of the drains and creeks within the floodplain is a primary indicator of the conveyance capacity of each of the waterways. There are several significant drainage paths through the Tuckean floodplain, including Hendersons Drain, Stibbards Creek, Marom Drain, Marom Creek, Tucki Canal, Stony Island Drain and Slatteries Drain, each of which were surveyed in 2018. Ideally, all the major drains would be inspected and surveyed to improve the understanding of the system. Drains within the boundaries of Tuckean Nature Reserve (owned by National Parks and Wildlife Services) and on select areas of private land (with landholder permission) were surveyed in March and June 2018. However, due to issues accessing private property across the floodplain, some of the drainage channels were not extensively surveyed.

Surveys were measured from a small boat or canoe using a Trimble RTK GPS. Shallow drain cross sections were waded as necessary. The location of the major drain cross section surveys is shown in Figure B-7 and cross sections are provided in Figure B-8 to Figure B-20. Cross sections are drawn left bank to right bank (looking downstream) and numbered from downstream to upstream.

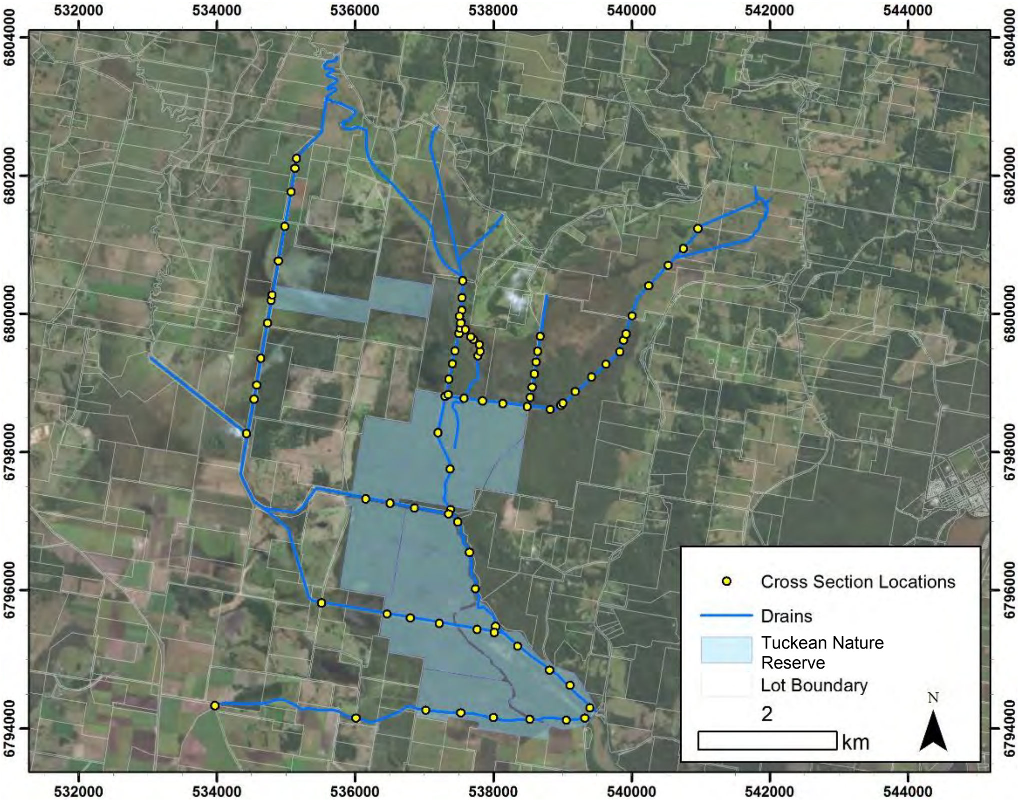


Figure B-7: Cross section locations

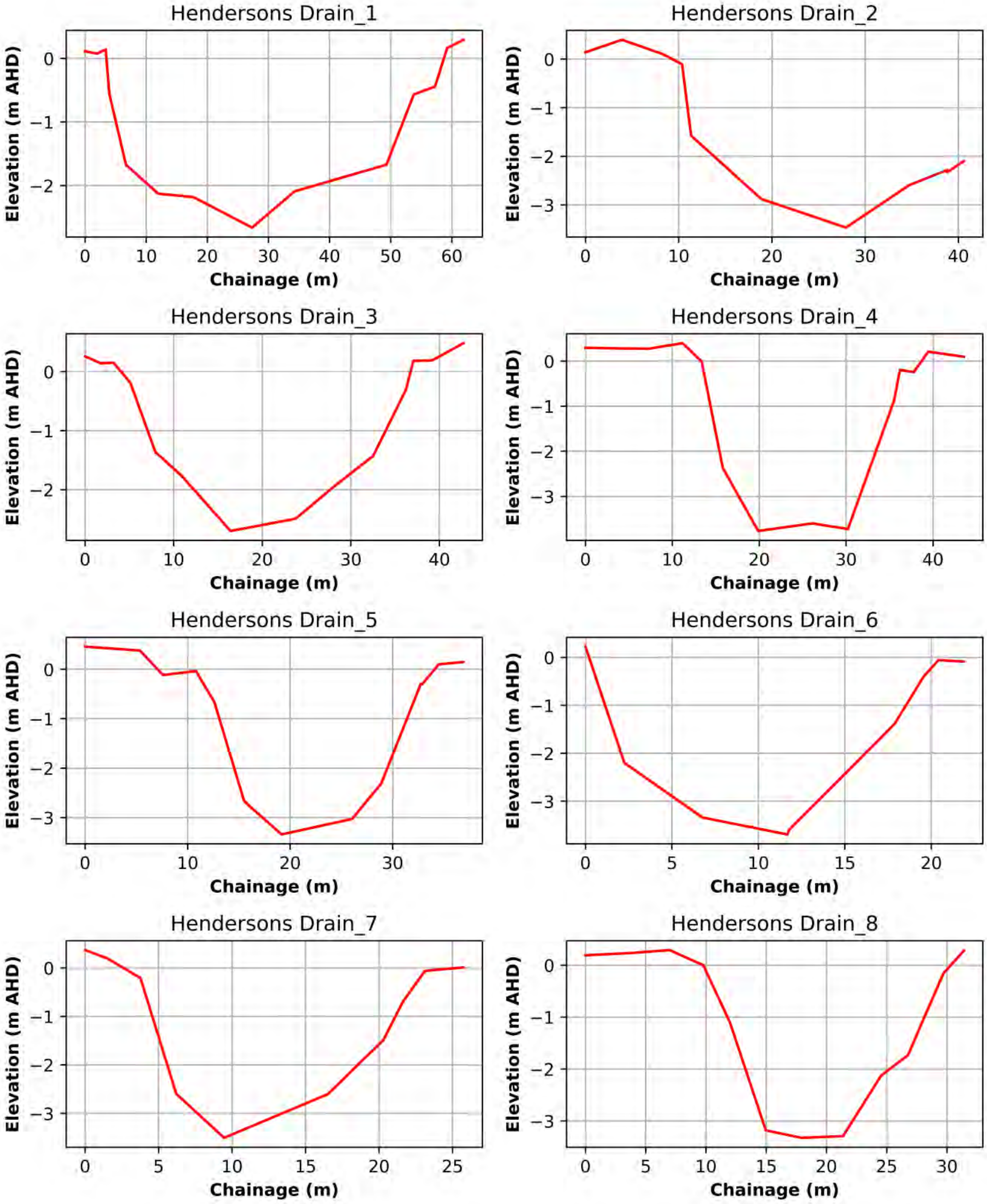


Figure B-8: Hendersons Drain cross sections 1 – 8

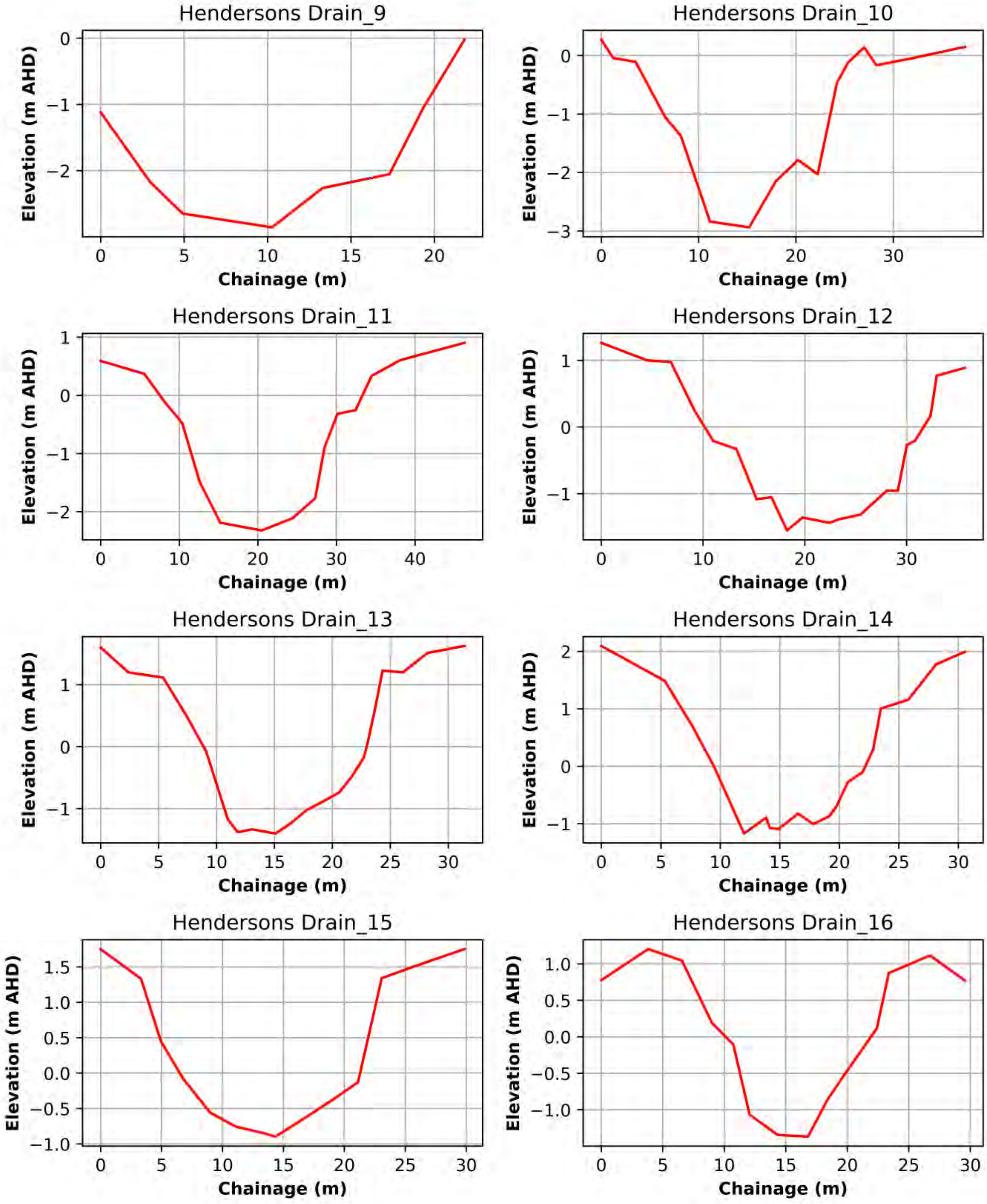


Figure B-9: Hendersons Drain cross sections 9 to 16

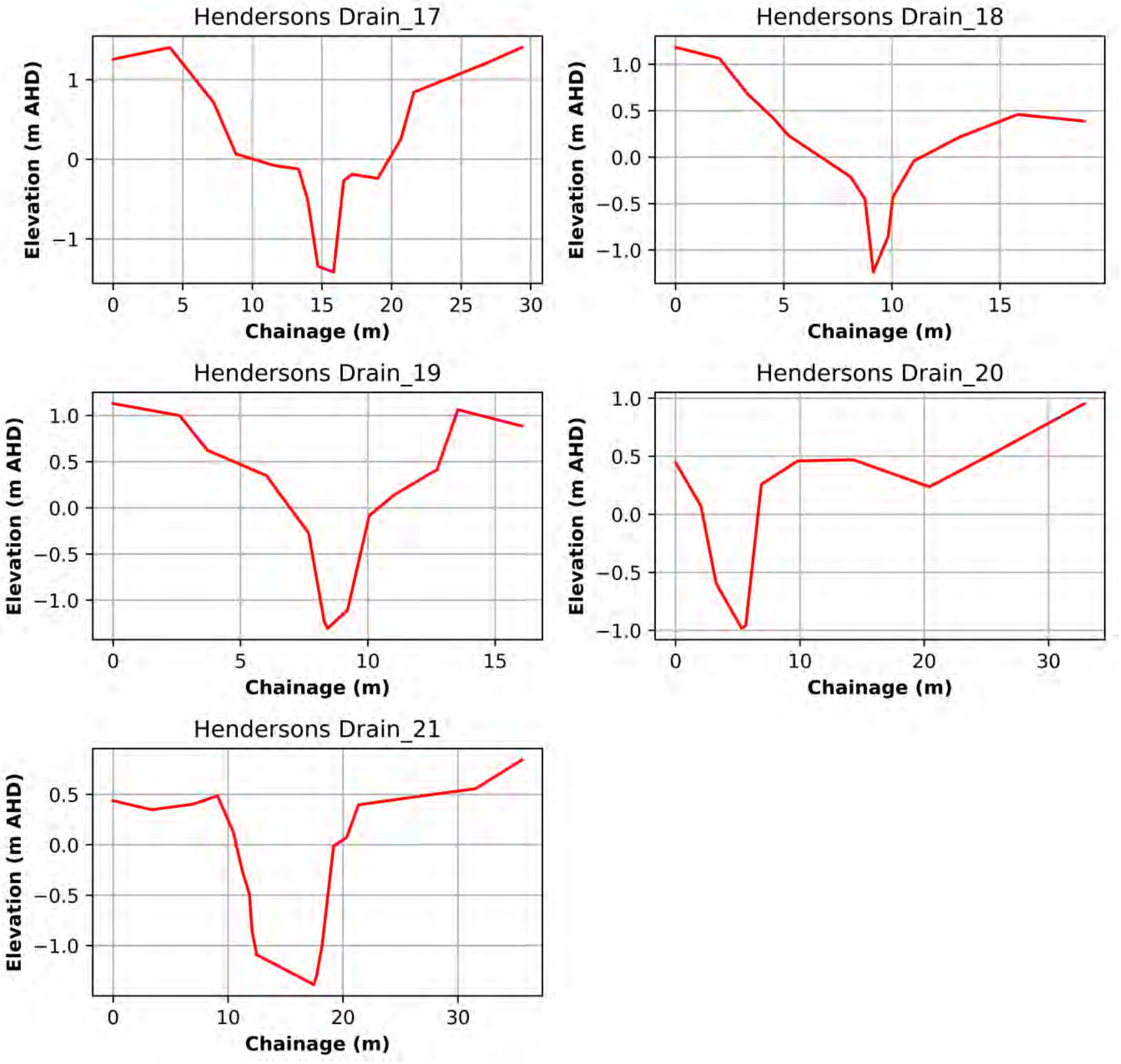


Figure B-10: Hendersons Drain cross sections 17 to 21

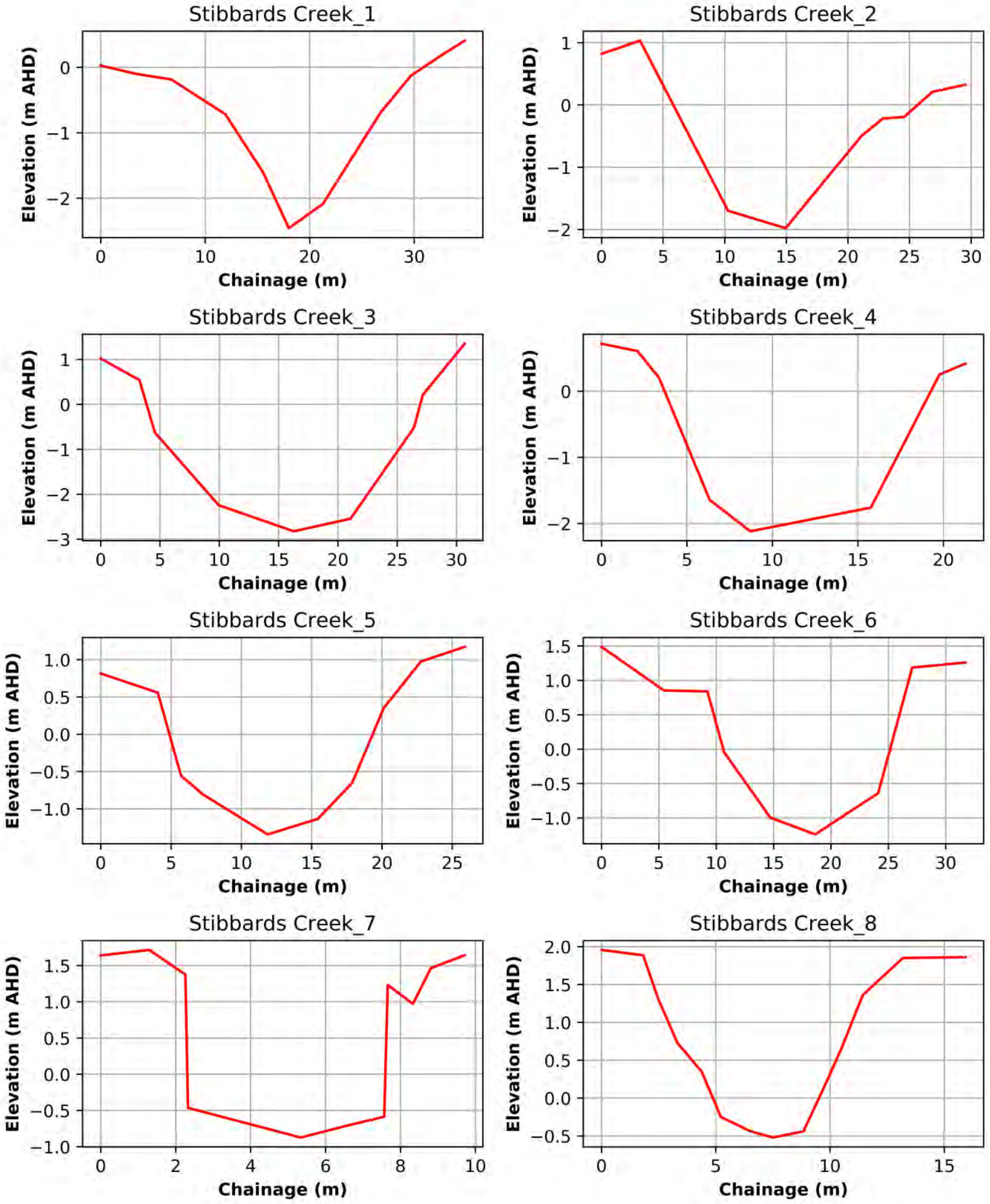


Figure B-11: Stibbards Creek cross sections 1 to 8

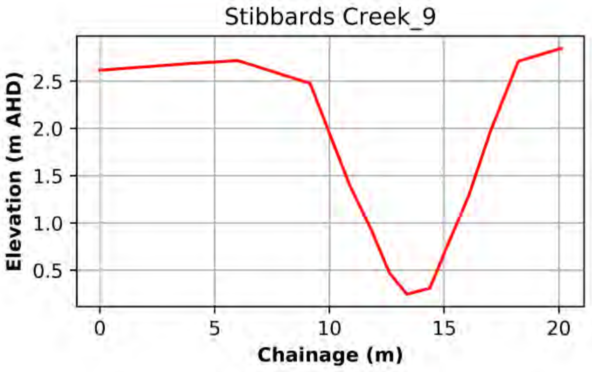


Figure B-12: Stibbards Creek cross section 9

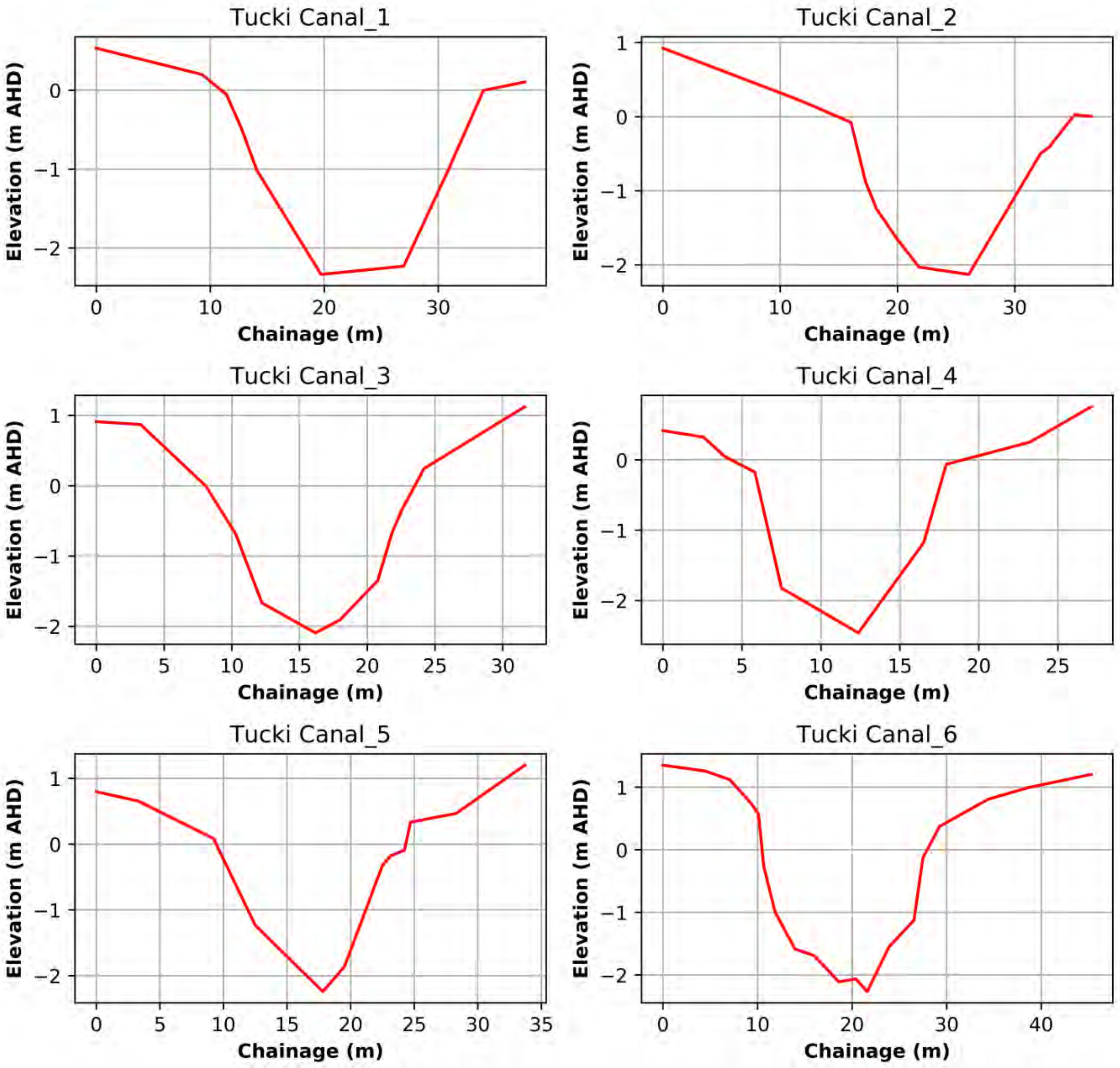


Figure B-13: Tucki Canal cross sections 1 to 6

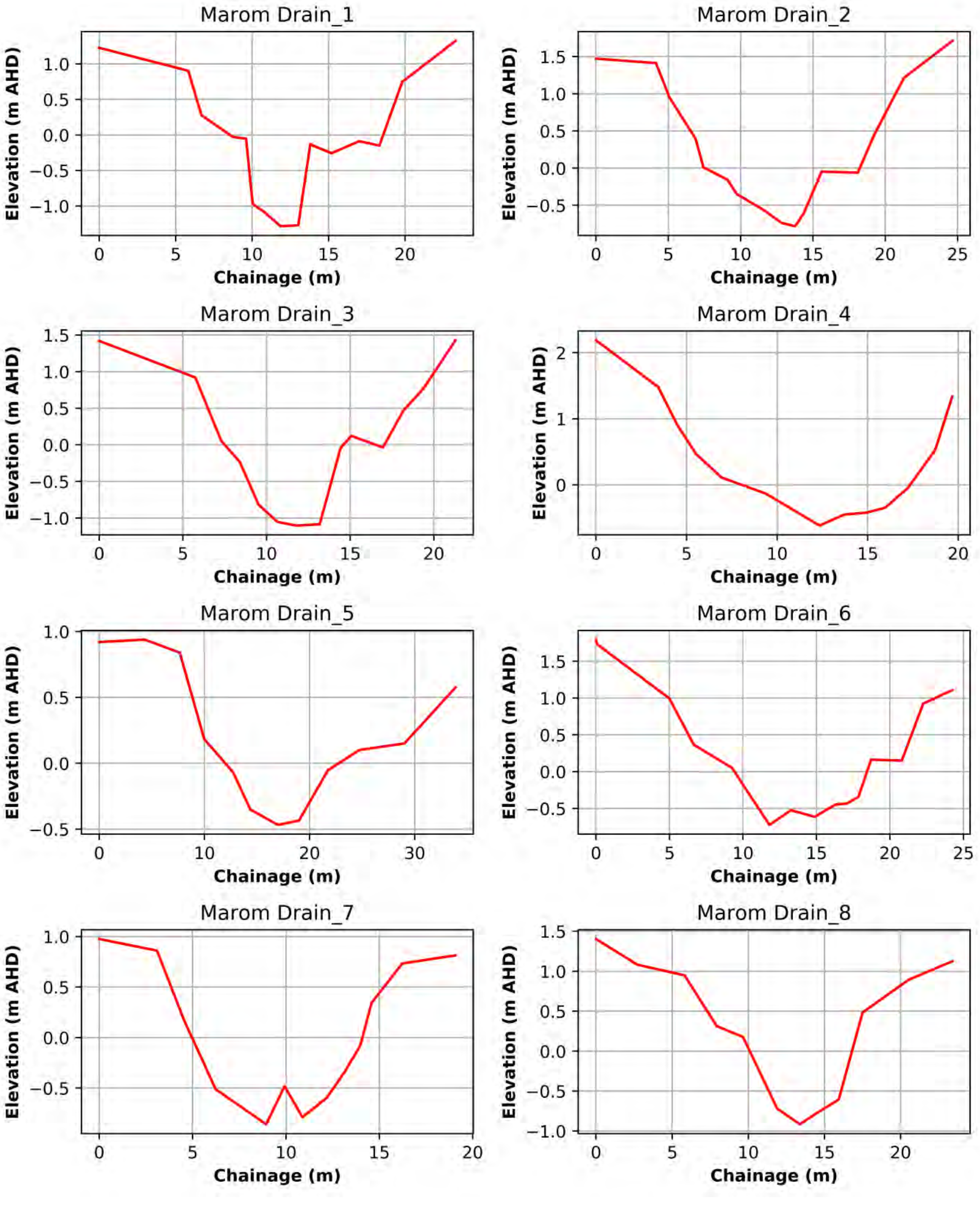


Figure B-14: Marom Drain cross sections 1 to 8

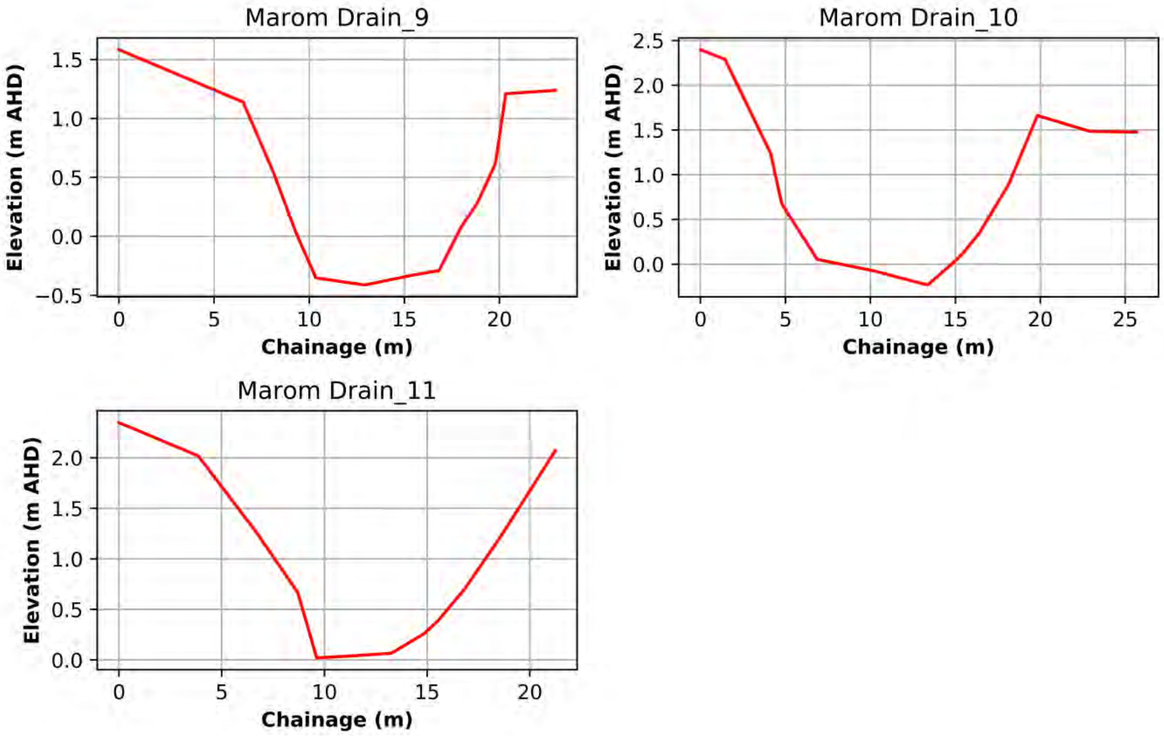


Figure B-15: Marom Drain cross section 9 to 11

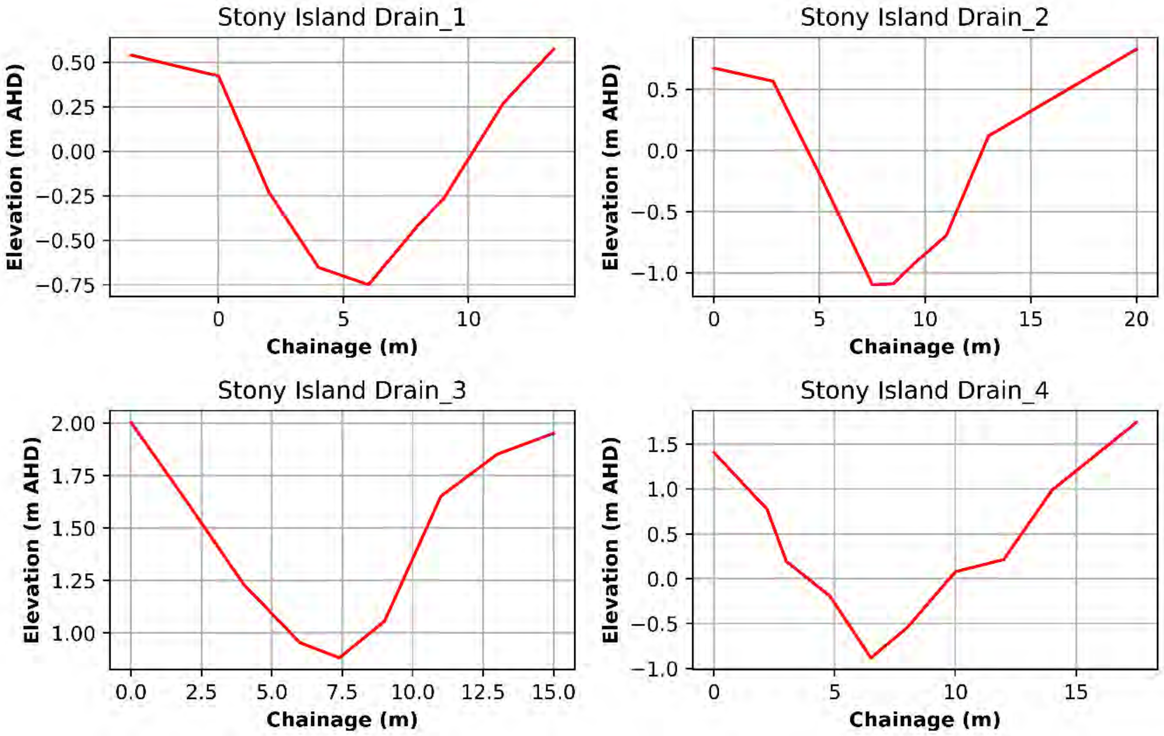


Figure B-16: Stony Island Drain Cross Section 1 to 4

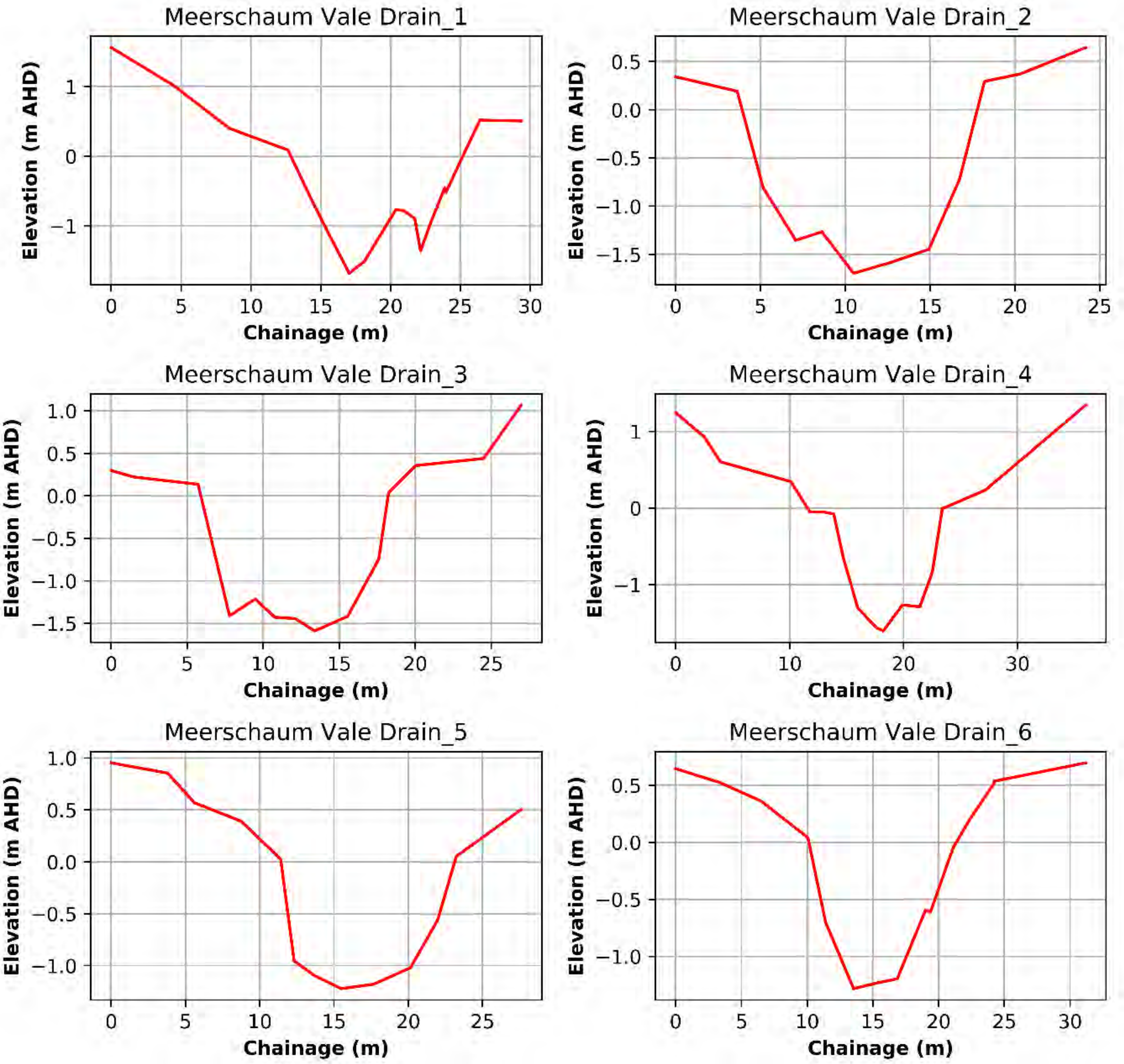


Figure B-17: Meerschaum Vale Canal cross section 1 to 6

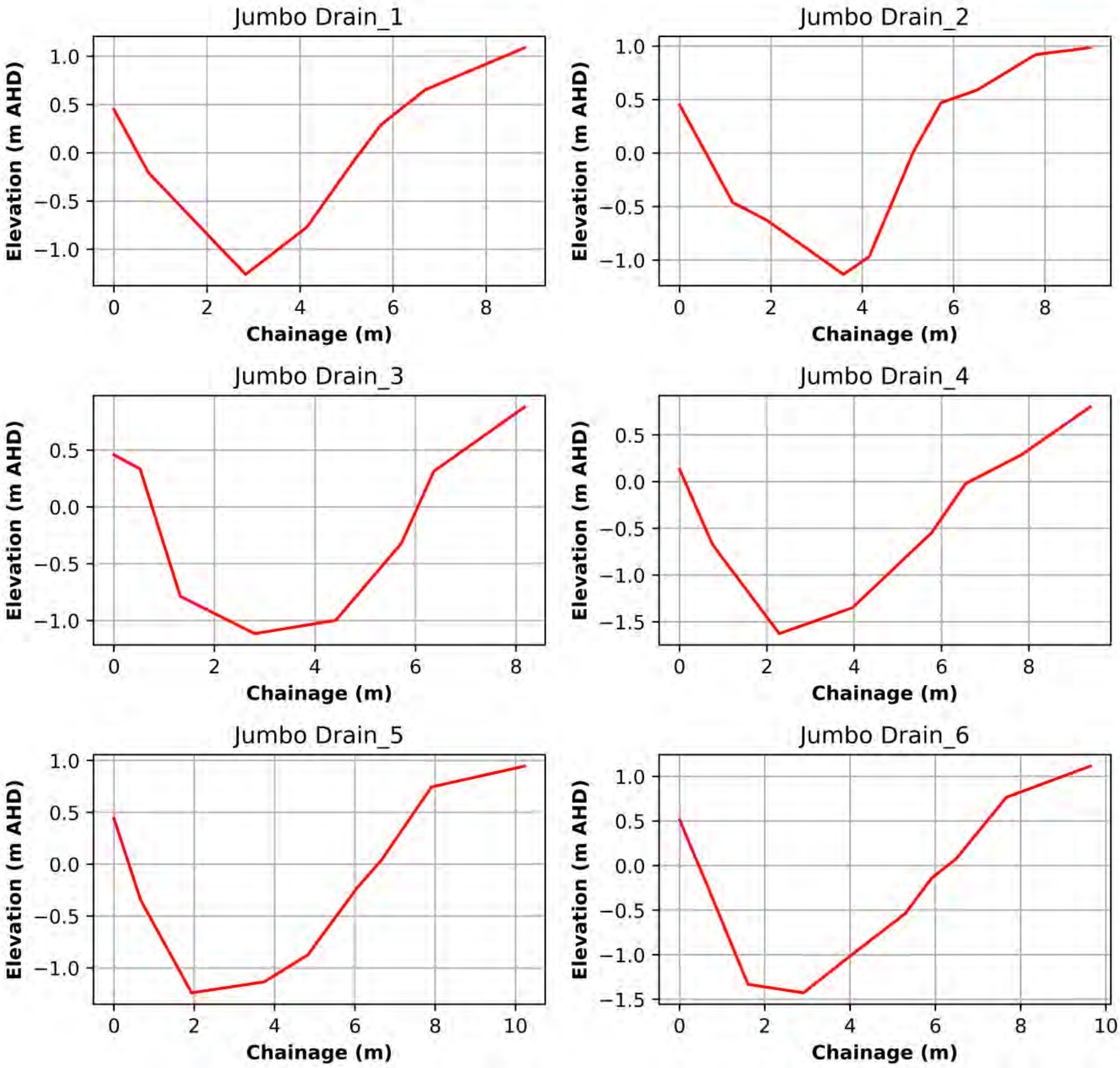


Figure B-18: Jumbo Drain cross sections 1 to 6

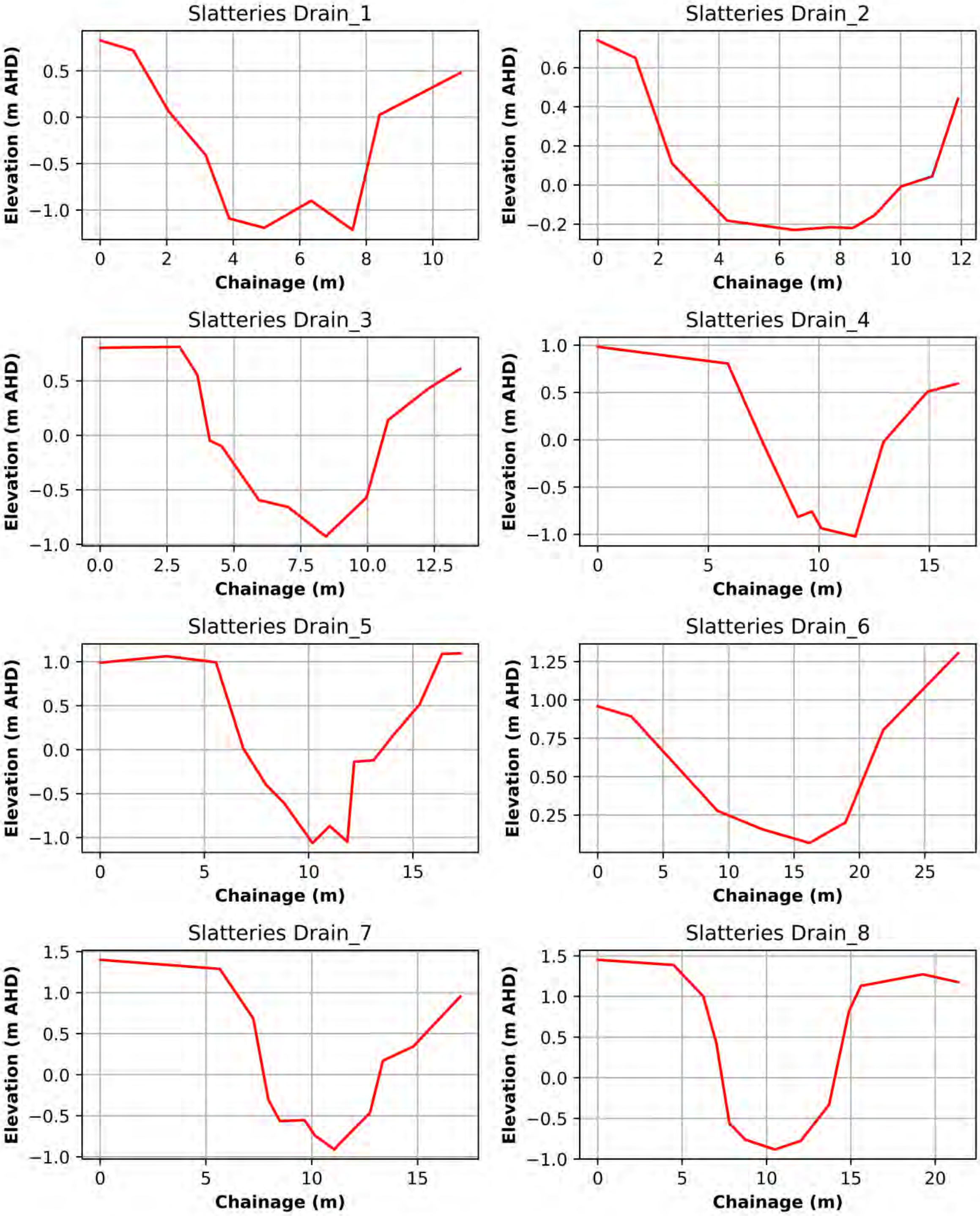


Figure B-19: Slatteries Drain cross section 1 to 8

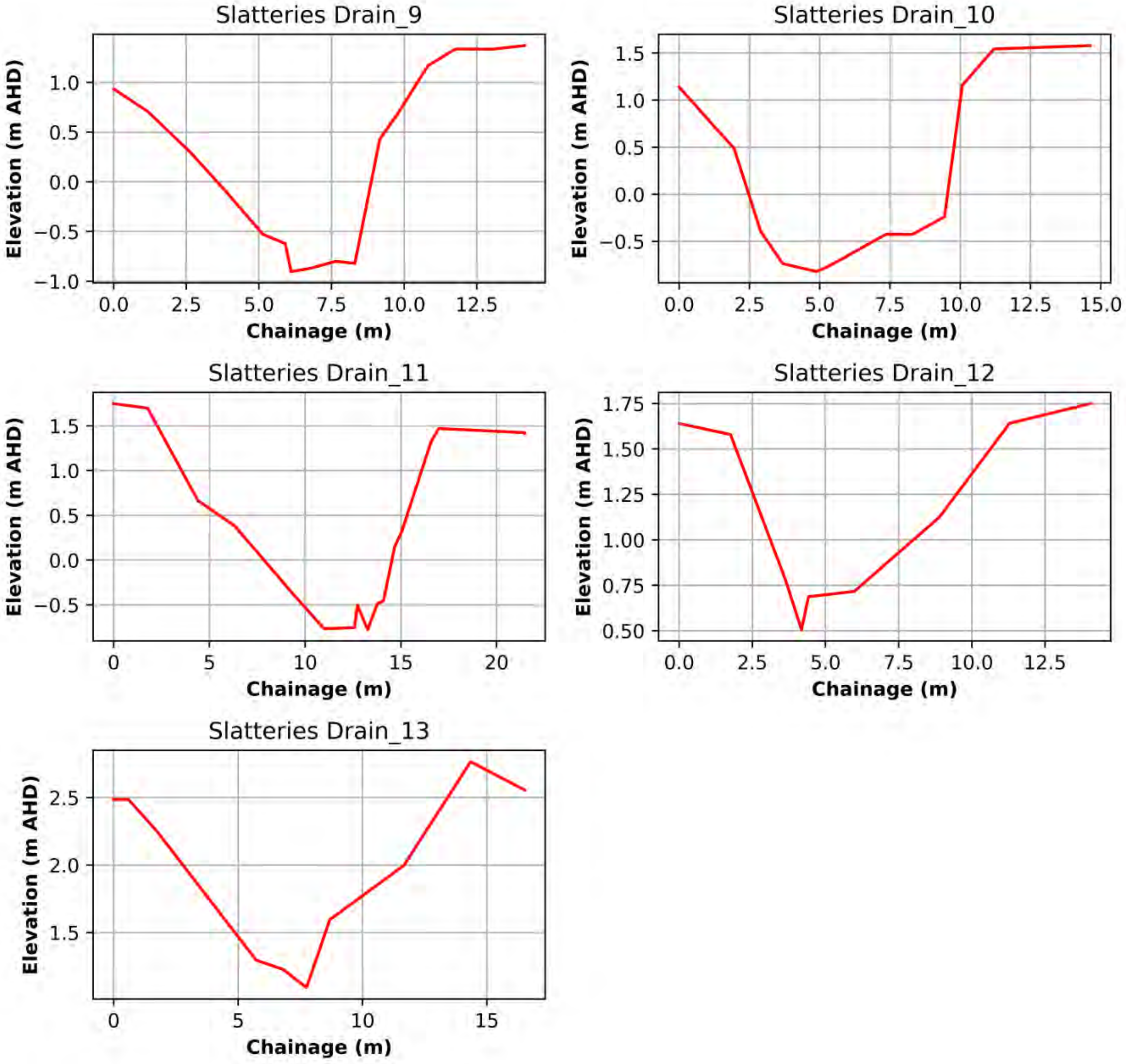


Figure B-20: Slatteries Drain cross sections 9 to 13

B.5 Water level and electrical conductivity monitoring

Water level recording instrument (referred to as “loggers”) were installed at key location across the floodplain, shown in Figure B-21 and summarised in Table B-2. At each of these locations the data loggers recorded absolute pressure, which was adjusted locally for barometric pressure using a barometric logger installed downstream of the barrage. Following the barometric corrections, all water levels were referenced to AHD. Adjusting water levels to AHD typically involves taking a water level measurement near the data logger using an RTK-GPS to provide a vertical correction that can be applied to the timeseries data. The logger placed downstream of the barrage also measured electrical conductivity (EC), which is an indirect measure of salinity.

In addition to the WRL loggers, Rous County Council operate three (3) monitoring stations measuring water level, and water quality (pH and EC) probes in the Tuckean region, which are located:

- Immediately downstream of the barrage;
- Approximately 500 m upstream of the barrage; and
- In Slatteries drain, upstream of the confluence with Meerschaum Vale Drain.

Data from these loggers was intermittent during the monitoring period, and water levels did not appear to be referenced to AHD. However, electrical conductivity data collected upstream of the barrage in January and February was used in the model calibration.

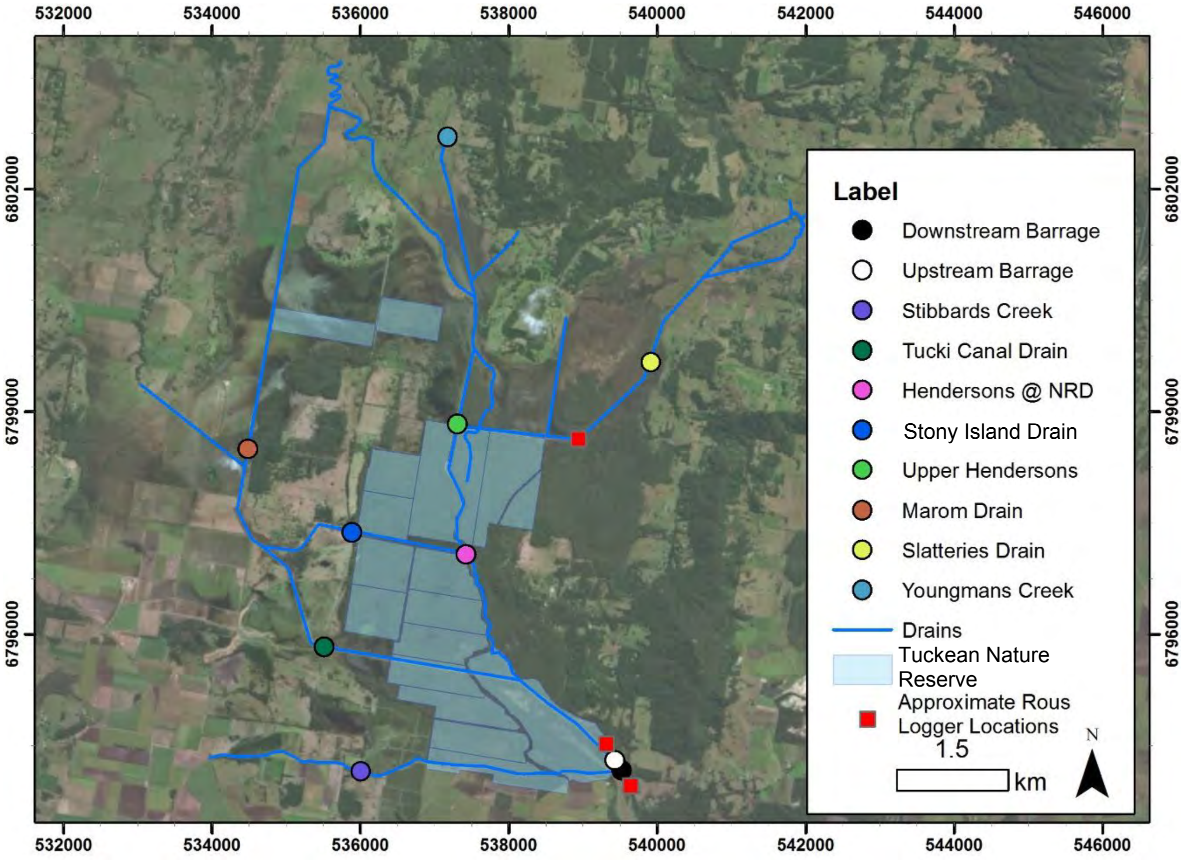


Figure B-21: WRL water level monitoring locations

Table B-2: WRL water level logger deployment information

Station Name	Easting (GDA94 MGA56)	Northing (GDA94 MGA56)	Start Date	End Date
Stony Island Drain	535886	6797377	12/3/2018	28/2/2019
Tucki Canal Drain	535509	6795833	12/3/2018	9/8/2018*
Hendersons Drain at Stony Island Drain	537420	6797078	15/3/2018	28/2/2019
Tuckean Broadwater Downstream of Barrage**	539519	6794197	15/3/2018	28/2/2019
Hendersons Drain at the Northern Boundary of Tuckean Nature Reserve	537305	6798836	14/3/2018	28/2/2019
Stibbards Creek	536008	6794150	12/3/2018	28/2/2019
Youngmans Creek at Marom Ck Road	537172	6802702	13/3/2018	28/2/2019
Tucki Creek at Robsons Bridge	533221	6802033	13/3/2018	28/2/2019
Hendersons Drain near the Barrage	539438	6794295	14/3/2018	28/2/2019
Marom Drain near Tucki Canal	534499	6798533	23/6/2018	28/2/2019
Slatteries Drain	539915	6799711	22/6/2018	28/2/2019

*logger failed during monitoring period

** also measured salinity

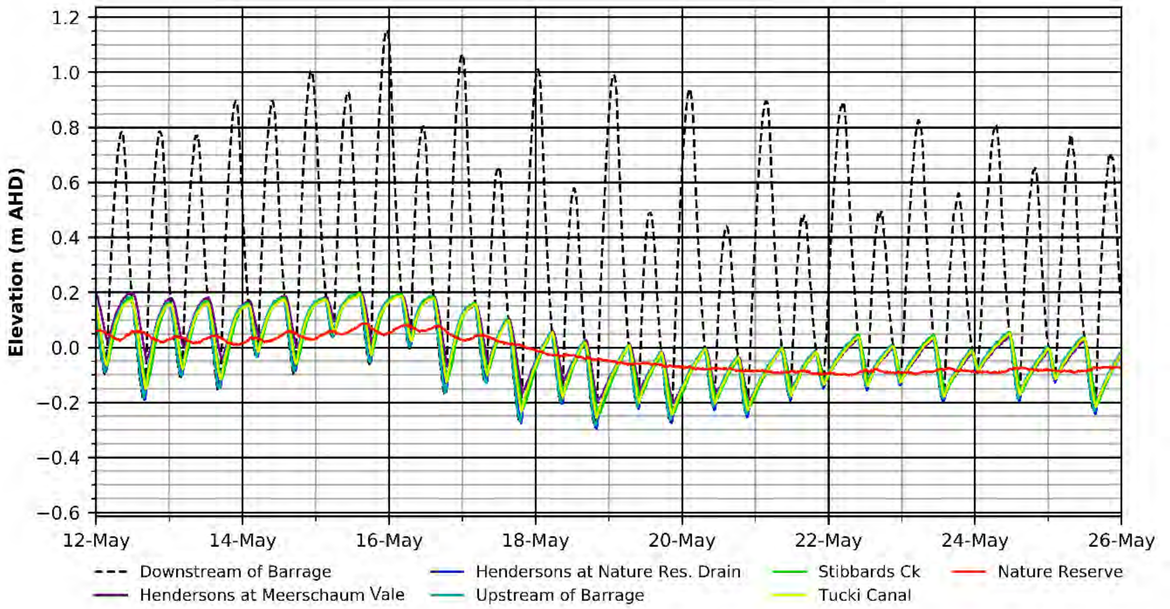


Figure B-22: Example period of water level data

B.6 Water quality

Spot water quality measurements were taken opportunistically in drains across the floodplain during field campaigns in March and June 2018. Water quality parameters collected included acidity (pH) and electrical conductivity (EC) primarily using a calibrated Hach handheld water quality meter. While the impact of Acid Sulfate Soils (ASS) on water quality is well documented, the purpose of the water quality data collection is to help identifying locations of acid sources on the floodplain. Neutral water pH is around 7, while the pH of rainwater is typically around 5.5.

The pH measurements across the Tuckean floodplain in both March 2018 and June 2018 are shown in Figure B-23. Highly acidic waters were evident in samples collected during both time periods. Acid observations throughout the floodplain indicate that the north eastern corner of the swamp and the Tuckean Nature Reserve are both major sources of acid. This is consistent with ASS testing that has previously occurred in the Tuckean region. The lowest pH measure was observed in Jumbo Drain where a pH of approximately 2.1 was observed, a pH comparable with the acidity of lemon juice and well below the standards suitable for aquatic fauna. These acidic regions discharge into Hendersons Drain, which was consistently observed to have a pH below 4 during both time periods. Acidity in Tucki Canal, Marom Drain and Stibbards Creek was generally observed to be near neutral. EC at all locations upstream of the barrage during the March and June 2018 field trips was observed to be below 2,000 µS/cm.

As discussed in the Section above, EC was also being measured downstream of the barrage by WRL and upstream of the barrage by Rous County Council. EC data from the Rous logger periodically is missing data, however Figure B-24 shows a period with near continuous data from October 2018 to February 2019. EC downstream of the barrage in the Tuckean Broadwater varied between fresh to an EC of approximately 28,000 µS/cm (approximately half of marine water) during the extended dry period in the 2018/2019 summer. The salinity upstream of the barrage varies depending on the salinity in the Broadwater, the sluice openings and the amount of freshwater catchment runoff. WRL was informed by Rous County Council that one of the three (3) sluice gates in the barrage was open 150 mm throughout January and February 2019. This combined with very dry weather over the two-month period, allowed salinity to increase upstream of the barrage to a similar level as the downstream Broadwater.

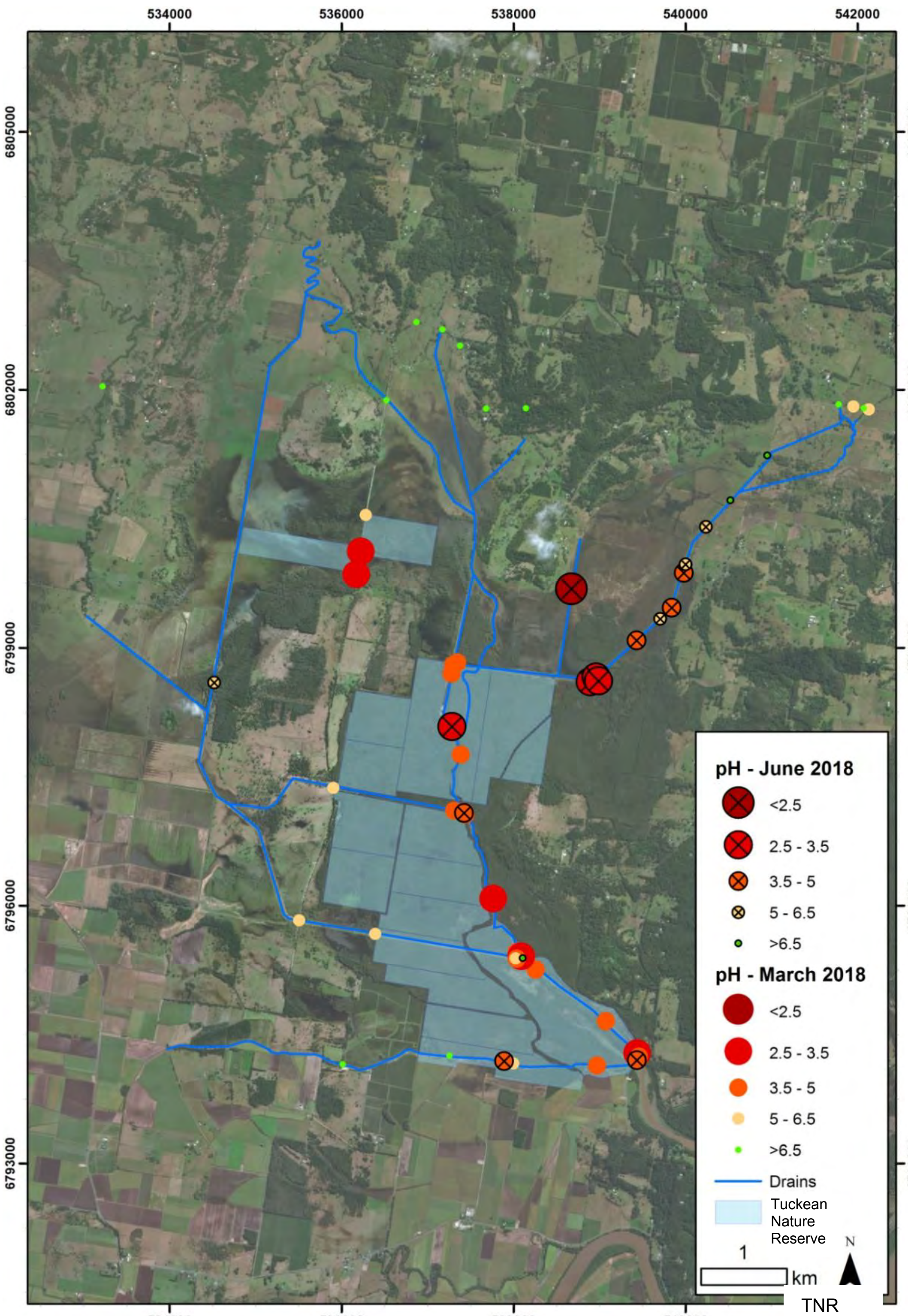


Figure B-23: pH measurements in March and June 2018

Note: Measurements were taken over multiple days in similar locations on both field trips, and the pH varied in some locations day to day.

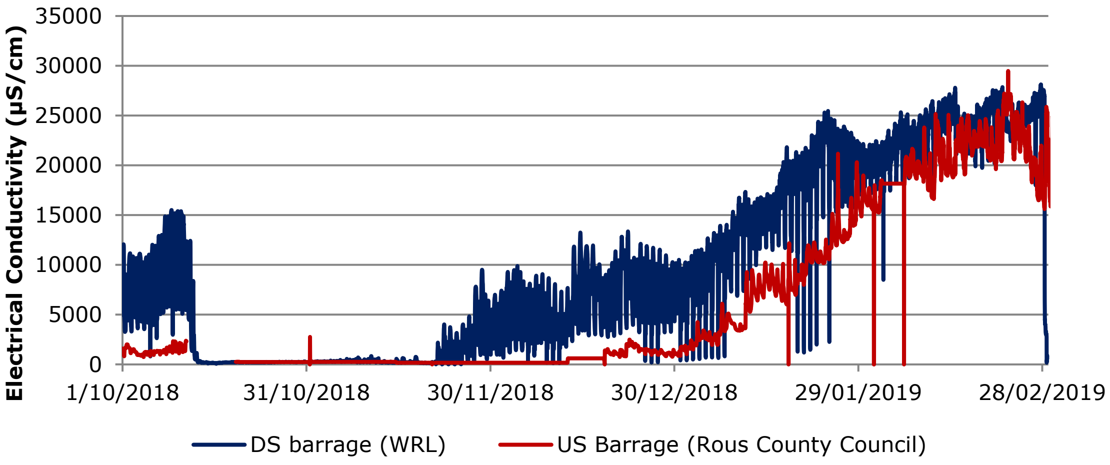


Figure B-24: Observed electrical conductivity (EC) up and downstream of the barrage

B.7 Catchment inflows

WaterNSW maintain a water level logger on Marom Creek at Graham Road (Site 203059), within one of the catchments that drains to Tuckean Swamp. There have been multiple gaugings of the logger since it was installed in August 2011, allowing for the development of a rating curve which is shown in Figure B-25. Using this rating curve, WaterNSW reports continuous discharge data (in ML/day) which is available from 2/8/2011 to the present. The catchment for the gauged station is shown in Figure B-26.

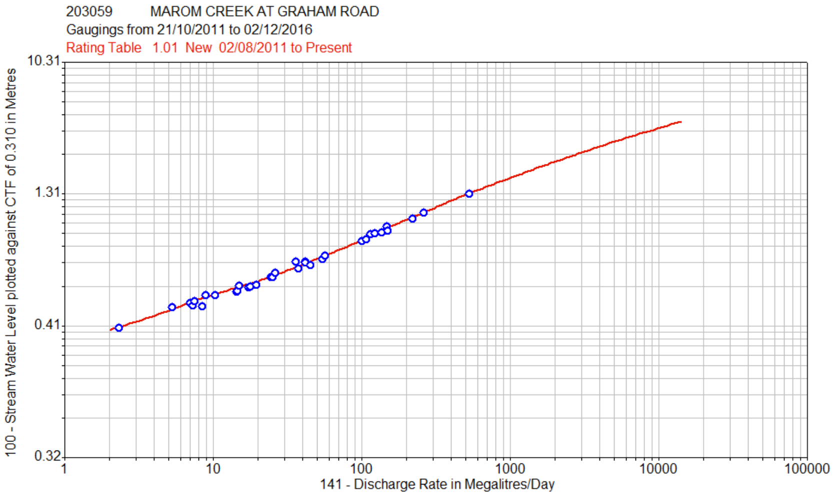


Figure B-25: WaterNSW rating curve for the Marom Creek logger

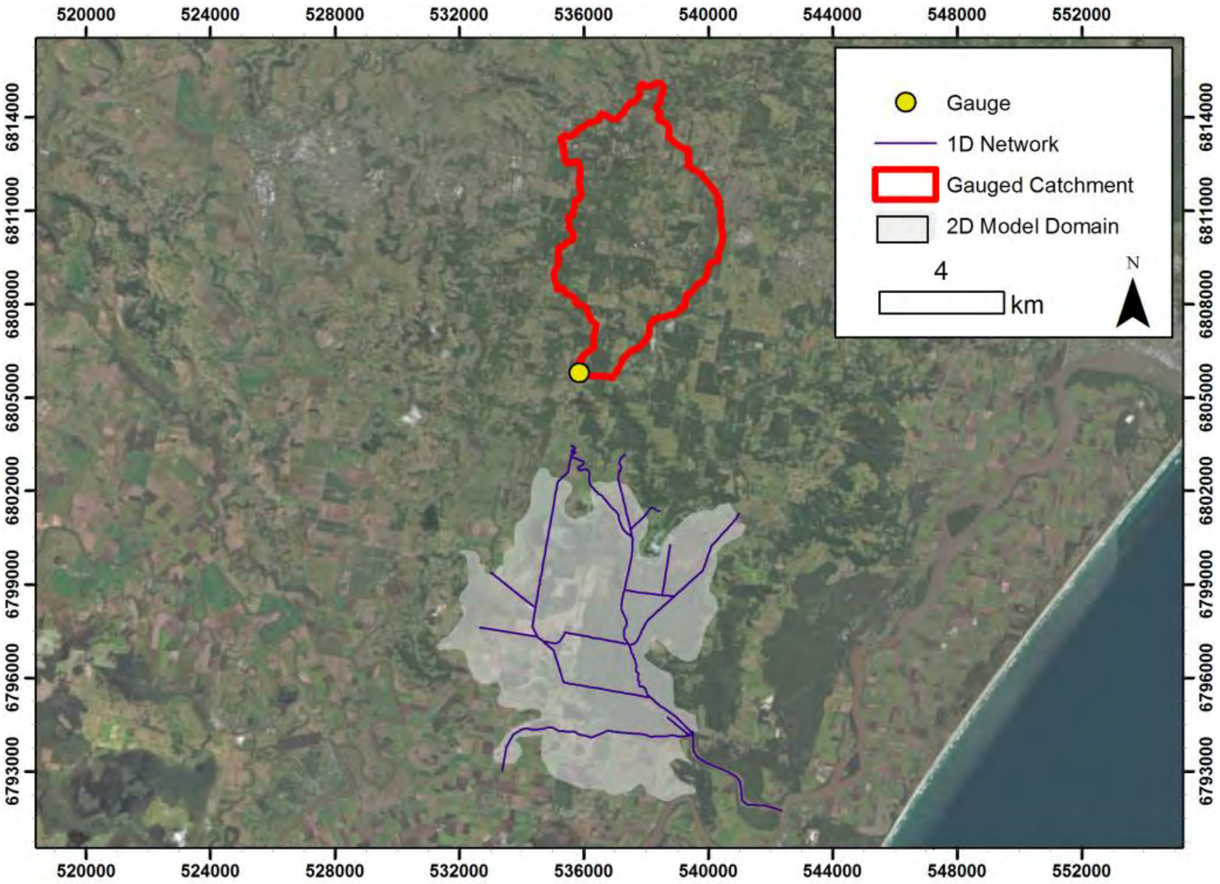


Figure B-26: Delineated catchment upstream of WaterNSW gauge

B.8 **Soil data**

Soil profiles from the NSW SALIS (Soil and Land Information Systems) were obtained to map soil acidity and permeability. Data from the 1995 Acid Sulfate Soil Survey (Smith, 1995), including percentage sulfur (an alternative measure of the presence of ASS) was also digitised and mapped, and is shown in Figure B-27. Additional profiles have also been logged by Sammut (1996), Brodie (2007) and Wong et al. (2016). Due to the extensive coverage of the existing soils data, minimal additional soil data was collected for this study.

In general, the soil profiles show that:

- ASS occur extensively across the Tuckean floodplain;
- The worst acid appears to be largely concentrated within the Tuckean Nature Reserve and in the north-east corner of the floodplain;
- Low pH values (<4) are typically observed near the surface (with the top 20 cm) and can persist to levels below the groundwater table (sometimes to 2 m below the surface water level);

- Brodie (2007) describes the ‘representative profile’ in the Tuckean region as follows:
    - An upper acidified section where all the pyrite has been oxidised, with significant iron mottling and jarosite present. Typical pH in this region is below 4;
    - An intermediate horizon which is partially oxidised. In this zone, pH generally increases gradually with depth; and
    - A deeper potential ASS layer, with a pH greater than 5. Pyrite is generally present in these regions but has not yet been oxidised. The PASS layers are typically 1.1 to 1.5 m below the surface.

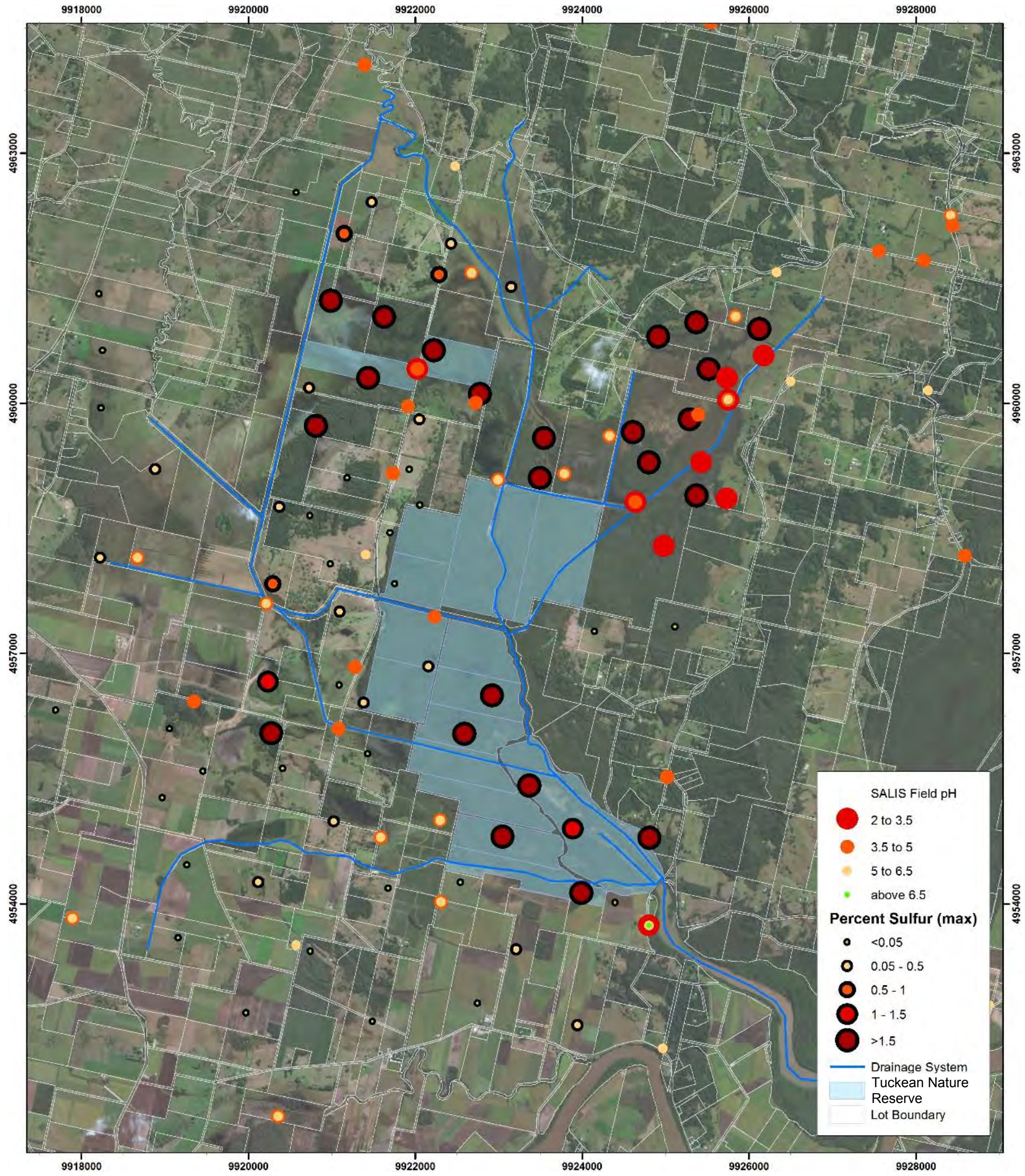


Figure B-27: Soils data from Smith (1995) and SALIS database

Brodie (2007) also conducted slug tests at locations throughout the floodplain to measure the groundwater hydraulic conductivity. The measurements showed that the low-lying Pimilco clay layers have an extremely low hydraulic conductivity (<0.001 m/day). This is consistent with observations by WRL in the 2018 investigation on the Sunshine Cane Farm (WRL, 2019) where very low saturated hydraulic conductivity was observed in the estuarine clays south of Stibbards Creek. The overlying acidified clay layers tend to have a higher hydraulic conductivity (0.1 – 1 m/day). Although this is still considered low compared to estuaries across NSW (Hirst et al., 2009), it is sufficient to allow acid export from these layers. Overlaying sands and sandy clays on top of the ASS clays (which can still be acidic) tend to have a much higher hydraulic conductivity (in the order of 50 m/day) and would easily transport groundwater when the water table is elevated. This overlaying sand was observed by WRL (2019) in the top 30 cm of the soil profile south of Stibbards Creek, which is supported by the SALIS database which shows shallow sand layers near Stibbards Creek (both to the north and south, west of the Tuckean Nature Reserve). Sand is known to be the primary soil constituent in the higher Tuckean Island in the western portion of the floodplain (Brodie, 2007). Other areas of sand may exist, as the SALIS data does not extensively cover the western portion of the swamp. However, the SALIS database shows that the clays in the north-east corner of the floodplain typically do not feature this shallow sandy layer, but have a thin layer of loam and peat, overlaying immediately over clays (with sand layers featuring at greater depths greater than 2.5 m at one profile).

B.9 Site photographs

Throughout the extensive field investigations undertaken by WRL, observations of the drains and the other environmental conditions were noted. This section provides several photographs that show the major drains throughout Tuckean Swamp. Figure B-28 is an overview of approximate locations where pictures were taken, and the corresponding pictures are on the following pages.

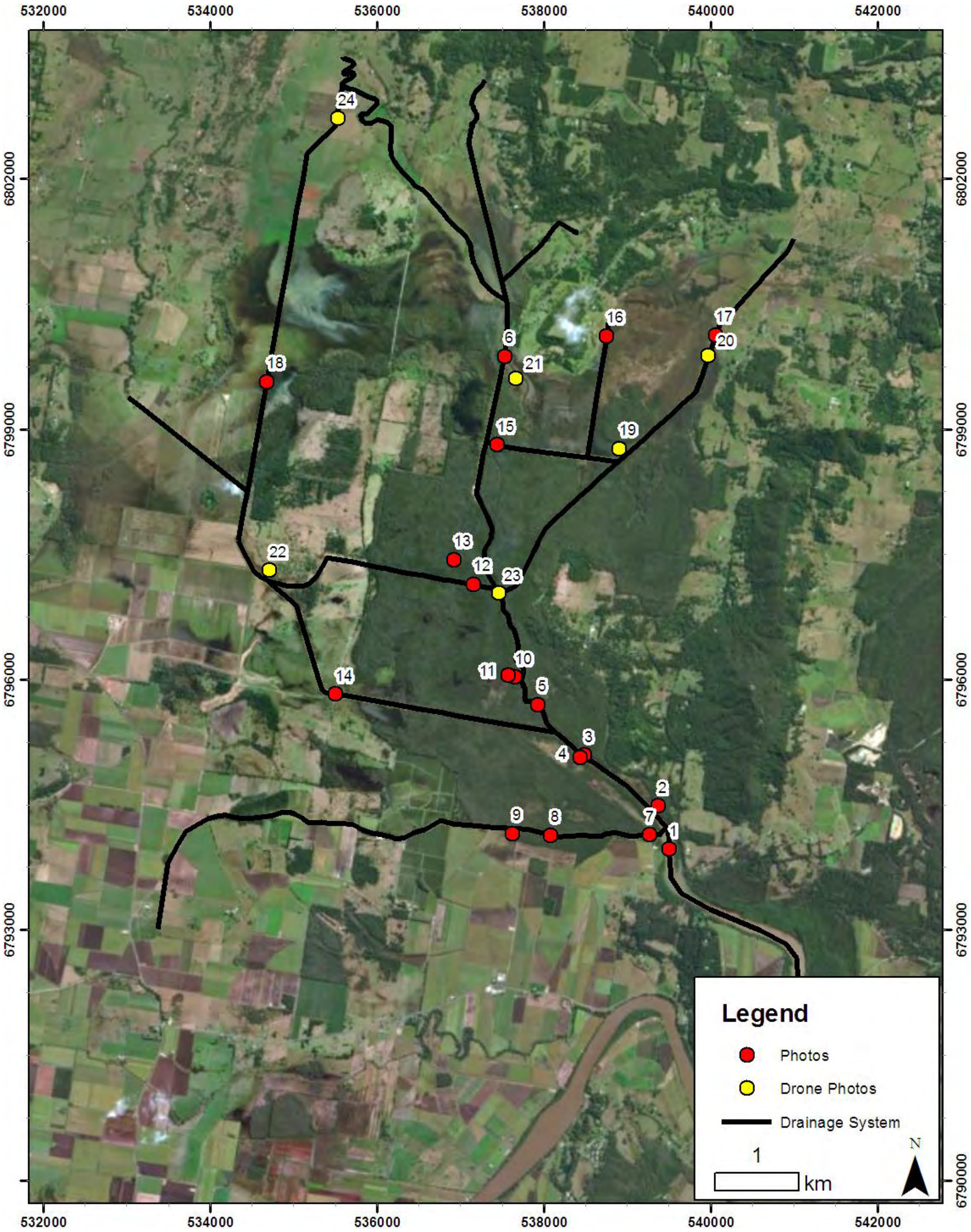


Figure B-28: Overview of picture locations


1: Upstream Bagotville Barrage


2: Downstream Bagotville Barrage flowing out


3: Iron floc in water sample, Hendersons Drain


4: Extensive iron floc plumes, Hendersons Drain


5: Iron staining on the banks of Hendersons Drain


6: Iron deposits, Hendersons Drain

7: Typical minor drain floodgate, Stibbards Creek

8: Narrow, more natural alignment of Stibbards Creek

9: Dense clays with low hydraulic conductivity near Stibbards Creek

10: Dense vegetation in the Tuckean Nature Reserve

11: Iron staining throughout the Tuckean Nature Reserve

12: Significant blockages of Stony Island Drain

13: Extensive inundation of low-lying area in Tuckean Nature Reserve

14: Wide, deep channel in Tucki Canal conveys majority of flow from the north western catchment of Tuckean

15: Aquatic vegetation through Meerschaum Vale Drain

16: Jumbo Drain, where pH comparable to lemon juice (pH=2) was observed

17: Narrowing of Slatteries Drain with significant iron floc deposits on bed and banks

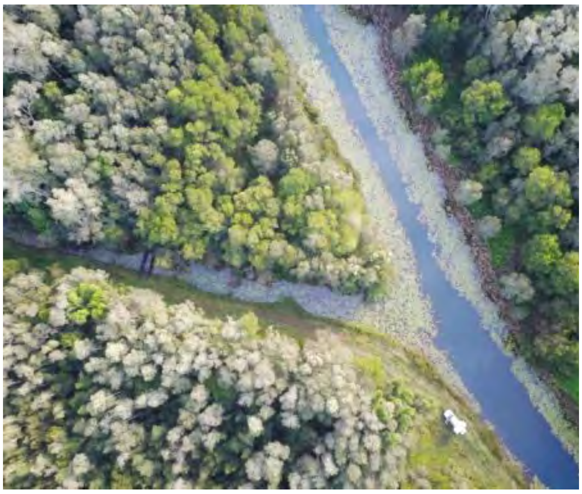
18: Marom Drain

19: Low lying land inundation at the confluence of Slatteries and Meerschaum Vale Drain

20: Looking downstream along Slatteries Drain

21: Hendersons Drain, looking downstream.

22: Tucki Canal looking downstream



23: Confluence of Hendersons Drain (right) and Stony Island Drain

24: Marom Drain, looking upstream

Appendix C Model development

C.1.1 Preamble

Understanding the dynamics of water flows through the drains and over the floodplain in Tuckean Swamp is important in developing an understanding the best way to improve the water quality at the site. In wetland projects, hydrodynamic modelling is used to simulate different management strategies and quantify potential impacts and risks in terms of inundation areas, flooded depths, flow distributions and velocities, and hydro-period.

The MIKE suite of modelling software (Version: Release 2018) was used to develop a dynamically linked 1-D/2-D hydrodynamic numerical model of the Tuckean Swamp floodplain. MIKE also allows for advection-dispersion modelling to be coupled with the hydrodynamic model, which permits salinity transport to be modelled as required.

Irrespective of the model size and complexity, a hydrodynamic model is a predictive tool that incorporates site characteristics and field data into a mathematical approximation of reality. This is achieved by dividing the study area into discrete pieces (or grid cells) and applying mathematical equations within each grid cell to simulate real world systems. A mathematical algorithm (or model) is then used to solve the mathematical equations in each grid cell at each model time step. Once the model has been developed and calibrated to real world observations (e.g. water levels, flow etc.), it can be used as a predictive tool to test “what if” scenarios.

C.2 Model domain

A MIKE 21 Flexible Mesh (FM) was selected for the model grid representing the 2-D model domain of the study area. A MIKE 21 FM was selected for the 2-D model domain due to the computational advantages of an unstructured grid and stability in dealing with shallow water depths across floodplains. The model domain covers the area of the Tuckean floodplain below 2 m AHD (shown in Figure C-1) and the Tuckean Swamp 2-D model contains over 105,000 triangular elements with an area ranging between 6 and 1000 m^2. The model grid was auto generated using the MIKE Flood Mesh Generator which provided greater resolution in areas around the channel drainage network and reduced resolution across open floodplain areas. Additional resolution was added in the areas around the lower Tuckean Nature Reserve, where there is frequent floodplain inundation. Floodplain topography was extracted from the ground-truthed DEM (discussed in Section B.2.3).

A 1-D model of the floodplain drainage channels was also developed. Channel geometry and hydraulic control structures were used to represent the 1-D channel drainage network. Due to the restricted access to the floodplain, smaller, paddock scale drains were not able to be surveyed and were therefore not included in the 1-D model but are represented in the 2-D model domain. The 1-D model extent and the associated boundaries included in the model are provided in Figure C-1. Available channel survey data was used to build the 1-D model (Section B.4). Note that where channel survey data was unavailable due to restricted access to the floodplain, channel geometry was interpolated or extrapolated from the nearest survey data, LiDAR data or inferred from an understanding of water levels throughout the swamp system (Section B.5). Improved representation of the floodplain may be achieved through additional bathymetry surveys. The 1-D network also included the major structures on the floodplain, based on the survey data summarised in Section B.3.

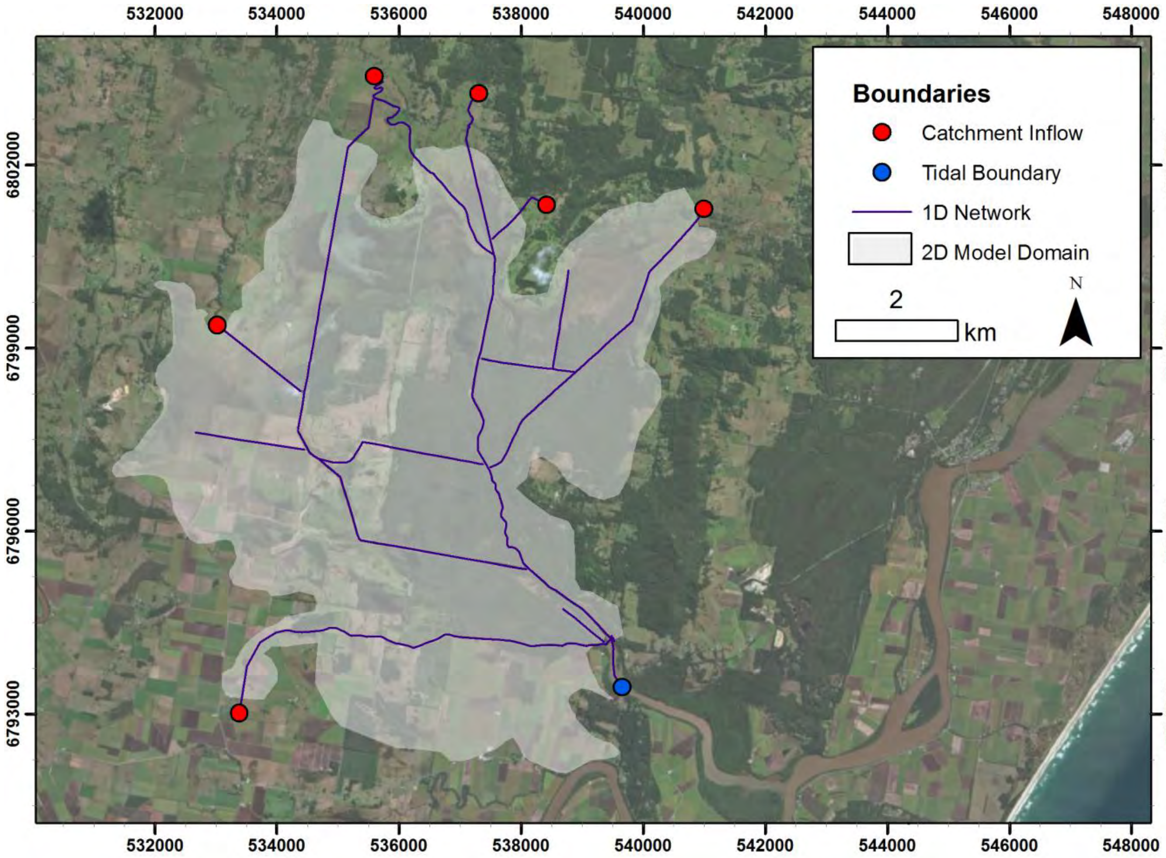


Figure C-1: Model domain

C.3 Boundary conditions

There were two types of hydrodynamic boundaries included in the Tuckean Swamp MIKE model – a downstream tidal boundary and six (6) upstream catchment inflow points which are all shown in Figure C-1. This section provides a summary of the data used for the boundary conditions of the model.

C.3.1 Downstream tidal boundary

The downstream tidal boundary was driven by the water levels observed by the downstream water level logger that WRL installed between March 2018 and February 2019.

Salinity has been included in the downstream boundary in any model scenario in which the barrage structure (including sluice gates) can allow tidal flows upstream. However, due to the variety of factors that drive salinity in the Tuckean Broadwater, the salinity boundary was set at a constant value to 100. Using this methodology, concentrations throughout the model can be reviewed as a percentage of the Tuckean Broadwater salinity (which varies depending on the flow and tidal dynamics of the wider Richmond River estuary). For example, a concentration in the model of 50 means that the water at that location has a salinity 50% lower than what occurs in the Broadwater.

C.3.2 Catchment inflows

The Tuckean Swamp has a substantial upstream catchment that flows in through each of the major drains. The catchment was delineated from LiDAR data using GIS techniques, and is shown in Figure C-2 and the contributing areas are summarised in Table C-1. As direct rainfall has not been included in the 2-D model, the area directly over Tuckean Swamp has also been sub-divided and attributed to the most appropriate inflow point.

The Marom Drain catchment includes the gauged area upstream of Marom Creek at Graham Road (Section B.7). Hourly inflows to the model were calculated by scaling the observed discharges in upper Marom Creek by the relative area of each sub-catchment. It was noted during the model calibration stage that during periods of high rainfall (e.g. October 2018), this method did not appear to be discharging sufficient volume into the model to replicate observed water level behaviour. As shown in Section B.7, the rating curve developed by WaterNSW for the gauged catchments has relatively few observations for flows greater than 110 ML/day, meaning there can be significant errors in the recorded discharges at high volumes. During wet periods, flow volumes were doubled to better reflect the volume of catchment inflow onto the floodplain during rainfall. The catchment inflow boundaries could be improved by a more comprehensive monitoring campaign that measures flows continually at each of the inflow points.

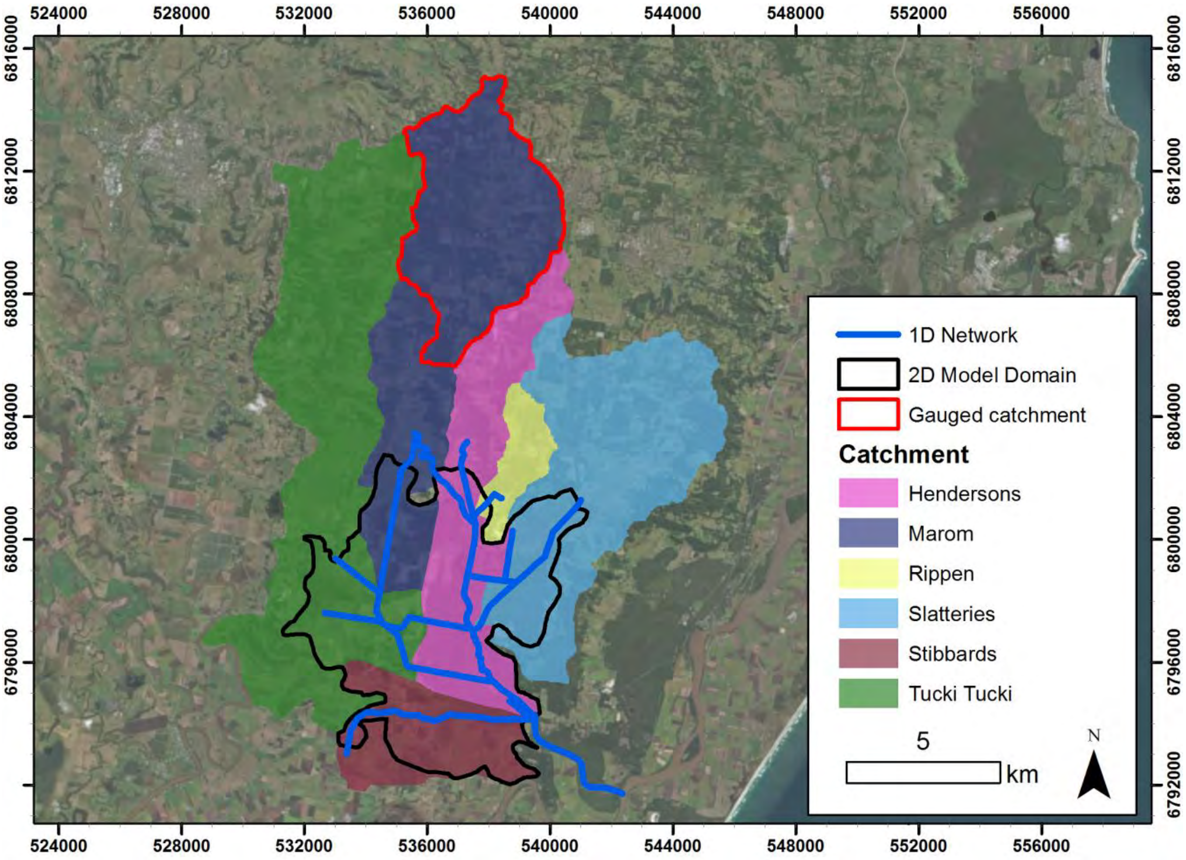


Figure C-2: Delineated catchments

Table C-1: Catchment sizes

Catchment	Area (m^2)
Gauged Catchment	30,467,300
Marom Drain	51,320,640
Hendersons Drain	29,665,500
Slatteries Drain	47,649,420
Tucki Creek	56,353,900
Rippen Drain	6,261,297
Stibbards Drain	16,381,180

C.3.3 Evaporation

Daily evaporation data was sourced from the Bureau of Meteorology from the Lismore Airport weather station. Daily evaporation was applied to every grid cell of the 2-D model domain in millimetre per day.

Appendix D – Model calibration

D.1 Preamble

This section provides the results of the hydrodynamic model calibration. Model calibration involves adjusting model parameters so that when a known set of external boundary conditions are applied, the model reproduces field measurements made within the model domain. To determine if the model is ‘fit for purpose’ and capable of testing potential management strategies, the model was run to simulate onsite conditions from the 1st October to the 15th November 2018, including a rainfall event in mid-October. Results from the model were compared to real water levels that were measured by water level loggers installed by WRL (Section B.5). The model geometry and boundary conditions were based on observations and measurements as discussed in Appendix C.

D.2 Hydrodynamic model calibration

D.2.1 Period of calibration

The hydrodynamic model was calibrated to the period from the 1st October to the 15th November 2018. This includes a seven (7) day wet period from the 11th – 18th October in which approximately 180 mm of rain fell in the area (between a 2 Every Year (EY) and 1 EY event based on local IFD (Intensity-Frequency-Duration) curves, Ball et al., 2019). The calibration period therefore includes the dry period prior to rainfall, the immediate response to rainfall and the drainage following the event. The model was run on a 5-second timestep, and the predicted (modelled) water levels were compared to the observed (recorded) water levels as shown in the following sections.

D.2.2 Internal model parameters

Model friction (Manning’s “n”) was adjusted to match the observed water levels and phasings throughout the model domain. The adopted model roughness is shown in Table D-1. A high model roughness was used in channels which were observed to be heavily choked with weeds, such as Meerschaum Vale Drain and Jumbo Drain. In most of the clear drains, a model roughness of 0.04 was adopted. As there was limited information available to calibrate floodplain flows, a low manning’s “n” of 0.03 was adopted on the floodplain (modelled in 2-D), as this will result in greater floodplain inundation and was considered conservative.

Where channel survey data was not available, cross sections were based on interpolated data and adjusted to provide acceptable replication of observed hydrodynamics. For example, observed water levels in Marom Drain (Figure D-1) showed significantly less drainage than was initially observed in the model, and appeared to have limited drainage below approximately -0.1 m AHD. This suggested that there might be a natural weir somewhere within the channel that prevents water levels draining down to what is observed in downstream Tucki Canal areas. An artificially high cross section (with an invert of -0.1 m AHD) was inserted into the model near the confluence of Marom Drain and Tucki Canal to replicate the water levels. Confirmation of such a section could be undertaken with additional field campaigns if required.

Table D-1: Model roughness

Model	Location	Chainage (m)	Manning's n
2D	Floodplain (global)	-	0.03
1D	Channels (global)	-	0.04
	Hendersons Drain	0 - 5467	0.06
	Meerschaum Vale Drain	All	0.06
	Jumbo Drain	All	0.06
	Slatteries Drain	3557 - 5619	0.08
	Slatteries Drain	0 - 3557	0.06
	Stony Island Drain	All	0.4

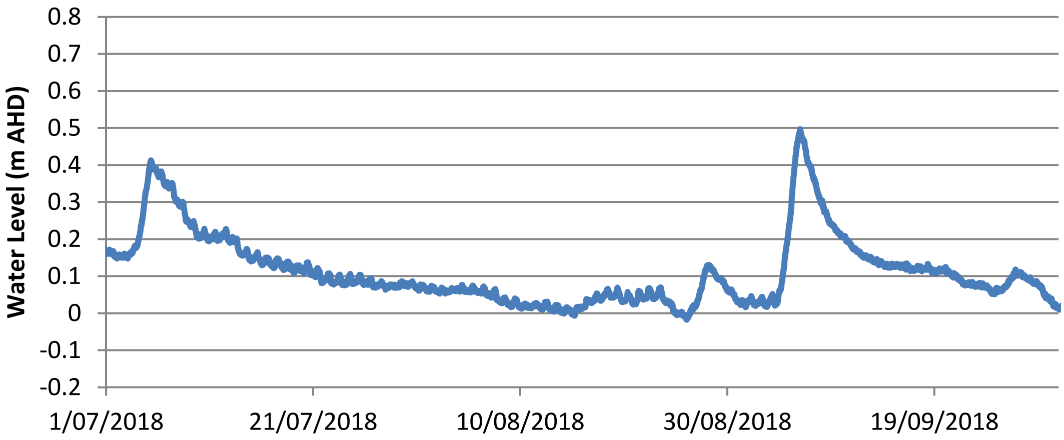


Figure D-1: Elevated observed water levels in Marom Drain

D.2.3 Water surface elevations

The hydrodynamic model was calibrated to the observed water levels at eight (8) locations across the floodplain (see Figure B-21 for locations). Note that the Tucki Canal logger failed prior to the calibration period, however tests were done in a dry period in May 2018 that showed that the model was able to adequately replicate water levels during this period.

The model was calibrated to replicate water levels throughout Hendersons Drain (Figure D-2, Figure D-3, Figure D-4 and Figure D-5). The results reproduce the “sawtooth” pattern observed upstream of the gates as catchment inflows backup behind the barrage before low tide. At each of the four monitoring locations in Hendersons drain, the peak water levels in mid-October 2018 were modelled within 6 cm of observed peak levels.

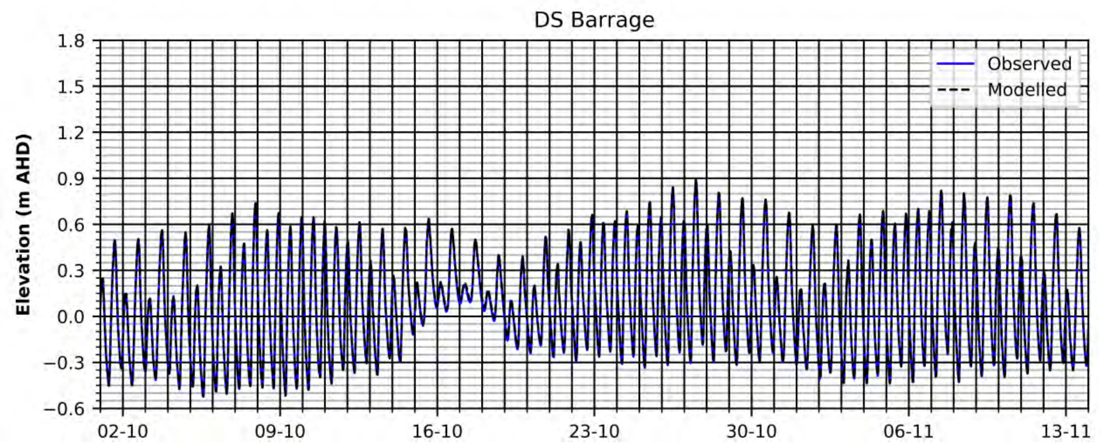


Figure D-2: Observed and modelled water levels downstream of the barrage

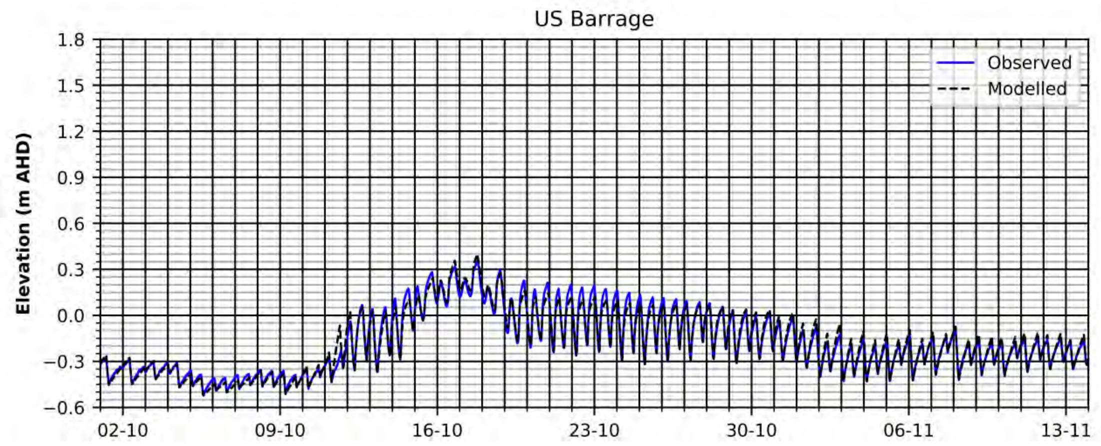


Figure D-3: Observed and modelled water levels upstream of the barrage

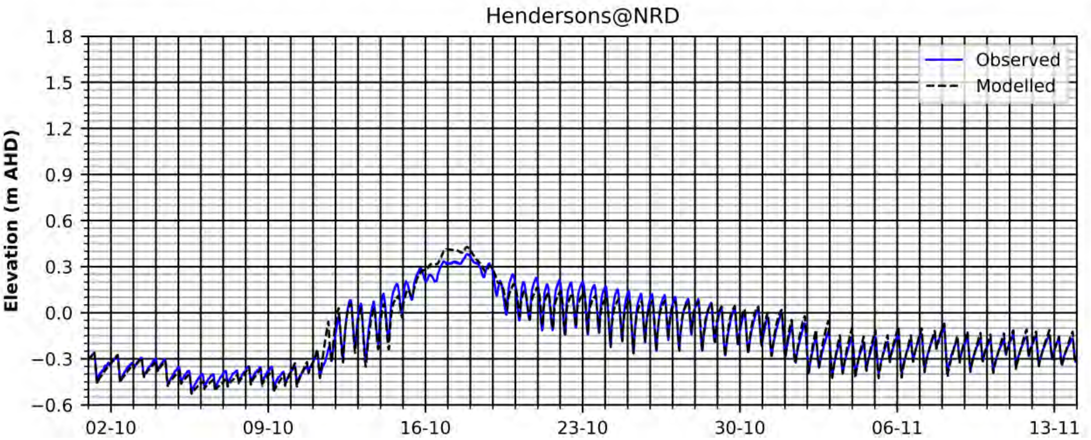


Figure D-4: Observed and modelled water levels at Hendersons Drain near Stony Island Drain

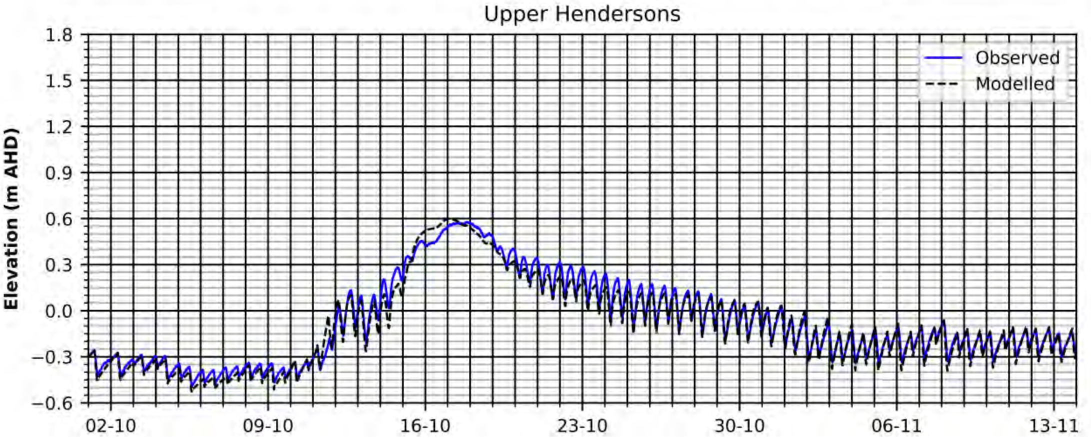


Figure D-5: Observed and modelled water levels at Hendersons Drain near Meerschaum Vale Drain

During the calibration period, the modelled Stibbards Creek location (Figure D-6) drains more efficiently than was observed in the drain (to approximately the same level as upstream of the barrage). However, this poor drainage of Stibbards Creek (where water levels remain elevated compared to the low tide levels in the Tuckean Broadwater) only started to occur after September 2018. This suggests that there may have been temporary blockages in the channel that had not been in place when the survey was undertaken in March 2018. Assuming any blockage is temporary, the physical geometry of the model was not changed, and the model results were considered acceptable.

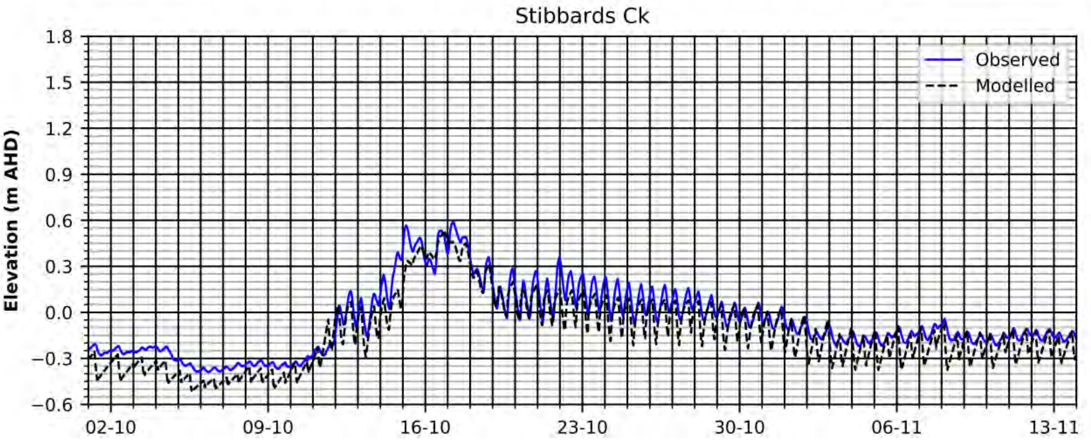


Figure D-6: Observed and modelled water levels on Stibbards Creek

The model replicates observed water levels in Stony Island Drain (Figure D-7) during dry periods and the peak water level during the October rain event was within 15 cm of the observed levels. However, the initial water level rise in the model during the wet period is much slower than what was observed. Stony Island Drain was observed to be densely vegetated by water lilies throughout the field campaigns between March 2018 and February 2019, which is accounted for in the model through a high Manning's "n". However, numerous fallen trees were also observed downstream of the monitoring location that may block the channel in rain events such as the one observed in October 2018. These blockages are not represented in the model but may have impacted the rate at which the water levels rose during this event. In addition, the connection between Stony Island Drain and Tucki Canal is still uncertain based on the available data. The drains appear to be poorly connected in aerial imagery; however, it is possible that Stony Island Drain is better connected to Tucki Canal during high water levels than is shown in the model.

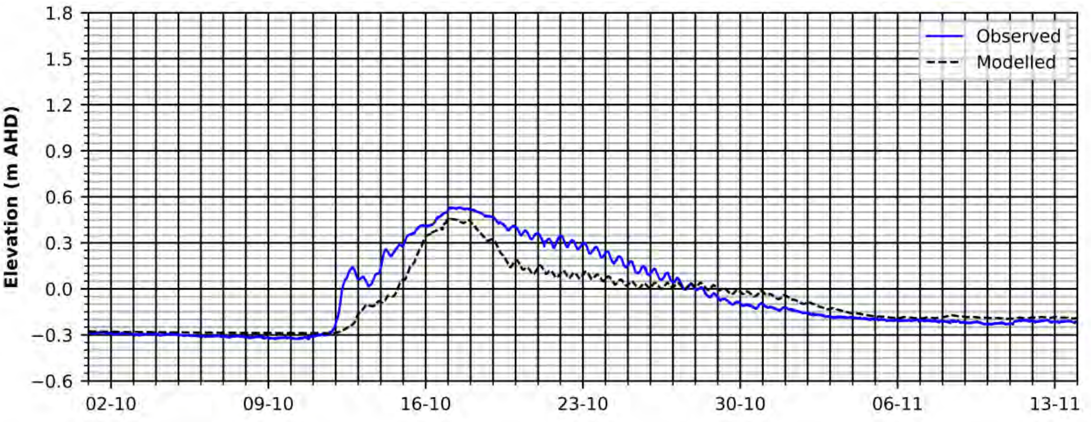


Figure D-7: Observed and modelled water levels at Stony Island Drain

Water levels in Slatteries Drain (Figure D-8) acceptably reproduce observed water levels during dry periods. The rate of filling and drainage during and after rainfall is consistent with the observations, although the peak water level in the model is lower than the observations. During field investigations, WRL surveyed a pair of culverts in Slatteries Drain, just downstream of the confluence with Meerschaum Vale Drain (structure 32 in Table B-1). These culverts connect the main part of Slatteries Drain to the relic drain that flows through the Tuckean Nature Reserve to the south. Both culverts were partially blocked at the time of the survey and it appeared that most flow is conveyed through Meerschaum Vale Drain to west. The culverts have been included in the model, however it is difficult to assess the conveyance of these structures due to the degree of blockage. Limited conveyance through these culverts may have resulted in higher water levels than predicted than the model.

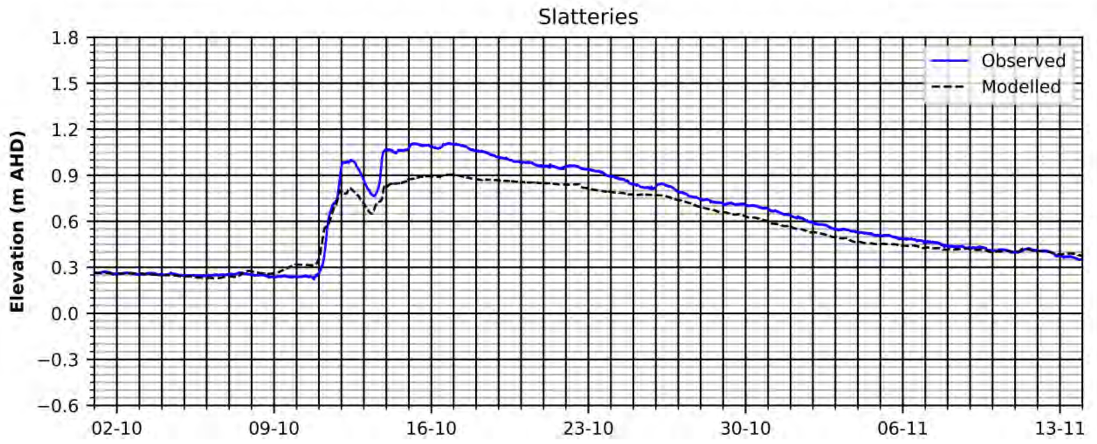


Figure D-8: Observed and modelled water levels at Slatteries Drain

During initial model runs, the water levels in Marom Drain were draining well beyond the levels observed during dry periods, as shown in Figure D-9. There is uncertainty in the channel bathymetry throughout this section of the model near the confluence of Tucki Tucki Creek, Tucki Canal, Stony Island Drain and Marom Drain due to limited data availability. However, the water levels observed in Marom Drain showed that the levels largely did not drain below -0.1 m AHD, even during extended dry periods. This indicates that there may be a weir (natural or otherwise) that holds water levels above -0.1 m AHD. While this was not physically observed, a high cross section, with an invert of -0.1 m AHD, was included in Marom Drain downstream of where the water level logger was installed (but upstream of the confluence with Stony Island Drain). This was to simulate a natural weir that may be situated somewhere in this stretch. As shown in Figure D-9, the adjusted model is able to replicate observed water levels during dry periods at Marom Drain.

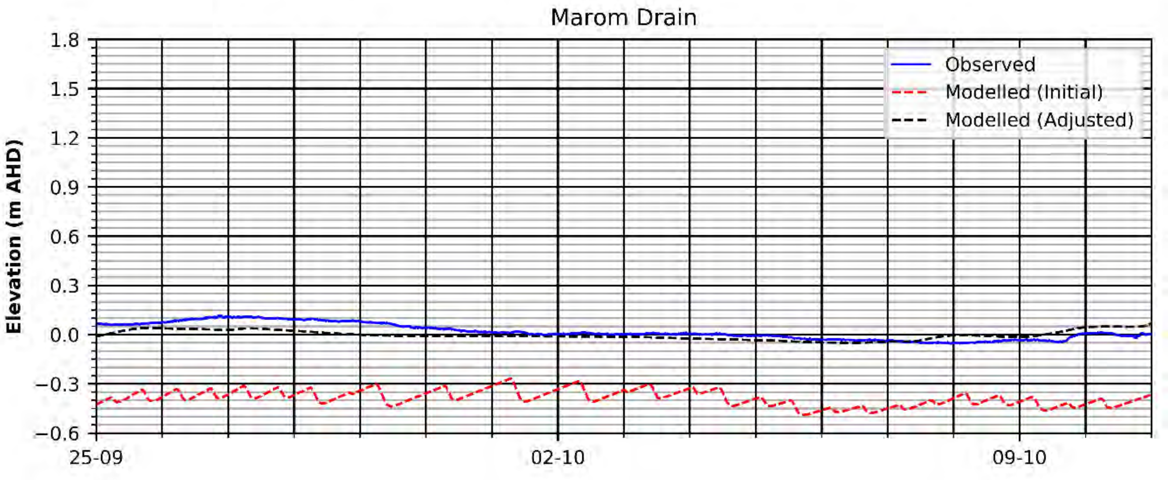


Figure D-9: Over drainage in the model at Marom Drain

Despite the changes to the model, Figure D-10 shows that the model seems to underestimate water levels during the rainfall event in October 2018. However, the observed water levels during the event (up to 1.2 m AHD) appeared to be unusually high. Based on WRL's observations, there are numerous "blow outs" (gaps) in the levee along Marom Drain, which would mean that the floodplain is well connected to drain above an elevation of approximately 0.7 m AHD. It is unlikely that this section of the floodplain is widely inundated in a 2 EY event. It is possible that the water level logger malfunctioned during the event and recorded high water levels than existed (possibly due to growths in the pressure sensor) and water levels from the monitoring station over-state the levels than occurred.

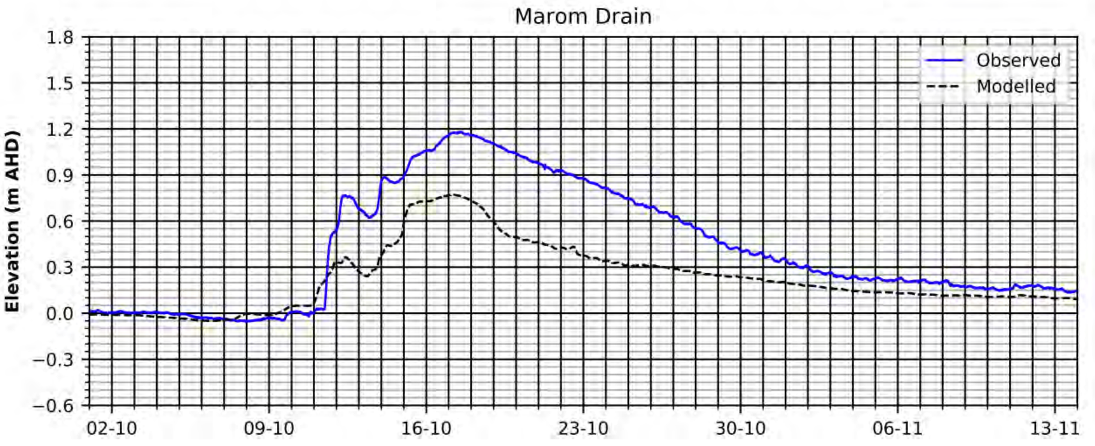


Figure D-10: Observed and modelled water levels at Marom Drain

It is acknowledged that the available data is limited around the confluence of Tucki Canal and Marom Drain. As a result, the ability of the model to replicate water levels in this region is more limited than areas where more complete information exists. The Marom Drain section of the model could be improved if further survey data was made available.

Overall, the model is able to adequately replicate observed water levels throughout the Tuckean floodplain during dry periods. In general, the filling and draining of the floodplain during small to medium catchment events is sufficiently reproduced by the model, although there is still uncertainty in the water levels in the western section of the drainage network where the available data (bathymetry, drain connections and levee heights) is more limited. The model is considered fit for purpose for understanding the relative impacts of drainage management strategies on water levels and floodplain inundation throughout the study area during dry periods and small to medium catchment events.

D.3 Salinity advection-dispersion modelling

Advection and dispersion are the mechanism that allow salinity transport within a water body. Advection is the transport due to physical displacement of water (e.g. in the direction of flow), while dispersion is transport through diffusive processes (i.e. spreading). Dispersion includes both molecular diffusion and turbulent eddy diffusion, although turbulent diffusion is typically orders of magnitude larger than molecular diffusion in river systems.

D.3.1 Period of calibration

The dispersion coefficient (D, m^2/s) is the main parameter that can be varied in an advection-dispersion model that impacts the way salinity moves through the system (assuming the hydrodynamics and advection are correct). Previous modelling on the Richmond River (Peirson et al., 1999) used dispersion coefficients ranging from 4.5 m^2/s in the headwaters to 42 m^2/s near the mouth. There is limited available information to calibrate dispersion within the Tuckean drainage system, with the only two (2) salinity measurements available immediately downstream of the barrage (WRL data) and approximately 500 m upstream of the barrage (Rous County Council). In addition to the limited locations, salinity is frequently low in the Tuckean Broadwater and the sluice gates (which facilitate saltwater inflows upstream of the barrage) are often closed.

However, there is a period of time in January – mid February 2019 in which salinity increased from near fresh in the Broadwater to around 60% of seawater by the middle February, and one of the sluice gates was continually open 150 mm. To determine an estimate of the dispersion coefficient, 1-D only models were run with dispersion coefficients ranging from 1 to 50 upstream of the Barrage.

The observed salinity downstream of the barrage was used as the boundary condition. Figure D-11 shows the results for the D = 5 m^2/s, which was adopted for all further modelling. A uniform dispersion coefficient was adopted throughout the 1-D model domain, except for in the Tuckean Broadwater, which was assumed to be 40 m^2/s to minimise the impact of the boundary condition location.

D.3.2 Modelling approach

There is limited available data to use as a boundary condition for this model in terms of salinity. While the observed salinity could be used, it is important that the model can replicate that greatest anticipated infiltration of saltwater, which will only occur when salinity in the Tuckean Broadwater is high. Instead of using a varying salinity boundary condition, a constant boundary condition concentration of 100 was implemented in the Tuckean Broadwater. This way, salinity modelled upstream of the barrage can be interpreted as a percentage of the salinity in the Tuckean Broadwater. For example, a modelled salinity of 50 implies that the salinity at that location is 50% of water observed in the Tuckean Broadwater.

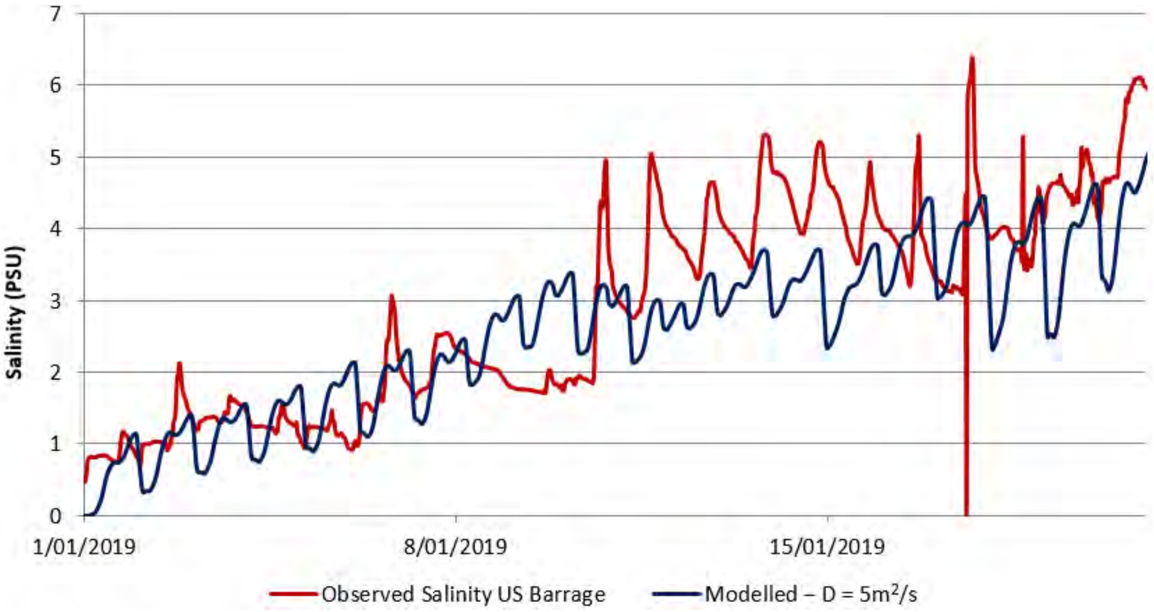


Figure D-11: Salinity test - 1 D model only