Coastal Floodplain Prioritisation Study – Background and Methodology

WRL TR 2020/32, May 2023

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UNSW Water Research Laboratory

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Executive summary

The Marine Estate Management Strategy (MEMS) (Marine Estate Management Authority, 2018) is a state wide strategy to protect and manage waterways, coastlines and estuaries over the ten year period 2018 – 2028. Initiative 1 of the Strategy is focused on improving water quality. Major sources of poor water quality across the marine estate include acid sulfate soil (ASS) and blackwater runoff into our estuaries. Over the past 25+ years, efforts to manage and remediate ASS and blackwater drainage have largely been piecemeal projects lacking a strategic and evidence-based approach. To overcome this limitation and better target remediation efforts, MEMS has initiated the Coastal Floodplain Prioritisation Study, based on a method detailed in Glamore and Rayner (2014) and adapted to integrate the MEMS approach for achieving environmental outcomes that consider social, cultural and economic benefits, to prioritise floodplain subcatchments in seven (7) coastal floodplains in NSW.

Since the turn of the 20th century, coastal floodplains in NSW have undergone extensive development, including the construction of significant artificial drainage infrastructure for flood mitigation and to improve agricultural productivity. However, Tulau (2011) notes that despite the often misleading use of terminology, the 1950-70s ‘flood mitigation’ schemes were overwhelmingly swamp drainage schemes. Artificial drainage of low-lying coastal floodplains has had significant impacts, including the oxidation and drainage of acid sulfate soils. Floodplain drainage has also enabled non-water tolerant vegetation to establish in historical wetland areas and, when combined with efficient drainage, resulted in the increased frequency and magnitude of low oxygen ‘blackwater’ runoff events.

Acid sulfate soil drainage and blackwater runoff have significant impacts to estuarine ecological health of the marine estate, with discharge events resulting in fish kills, degraded aquatic habitats, and reduced wetland values. Diffuse agricultural runoff has been identified during a threat and risk assessment (TARA) as one of the priority threats to environmental assets as well as social, cultural and economic benefits within the marine estate (Fletcher and Fisk, 2017). Increasingly, the benefits of improving the management of floodplain areas that discharge acidic water and generate low oxygen blackwater are being realised. Improvements in floodplain management have resulted in a range of benefits from improved agricultural productivity to improved water quality, establishment of wetland habitats, greater ecosystem services, and recovery of degraded estuarine environments. Understanding the areas that contribute the most to the generation of acidic discharge or blackwater is an important step to guide future investment and overall management of coastal floodplains in NSW.

The objectives of this study were to develop and apply multi-criteria prioritisation methodologies to rank drainage subcatchments within NSW coastal floodplains by their contribution to acidic discharge and blackwater generation and discharge, to determine the subsequent risks to the estuarine waterways, and to guide the future management of coastal floodplains. The approach enables evidence-based identification of high-priority subcatchments within coastal floodplain systems for targeted remediation and restoration. The outcomes of the multi-criteria assessment, together with the potential management options and supporting information, provide an objective prioritised list of floodplain subcatchments that pose a risk to the health of the marine estate, whilst also summarising key information and floodplain datasets. The seven (7) coastal floodplains prioritised as a part of the study are (Figure ES-1):

- Tweed River floodplain;
- Richmond River floodplain;
- Clarence River floodplain;
- Macleay River floodplain;
- Hastings River floodplain;
- Manning River floodplain; and
- Shoalhaven River floodplain.

The study approach features two (2) primary prioritisation methods that assess and rank floodplain subcatchments based on the risk of:

1. Discharge from acid sulfate soils; and
2. Generation of low oxygen 'blackwater'.

These methods utilise multi-criteria analyses to assess the risk of poor water quality from floodplain subcatchments and rank them relative to their contribution to these key water quality issues. Figure ES-2 provides an overview of the study approach. A summary of the factors influencing the risk of acidic discharge and blackwater runoff is outlined in Figure ES-3.

The purpose of this prioritisation is to establish an evidence-based list of high priority subcatchments to be targeted for on-ground management actions or remediation. This prioritised list of floodplain subcatchments identifies sources of poor water quality within each floodplain and outlines potential management strategies to mitigate water quality impacts. Conversely, the study approach also identifies low risk/priority floodplain areas with respect to the generation of poor water quality from acid discharge and blackwater runoff. The individual floodplain assessments and prioritisations provide subcatchment management options and data summaries to guide land managers and decision makers in implementing on-ground actions on both floodplain and paddock scales. It should be noted that potential management options are supplied as a guide for potential future floodplain management, and will require land managers to determine the scale at which they are implemented. Detailed site-specific investigations should be completed to assess the feasibility of potential management options.

There are a number of management strategies that can be employed to address acid and blackwater discharges from coastal floodplains. Some of these strategies can be implemented immediately without significant impacts to existing land uses, while others require substantial changes to existing land uses to create effective improvement in water quality outcomes. A range of site-specific and administrative constraints were identified to not influence the physical generation of acid and blackwater but influence implementation of potential management strategies. All physical and administrative factors relating to each floodplain subcatchment were summarised in individual subcatchment management options. To develop on ground management options for each subcatchment, the following factors were considered:

- Priority ranking for acidic water and blackwater discharges;
- Proximity to sensitivity receivers;

- Condition of existing floodplain infrastructure;
- Current and future land uses and land values;
- The relative costs and benefits of remediating the floodplain;
- Predicted vulnerability to sea level rise; and
- Types of waterways (classified as natural waterbody watercourse, artificial waterbody, watercourse, and connector watercourse)

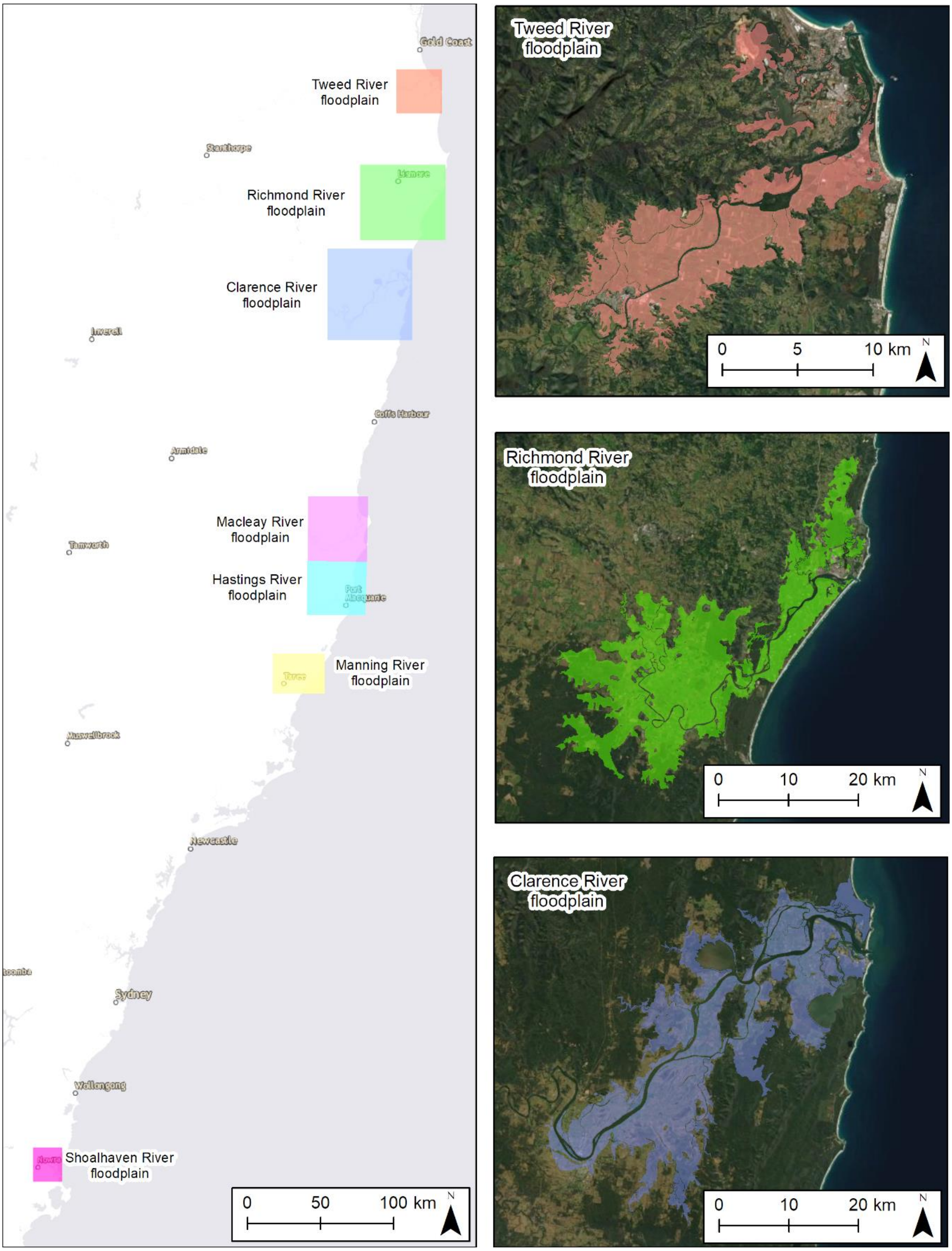

Figure ES-1: Study areas (1 of 2)

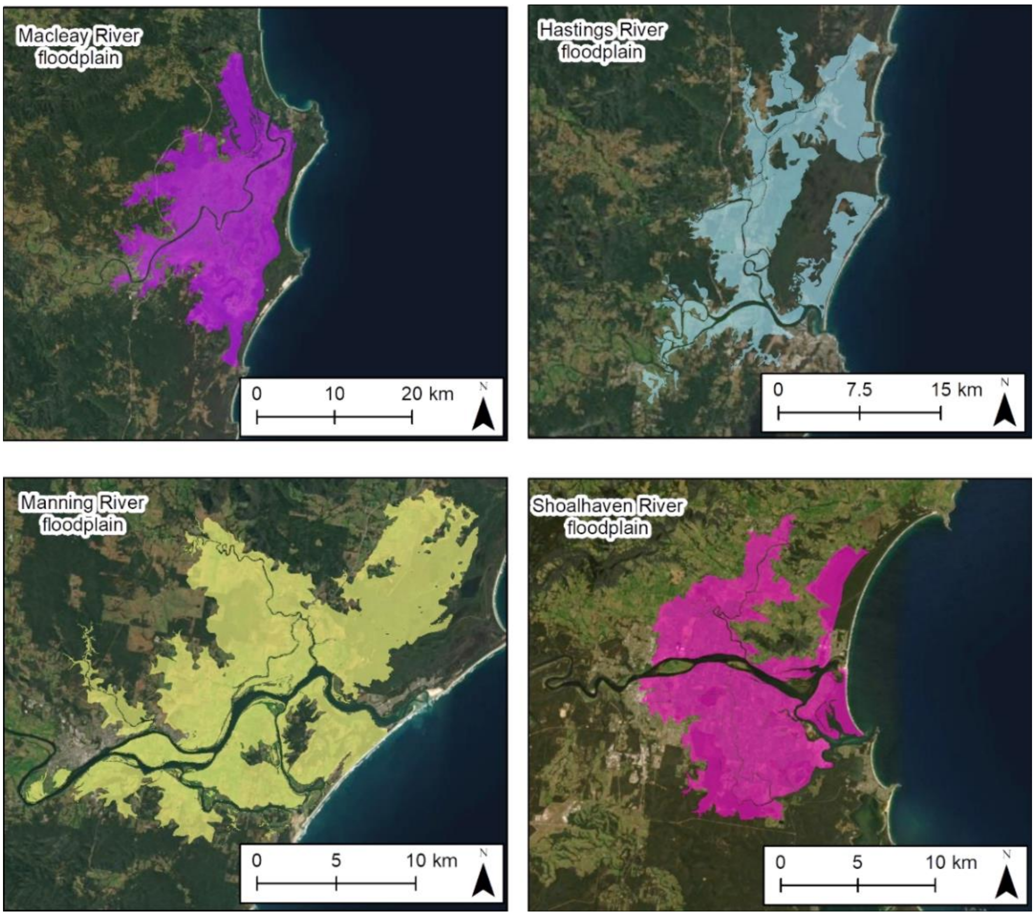

Figure ES-1: (cont'd): Study areas (2 of 2)

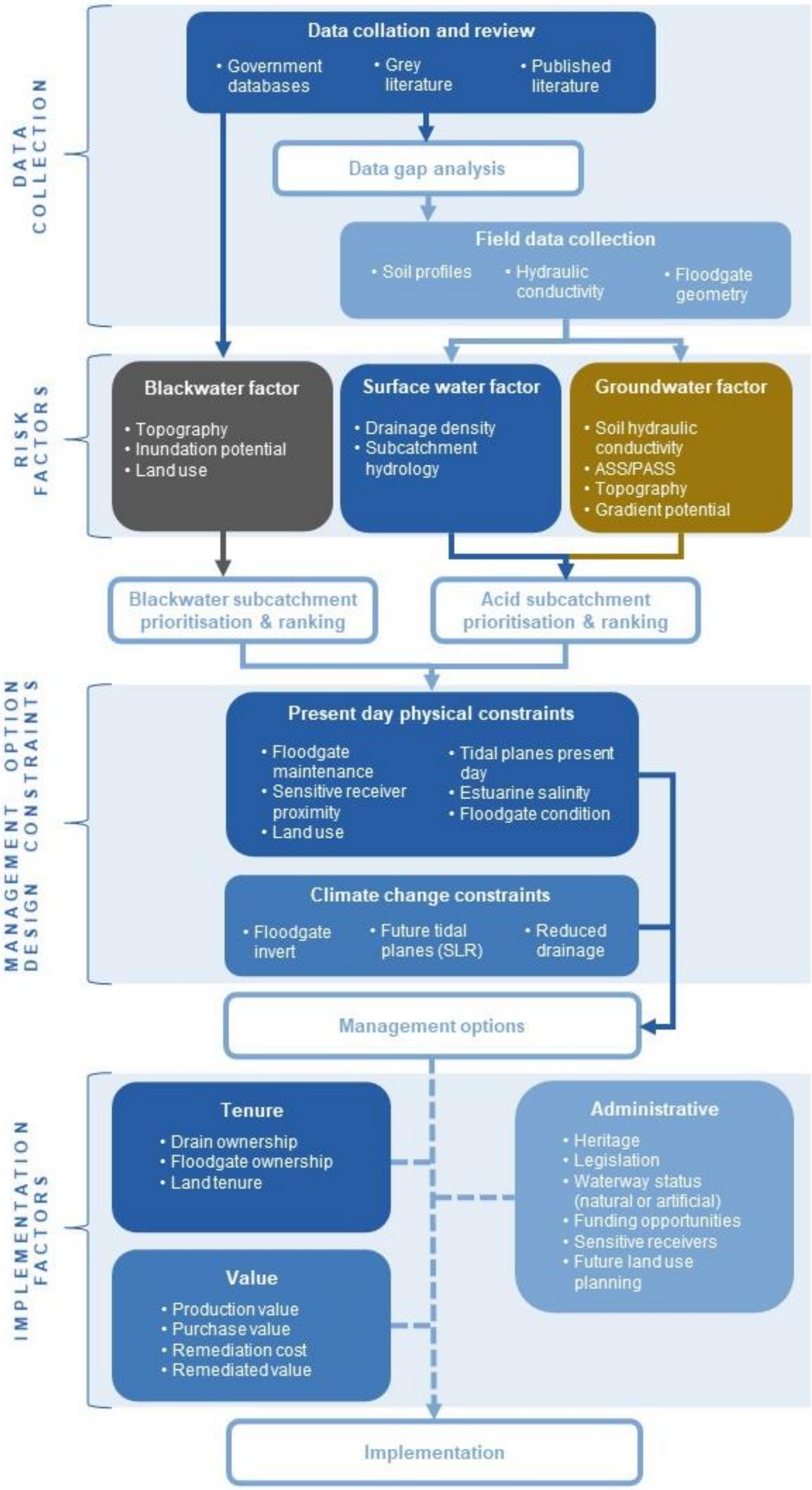

Figure ES-2: Study approach overview

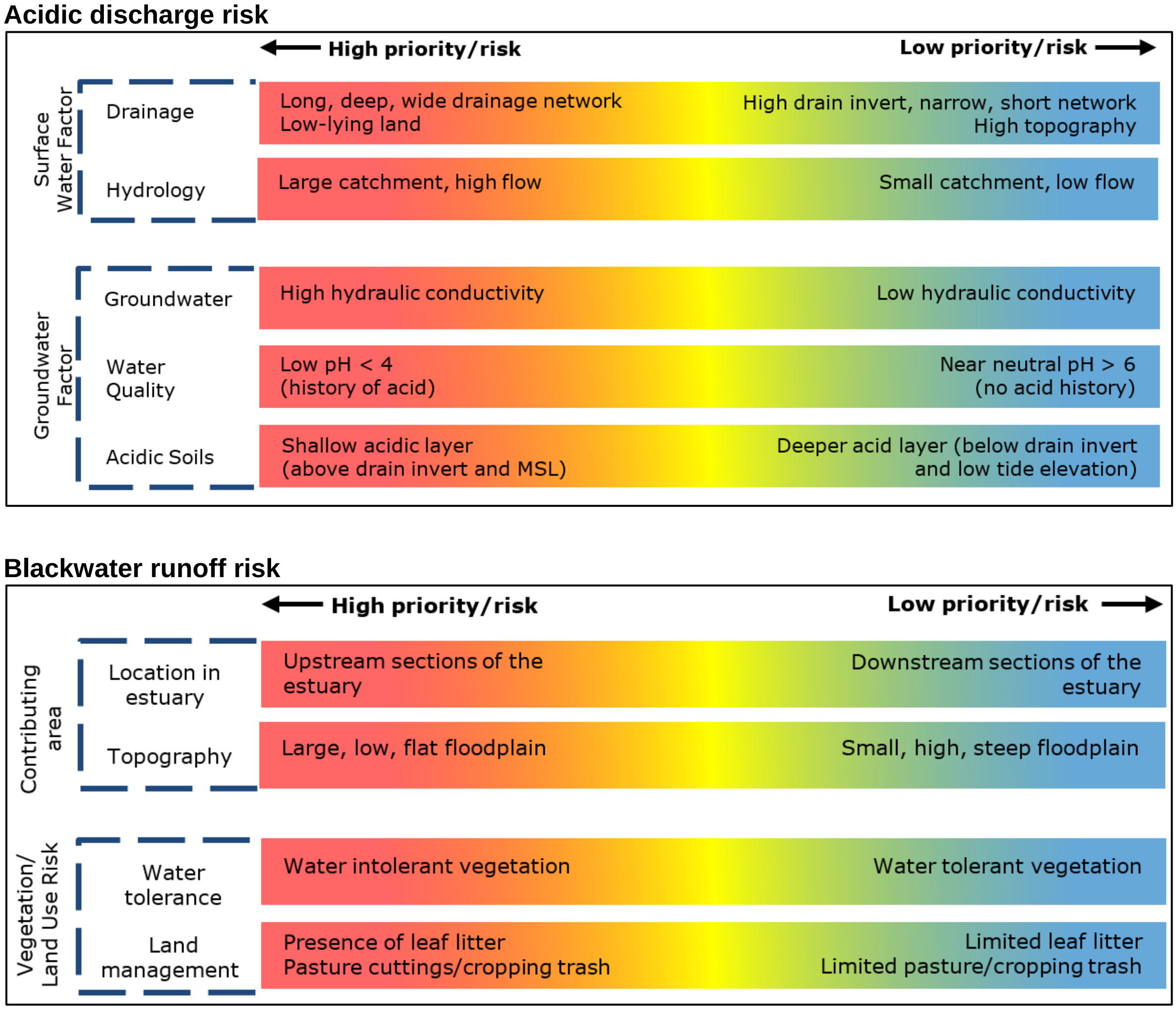

Figure ES-3: Factors influencing acid sulfate soil discharge and blackwater runoff from NSW coastal floodplain subcatchments

A range of additional analyses and assessments were undertaken to complete the study, including:

- Development and calibration of hydrodynamic numerical models of each study estuary to facilitate detailed assessment of floodplain vulnerability to sea level rise;
- Collation of data relating to existing floodplain land use, productivity, and land value; and
- Multi-criteria assessment to determine waterway classification.

The results from this study, including the management options, require detailed stakeholder consultation and training prior to implementation of on-ground works. Several of the recommended strategies are different to existing land practices, however detailed engineering plans or changes to land tenure would result in win-win outcomes. Training for landholders in acid sulfate soil management and remediation techniques would be beneficial and may assist in developing improved long-term outcomes across all coastal floodplains.

This report provides an overview of the project background and details the methodologies for prioritising coastal floodplain subcatchments with respect to acid discharge and blackwater generation potential. A summary of the approach used to assess floodplain drainage vulnerability under sea level rise is also provided, coupled with the approach used to assess floodplain waterway type. The application of these methods to assess and prioritise the seven (7) studied NSW coastal floodplains is detailed in a series of individual reports, one for each assessed floodplain.

This study was funded by the NSW Government under the NSW Marine Estate Management Strategy (MEMS). The ten-year Strategy was developed by the NSW Marine Estate Management Authority (MEMA) to coordinate the management of the marine estate. The study was commissioned by NSW Department of Primary Industries - Fisheries under the MEMS Stage 1 and delivered by the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney.

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Glossary of terms

Acid	A substance that has a pH less than 7 (a pH of 7 being neutral i.e. neither acidic nor alkaline). Specifically, an acid has more free hydrogen ions (H^+) than hydroxide ions (OH^-).
Acid export	The mass of acid discharged from a system (e.g. a drain or floodplain). Acid can be exported via two common mechanisms, by either a hydraulic gradient (water level or pressure head difference along a channel or pipeline) or a concentration gradient (natural mixing through a water body from a higher concentration to a lower concentration).
Acid sulfate soil (ASS)	Sediments in which iron sulfides (mainly pyrite) accumulate below the groundwater table in anaerobic conditions. The exposure of these sediments to air enables the oxidation of pyrite/sulfides to produce sulfuric acid. Oxidised acid sulfate soils are referred to as actual acid sulfate soils (AASS), unoxidised acid sulfate soils are referred to as potential acid sulfate soils (PASS).
Alkali	A substance that has a pH greater than 7 (a pH of 7 being neutral i.e. neither acidic nor alkaline). Specifically, an alkali has more free hydroxide ions (OH^-) than hydrogen ions (H^+).
Anaerobic conditions	The absence of atmospheric oxygen (often required for certain biological processes).
Annual exceedance probability (AEP)	The probability of a flood or rainfall event of a predetermined size or larger occurring in a one-year period.
Antecedent conditions	The moisture stored within a catchment prior to a rainfall event.
Australian Height Datum (AHD)	A datum surface for Australia used for measuring elevation. The zero metres AHD height at 30 tide gauges across Australia corresponds to mean sea level as measured from 1966 to 1968.
Auto-tidal gate	A mechanism whereby a small opening on a floodgate flap is allowed to automatically let a controlled volume of water upstream of a floodgate as the water level increases on the downstream side. This can be mechanical or power driven. As the water rises to a designed level (on the downstream side) the mechanism on the gate shuts, closing the small opening on the floodgate flap. This mechanism allows for controlled flushing of waterbodies upstream of a floodgate in addition to fish passage.
Backwater	Water held up in its course (being controlled by downstream conditions) as compared with its normal or natural condition of flow.
Baseflow	Flow of a waterway sustained between periods of rainfall by groundwater discharge.
Bathymetry	The measurement of depth of water from the surface to the bottom a waterbody.
Blackwater	Deoxygenated water usually dark in colour and resulting from decomposing organic matter.
Buoyancy tidal gate	A buoyancy tidal gate (often referred to as a fish gate) is a mechanism whereby a small opening on a floodgate flap is allowed to let a controlled volume of water upstream of a floodgate as the water level increases on the downstream side. As the water rises to a designed level (on the downstream side) the buoyancy mechanism on the gate shuts, closing the small opening on the floodgate flap. This mechanism allows for controlled flushing of waterbodies upstream of a floodgate in addition to fish passage.
Catchment	The land area upstream of a particular point of interest into which precipitation drains. Each waterway has its own individual catchment. Also called a "watershed."
Climate change	A change in climate patterns as a result of increases in atmospheric carbon dioxide.
Connector watercourse	A waterway with either natural or artificial sections that provides a connection between two natural waterbodies.

Crest	The crest is the elevation at which weirs, levees or drop board structures are designed to overtop.
Culvert	Culverts are structures that allow water to move between two open waterbodies and bypass an obstruction such as a levee or road. Culverts have two open ends which do not inhibit flow. However, they can also have separate mechanisms such as floodgates or sluice gates attached to them to further control the flow of water.
Digital elevation model (DEM)	A 3D computer model of land surface elevation. A DEM is composed of a grid of cells which each represent an elevation value. The size of individual grid cells (e.g. 1 m times 1 m or 5 m times 5 m) is one measure of the accuracy of a DEM.
Discharge	Flow rate measured by volume per unit time (usually in cubic metres per second).
Dissolved organic carbon (DOC)	Organically bound carbon present in water that can pass through a membrane filter with a 0.45µm pore size.
Dissolved oxygen (DO)	Atmospheric oxygen that dissolves in water. The solubility of oxygen depends upon temperature and salinity.
Downstream/ upstream	Downstream is the location in a channel that is closest to the ocean. Upstream is the location in a channel that is furthest from the ocean.
Drop board	Drop boards are frames built across a waterway which enable the manipulation of flow and water levels by the insertion of 'boards' into specifically designed slots to act as a barrier to water movement. Drop boards are similar to weirs in that they only allow water to flow over the top of them. Unlike weirs, drop boards are adjustable in height. Multiple boards with different heights can be used to adjust and set the weir level. Drop boards can be fitted to culverts or can be standalone structures.
Drought	A prolonged period of reduced or low precipitation resulting in a shortage of water.
Electrical conductivity (EC)	A measure of dissolved salt in water in the units of micro Siemens per centimetre (µS/cm) usually at a temperature of 25ºC.
Estuary	A semi-enclosed waterbody where fresh water from catchment runoff and saltwater from the ocean mix.
Evaporation	The process of liquid water on the land surface becoming water vapour in the atmosphere.
Evapotranspiration	The sum of evaporation and transpiration.
Exceedance per year (EY)	The likelihood that a flood or rainfall event of a predetermined size will occur a certain number of times within any one-year period.
Flood	High flow of water within a waterway that results in the overtopping of natural or artificial banks (or levees) of a waterbody and inundation of usually dry land.
Floodgate/ floodgate flap	A plate that is hinged on its top edge to cover the outlet of a culvert. The flap is positioned so that it only opens when the water level on the upstream (floodplain side) is higher that the level on the downstream (river side) of the culvert, thereby only allowing water to flow in the downstream direction effectively draining the floodplain. Floodgates typically open and close with fluctuating tidal water levels in the river. It is common for floodgates to have rubber seals to prevent leaking. Floodgate flaps can be made of many materials such as aluminium, plastic, fibre glass or wood.
Floodplain	The area of land adjacent to a waterbody that is often relatively flat and usually dry unless exposed to water as occurs during a flood.
Freshwater	Water that contains less than 1,000 milligrams per litre (mg/L) of dissolved solids.
Gate	A term used to describe the part of either a floodgate or sluice gate flow control structure that controls water movement.
Groundwater	Water under the ground surface within soil and rock formations that are fully saturated.
Groundwater table	The upper surface of soil or rock formations that is fully saturated by groundwater.
Headwall	The concrete structure surrounding and supporting a culvert. Floodgate flaps or other mechanisms are usually mounted to the headwall.

Hydraulic gradient	The difference in pressure or elevation of water over a distance. The hydraulic gradient results in the flow of water (from high elevation or pressure to low elevation or pressure).
Hydrodynamics	The branch of science concerned with the movement of, and forces acting on or exerted by fluids.
Hydrodynamic model	A numerical representation of the movement of water through a system.
Hydrograph	A graph showing the level, discharge, velocity, or other property of water with respect to time.
Hydrology	The branch of science concerned with the movement and quality of water in relation to land.
Impermeable layer	A layer of solid material, such as rock or clay, which does not allow water to pass through.
Invert	The elevation of the lowest internal point of a culvert.
Leaching	The process by which soluble materials in the soil such as salts, nutrients, pesticide chemicals or contaminants are dissolved and carried away by water.
Left bank/right bank	The side of a waterway when looking in the downstream direction (i.e. toward the ocean).
LEP	Local Environmental Plan - LEPs are planning instruments that guide planning decisions for local government areas. They do this through zoning and development controls, which provide a framework for the way land can be used. LEPs are the main planning tool to shape the future of communities and also ensure local development is completed appropriately.
LGA	Local Government Area.
Levee	An embankment that prevents or reduces flow from a waterway to the floodplain. Levees can be naturally formed as river banks or manmade for the purpose of flood mitigation or to prevent inundation of low-lying land.
Lidar	Light detection and ranging technology that can be used to measure ground surface elevations and create DEMs.
Marine estate	Tidal rivers and estuaries, the shoreline, submerged lands, offshore islands, and the waters of the coast up to three nautical miles offshore.
Management area	A subset or smaller area of a subcatchment often delineated based on floodplain tenure and ownership in addition to floodplain hydrological and geomorphological characteristics. Generally, a management area is of small enough scale that implementation of on-ground works to address water quality issues can be completed.
MBO	Mono-sulfidic black ooze – deposits in drainage channels created by iron and sulphur minerals (pyrite) within acid sulfate soils which, when mobilised, can remove oxygen from the water through a chemical reaction.
Obvert	The elevation of the highest internal point of a culvert.
Organic matter	Substances made by living organisms and based on carbon compounds.
Peak flow	The maximum instantaneous discharge of a waterway at a given location.
pH	A measure of the acidity or alkalinity of water. Water with a pH of 7 is neutral; lower pH levels indicate increasing acidity, while pH levels higher than 7 indicate increasing alkalinity
Pipe	A pipe is a circular culvert. Pipes can be made of many materials such as concrete, PVC or fibre glass.
Precipitation	Water that falls on land surfaces and open waterbodies as rain, sleet, snow, hail or drizzle.
River	A major watercourse carrying water to another river, a lake or the ocean.
Runoff	Excess rainfall that becomes streamflow.
Salinity	The total mass of dissolved salts per unit mass of water. Seawater has a salinity of about 35 g/kg or 35 parts per thousand (ppt).
Sediment	Material suspended in water or deposited from suspension.
Seepage	The infiltration of water from surface waterbodies to the groundwater.

Sluice/sluice gate	A gate that operates by sliding vertically to control water flowing through or past a restriction point. Sluice gates act so that water flows underneath the 'sluice' or the sliding section of the gate. A sluice gate can be set to different levels to control the volume of water that flows. There are many different designs for sluice gates.
Soil profile	A vertical section of soil (from the ground surface downwards) where features such as layers (soil horizons), texture, structure, consistency, colour and other characteristics of the soil can be observed.
Streamflow	The flow of water in open waterbodies (such as streams, rivers or channels).
Subcatchment	A section of the floodplain that is geologically and hydrologically similar but can also be delineated based on floodplain management objectives.
Surface water	Water that flows or is stored on the Earth's surface.
Tidal exchange	The proportion of water that is flushed away and replenished with new ocean water each tidal cycle.
Tidal limit	The maximum distance upstream of a waterway where the influence of tidal variation in water levels is observed.
Tidal planes	Reference elevations that define regular tide elevations, including: MHWS - Mean High Water Springs MHW - Mean High Water MSL - Mean Sea Level MLW - Mean Low Water MLWS - Mean Low Water Springs
Tidal prism	The volume of water that flows in and out of an estuary during a tidal cycle (e.g. high tide to low tide).
Transpiration	The release of water vapour from plants to the atmosphere.
Tributary	A smaller river or stream that flows into a larger waterbody.
Water table	The surface of water whether it is under or above ground.
Waterbody	Either: • An artificial body of water, including any constructed waterway, canal, inlet, bay, channel, dam, pond, lake or artificial wetland, but does not include a dry detention basin or other stormwater management construction that is only intended to hold water intermittently; or • A natural body of water, whether perennial or intermittent, fresh, brackish or saline, the course of which may have been artificially modified or diverted onto a new course, and includes a river, creek, stream, lake, lagoon, natural wetland, estuary, bay, inlet or tidal waters (including the sea).
Watercourse	Any river, creek, stream or chain of ponds, whether artificially modified or not, in which water usually flows, either continuously or intermittently, in a defined bed or channel, but does not include a waterbody (artificial).
Waterway	The whole or any part of a watercourse, wetland, waterbody (artificial) or waterbody (natural).
Weir	Weirs are permanent structures that block a channel and only allow water to flow over the top of them.
Winch	A mechanism used to open floodgate flaps or sluice gates. The winch system usually involves pulling the gates open via chains or cables.

1 Introduction

1.1 Preamble

The NSW Marine Estate Management Strategy (MEMS) (Marine Estate Management Authority, 2018) is a state wide strategy to protect and manage waterways, coastlines and estuaries over the ten year period 2018 – 2028. Initiative 1 of the Strategy is focused on improving water quality. Major sources of poor water quality across the marine estate include acid sulfate soil (ASS) and low oxygen blackwater runoff into our estuaries. Over the past 25+ years, significant efforts have been made by local councils and landholders to remediate ASS and blackwater drainage from coastal floodplains, however this has been limited by insufficient funding, resources, and community willingness. To better target remediation efforts and land management decisions on coastal floodplains, the Department of Primary Industries (DPI) – Fisheries commissioned the Coastal Floodplain Prioritisation Study. This study is based on a method detailed in Glamore and Rayner (2014) and adapted to integrate the MEMS approach for achieving environmental outcomes that consider social, cultural, and economic benefits, to prioritise floodplain subcatchments in seven (7) coastal floodplains in NSW for the risk of diffuse poor water quality from ASS and blackwater runoff.

Coastal floodplains in NSW have undergone extensive development since the turn of the 20th century, including the construction of significant artificial drainage infrastructure for flood mitigation and to improve agricultural productivity. However, Tulau (2011) notes that despite the often misleading use of terminology, the 1950-70s 'flood mitigation' schemes were overwhelmingly swamp drainage schemes. The expansion of urban and agricultural land uses resulted in the construction of significant floodplain drainage systems that provide flood protection and improve agricultural productivity Johnston et al. (2003a). Over drainage has resulted in the oxidation of acid sulfate soils and the establishment of non-water tolerant vegetation in historical wetland areas. The proliferation of artificial drainage has also contributed to the increased frequency and magnitude of poor water quality discharge due to acid and blackwater (Johnston et al., 2003b; Naylor et al., 1998; Tulau, 2011; Wong et al., 2011b). Diffuse agricultural runoff has been identified during a threat and risk assessment (TARA) as one of the priority threats to environmental assets as well as social, cultural and economic benefits within the marine estate (Fletcher and Fisk, 2017).

Acid sulfate soils (ASS) are commonly found in low-lying coastal floodplains in NSW (Naylor et al., 1998). Although ASS are naturally occurring sediments, construction of deep drainage systems on coastal floodplains has increased the oxidation of ASS and exacerbated the generation and export of acid from ASS (Stone et al., 1998; Johnston et al., 2003a). The discharge of acidic and deoxygenated blackwater runoff is exacerbated by man-made drainage channels and one-way floodgates, which prevent tidal waters from inundating low-lying areas of the floodplain. Floodgates also act to maintain low drain water levels, creating a strong hydraulic gradient that increases the potential for acidic groundwater transport into estuarine receiving waters.

The drainage of low-lying backswamps and wetland areas has reduced the residence time of floodwaters on coastal floodplains and lowered the average water table below the ground surface. This drainage has enabled non-water tolerant vegetation, such as pasture grasses, to grow at low elevations that were historically inundated with water. Although this has led to some improved productivity during extended dry periods, these low-lying areas remain prone to prolonged inundation during wet periods, leading to the die off and decay of non-water tolerant vegetation and the generation of low oxygen runoff (Eyre et al., 2006), often referred to as ‘blackwater’.

Although the impact of over drainage of coastal floodplains has been known since the 1970s, the full impact of degraded wetlands and backswamps has only been realised in recent decades, with a push for remediation and improved land management ever increasing. However, floodplain remediation works have generally been undertaken using a ‘path of least resistance’ approach, where small scale projects have been pursued where there is support from local landholders, rather than based on targeting subcatchments that pose the greatest risk to the health of the marine estate.

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney was commissioned by NSW DPI – Fisheries under the Marine Estate Management Strategy (MEMS) Stage 1 to undertake the Coastal Floodplain Prioritisation Study (the ‘study’) to prioritise ASS and blackwater affected subcatchments in seven (7) coastal floodplains in NSW using the coastal floodplain prioritisation method. Note that the Hunter River floodplain is a major coastal floodplain that was not assessed as a part of the study, as the management of the wider Hunter River floodplain is being currently considered by other ongoing investigations. The coastal floodplains investigated in this study are:

- Tweed River floodplain;
- Richmond River floodplain;
- Clarence River floodplain;
- Macleay River floodplain;
- Hastings River floodplain;
- Manning River floodplain; and
- Shoalhaven River floodplain.

The purpose of the study is to provide an evidenced based list of high-priority floodplain subcatchments, along with potential management strategies to address land and water quality impacts in each estuary over short and long-term planning horizons. Importantly, this study provides an opportunity to identify localised and site-specific management responses that are targeted to address the water quality risk of a defined subcatchment, as well as considering all environmental, social, economic, cultural, and regulatory criteria, along with future sea level rise due to climate change. The outcomes from the study will provide a strategic pathway for floodplain remediation and potential management responses to facilitate the streamlined implementation of the actions over coming years.

Outcomes from this study align with key aspects of the Coastal Management Program (CMP), including identification of floodplain subcatchments that are a high priority for improving water quality and the ecological health of the marine estate. The assessment of sea level rise within estuaries also enables waterway and habitat vulnerability to climate change to be determined.

This study was funded by the NSW Government under the NSW Marine Estate Management Strategy (MEMS). The ten-year Strategy was developed by the NSW Marine Estate Management Authority (MEMA) to coordinate the management of the marine estate. The study was commissioned by the NSW Department of Primary Industries - Fisheries under the MEMS Stage 1 and delivered by the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney.

1.2 About this report

This report provides the necessary background to the methods used to prioritise each floodplain and develop on-ground management options and should be read prior to reviewing and interpretation of individual floodplain reports. The background, data, prioritisation and subcatchment management options for each floodplain can be found in individual reports for each estuary floodplain.

The first four (4) chapters of this report provide the necessary theory and objective methods used for prioritising subcatchments within a floodplain for ASS and blackwater drainage. The remainder of the report outlines the additional information and analysis used to support the development of management options for each area.

The report is comprised of the following sections:

- **Section 2** provides an overview of the study approach;
- **Section 3** provides an overview of the formation and impacts of ASS;
- **Section 4** outlines the objective method used for ASS prioritisation;
- **Section 5** provides an overview of the formation and impacts of blackwater;
- **Section 6** outlines the objective method used for blackwater prioritisation;
- **Section 7** provides an overview of the management options available for addressing ASS and blackwater issues on coastal floodplains;
- **Section 8** discusses the indirect factors considered in development of management options;
- **Section 9** introduces the data used to assess current land uses in each catchment;
- **Section 10** outlines the economic costs and benefits that are considered when developing management options;
- **Section 11** outlines estuary modelling process that has been used to assess the impact of sea level rise; and
- **Section 12** outlines the process used to classify waterways as natural or artificial on coastal floodplains.

In addition, the following appendices have been included to provide necessary background information:

- **Appendix A** provides an overview of data collection methods used during this study; and
- **Appendix B** provides detailed theory of hydraulic conductivity measurements.

2 Study approach overview

2.1 Study objectives

A key objective of the Marine Estate Management Strategy (MEMS) (Marine Estate Management Authority, 2018) is to address the sources of poor water quality across NSW coastal waterways and estuaries to provide benefit to marine habitat, wildlife and the community. In many major NSW estuaries, poor water quality discharged as a result of acid sulfate soils and low oxygen blackwater have caused major environmental damage, including mass fish kills (NSW DPI, 2020), chronic diseases in aquatic life (Tulau, 2007) and compromised aquatic habitats (Johnston et al., 2003a). These have flow on effects to a number of key industries that rely on a healthy marine estate, including commercial and recreational fisheries (Moore, 2007; Southern Cross GeoScience, 2019) and the oyster industry (Dove, 2003; Dove and Sammut, 2013), as well as compromising the productivity of land uses on the floodplain (Johnston et al., 2003a).

The objective of this study was to develop and apply multi-criteria prioritisation methodologies to rank drainage subcatchments within NSW coastal floodplains by their contribution to acid and blackwater generation and discharge and subsequent risk to health of the marine estate. This methodology allows for evidence-based identification of high-priority subcatchments within coastal floodplain systems, which enables a strategic approach to improvements in land management and remediation. The outcomes of the multi-criteria assessment, management options and supporting information aim to provide an objective, prioritised list of floodplain subcatchments that pose a risk to the health of the marine estate, whilst also summarising key information and floodplain datasets.

The outcomes of this study are designed to identify localised, site specific management responses that are targeted to address the specific water quality risks of a subcatchment, as well as considering environmental, social, economic, and cultural criteria. Identifying existing high-risk acidic or blackwater subcatchments is fundamental in formulating objective, on-ground management options for floodplain subcatchments, and to improve the ecological health (eco-health) of the marine estate. Short-term (1 to 10 years) and long-term (>10 years) management options were developed for each coastal floodplain subcatchment to address the risk of acid and blackwater discharge into the wider estuary. The management options outline and map management responses to facilitate future implementation of potential remediation actions. These management options are detailed in each individual floodplain report. The management options provided in this study are only intended to be a guide, and on-ground work is not recommended without further assessment into the applicability and potential impacts of any changes in management. This will typically include extensive consultation and consideration of the social, cultural, and economic impacts on local landholders.

The study also aimed to define and quantify a range of administrative constraints to assist land managers and decision makers in the implementation of management options. This included key variables or processes that, while not directly influencing the risk of acid discharge or blackwater generation from a floodplain subcatchment, may guide further detailed assessment and the overall implementation timeline. These include criteria such as: drainage vulnerability under rising sea levels, tenure of land and drainage infrastructure, proximity of discharge locations to sensitive environmental receivers, land and production values, and future land use.

2.1.1 Previous studies

This study follows research on the Shoalhaven River floodplain in 2014 (Glamore and Rayner, 2014) and the Manning River floodplain in 2016 (Glamore et al., 2016a) which pioneered the development of an innovative ASS prioritisation methodology through the use of multi-criteria assessment systems. In these studies, drainage subcatchments across the Shoalhaven River and Manning River estuarine floodplains were assessed and quantitative variables such as acid input, discharge, groundwater risk and sea level rise were used to develop a prioritised list of drainage subcatchments. For each subcatchment, a set of management options were then developed to address potential short and long-term management strategies for addressing ASS runoff. These studies have continued to inform floodplain management in both catchments and formed the basis of the acid prioritisation method used in this study.

2.1.2 Study areas

This study includes the prioritisation and development of management options for five (5) additional coastal floodplains in NSW and updating the prioritisation of the existing two (2) floodplain prioritisation studies, shown in Figure 2-1. Boundaries of coastal floodplain catchments for this study have been identified as the 5 m AHD contour. This study covers the coastal floodplains of the:

- Tweed River;
- Richmond River;
- Clarence River;
- Macleay River;
- Hastings River;
- Manning River (updated); and
- Shoalhaven River (updated).

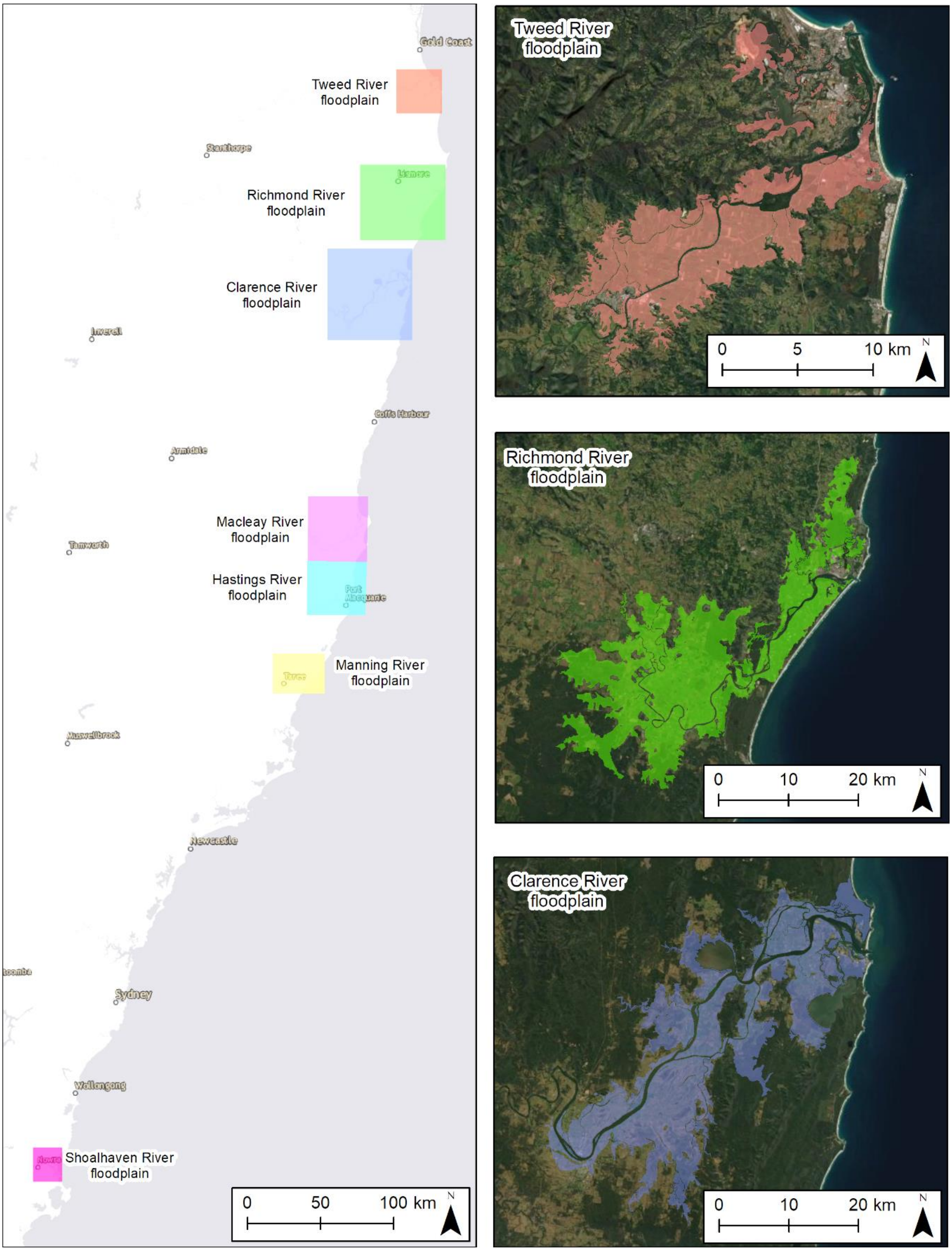


Figure 2-1: Study areas (1 of 2)

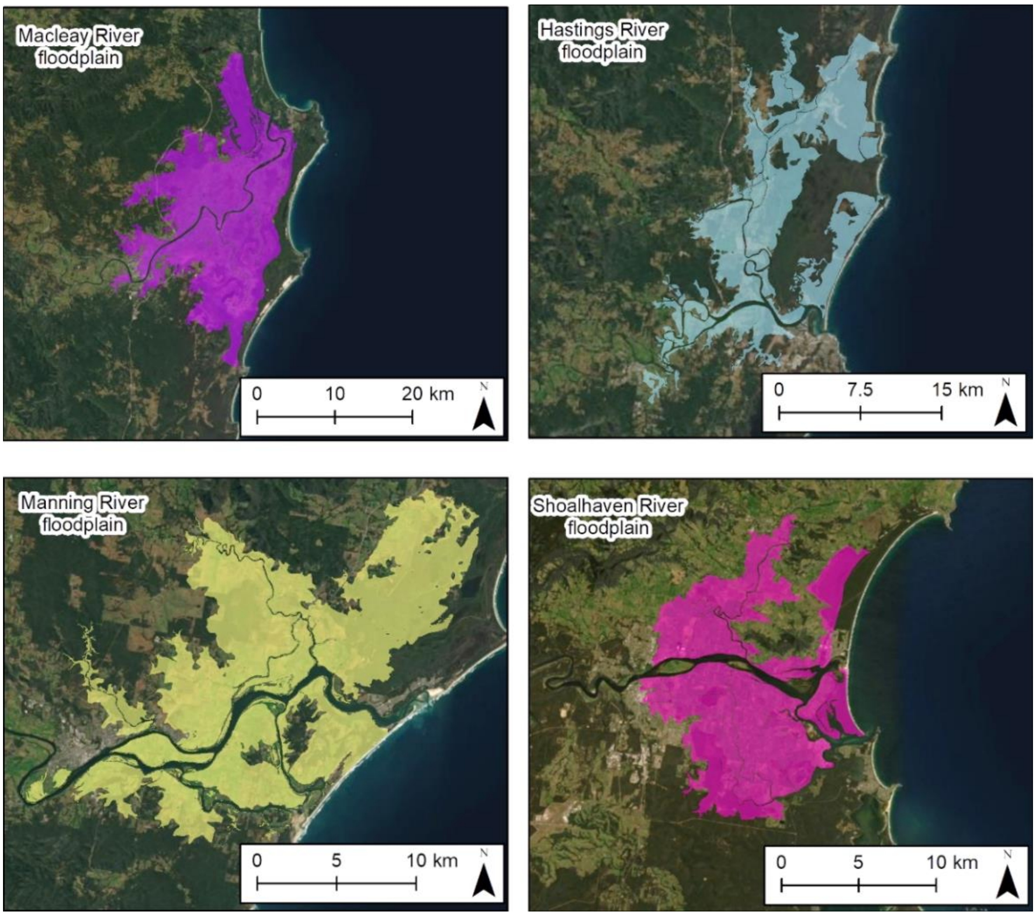


Figure 2-1 (cont'd): Study areas (2 of 2)

2.2 Approach and methodology

The completion of the prioritisation of floodplain subcatchments and development of management options for each of the seven (7) study floodplains required a systematic approach to ensure an equivalent level of rigour and detail is achieved across all floodplains. Figure 2-2 provides an overview of the study approach, including:

- **Data collection:** existing data is collated and reviewed. Where required, additional field data has been collected to support the implementation of the prioritisation;
- **Risk factors:** a range of quantifiable, objective physical factors that directly relate to the risk posed by a drainage subcatchment to the wider estuary are combined to determine the subcatchment priority ranking;
- **Management constraints:** site specific physical factors that influence what potential land management and remediation options are physically applicable to that particular subcatchment; and
- **Implementation constraints:** while the implementation of management options is beyond the reach of this study, potential constraints are highlighted in the management options to assist decision makers and land managers.

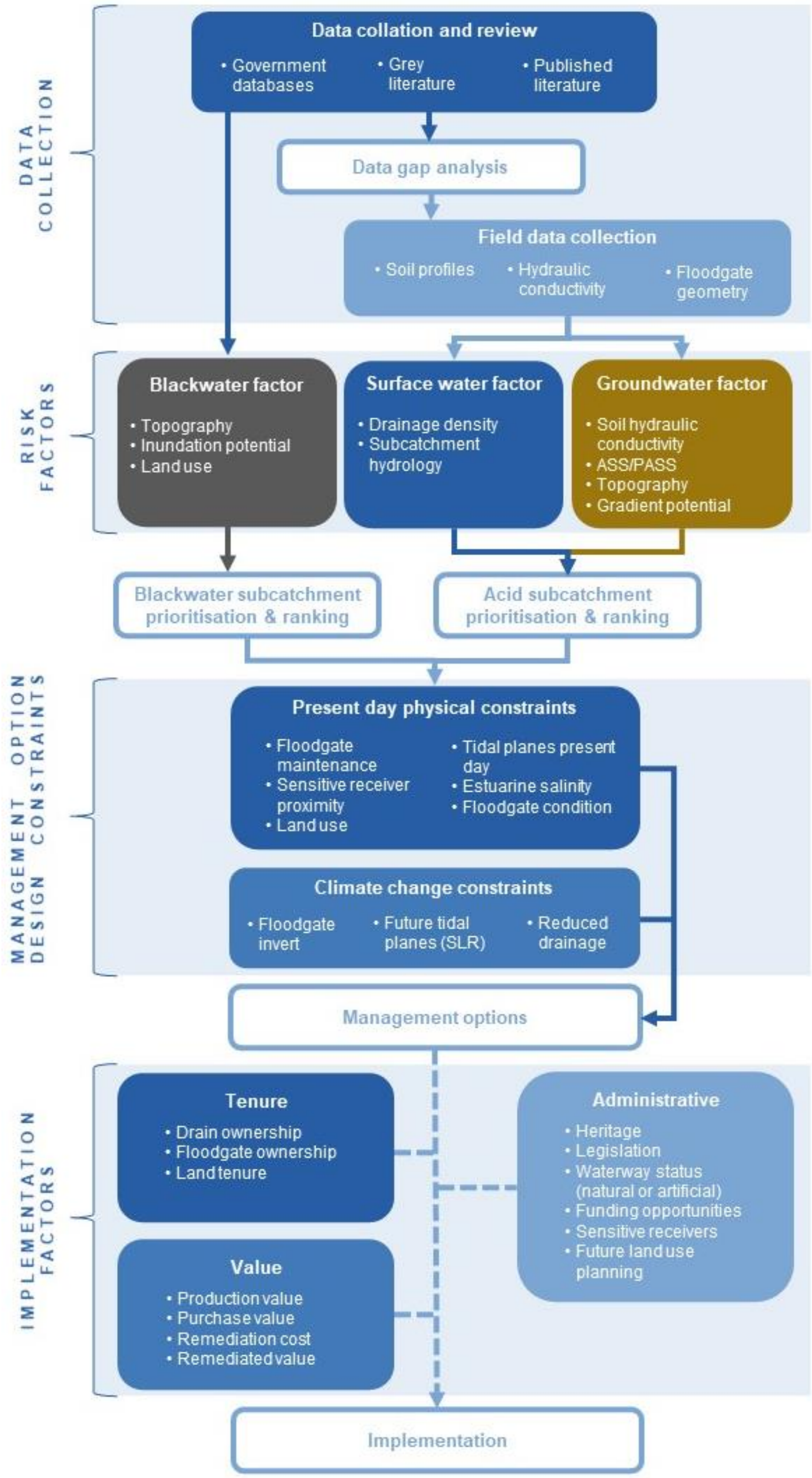


Figure 2-2: Overview of study approach

2.2.1 Key datasets

Providing an evidence-based prioritisation for acid and blackwater generation in coastal floodplains requires a reliable dataset across a large spatial extent at comparable resolutions on all study floodplains. Available literature and government databases were reviewed as part of this study to assess whether existing data was sufficient to implement the prioritisation methodologies and develop subcatchment management options with an acceptable level of certainty. When data was found to be insufficient or incomplete, additional data was collected to infill critical data gaps. This section lists a number of key datasets required to complete the study. Appendix A provides details on field data collection methods. Datasets for each floodplain are presented in appendices of the individual floodplain reports.

Acid sulfate soil data

Understanding the acidity and hydraulic conductivity of the soils throughout the floodplains is essential to implementing the ASS prioritisation method. A considerable amount of existing data is available through the NSW government eSpade database, as well as published and grey literature. However, a substantial amount of additional soil profile and hydraulic conductivity information was collected in the five (5) new floodplains considered in this study to infill critical data gaps. This included:

- 179 soil profiles, including information on soil profile acidity and potential acidity and lithology; and
- 145 in-situ measurements of soil hydraulic conductivity.

Data collection methods used for measuring and analysing soil profiles and hydraulic conductivity are provided in Section A3.1 and A3.2 of this report, respectively. Locations and results of additional measurements undertaken as part of the Coastal Floodplain Prioritisation Study can be found in appendices of each individual floodplain reports.

Topography

Floodplain topography is critical to determining the blackwater prioritisation and understanding floodplain vulnerability to sea level rise. Topography has been sourced from 1 m and 5 m digital elevation models (DEM) available from NSW Spatial Services (DFSI Spatial Services, 2020).

Waterways and waterway classification

The acid prioritisation method includes consideration of the drainage density within a floodplain, and requires a detailed, uniform spatial dataset with the location of all waterways below 5 m AHD within each floodplain. While existing datasets held by NSW Spatial Services provide a base layer of drainage, this state-wide dataset was reviewed as a part of this study and found to be out-dated in some locations. This data has been updated in this study using:

- Digital elevation models (DEMs) on a 1 metre grid resolution;
- High resolution aerial imagery; and
- Inspections completed during field investigations.

In addition, a multi-criteria assessment was developed for categorising waterways as natural or artificial. This assessment was a data focused approach utilising quaternary geology, Crown land, waterway name, waterway sinuosity and stream order information to categorise waterways. The waterway categorisation has been implemented to provide an updated waterways layer and has been used to guide what types of management options have been suggested in each subcatchment.

The multi-criteria assessment for waterways enables an evidence-based approach for determining aquatic habitats. This is of particular relevance to floodplains progressively modified through drainage works and construction of floodgates, resulting in significant changes to the historical flow paths and interrupted the previous connection between the upper-catchment and estuary. The adopted approach has considered all relevant legislation and developed a tool that may assist in identifying Key Fish Habitat pertaining to the Fisheries Management Act 1994 and guide future management arrangements.

Land use

Present day land use is utilised in the blackwater prioritisation and is a constraint considered when developing short-term management options. Knowledge of present-day land use assists in the understanding of the impacts of changes in land management. A state-wide land use database was sourced from the Australian Government Department of Agriculture and Water Resources from 2013 (DPIE, 2013). This data has been summarised in the management options for each subcatchment. More information on the land use data used for this project is provided in Section 9.

Estuary models

Hydrodynamic models of estuaries are able to replicate and predict water levels throughout a model domain and can be used to better understand the sensitivity of an individual estuary to future sea level rise conditions. While flood models had already been developed for each coastal floodplain, these models are calibrated to extreme flood events and do not typically have sufficient detail in the intertidal zone to replicate tidal dynamics. To assess the impact of sea level rise during non-flood periods, hydrodynamic models have been specifically developed for this project for each of the seven (7) estuaries. The numerical models were calibrated to tidal levels and flows throughout each estuary and used to assess sea level rise vulnerability across each floodplain. More information on the approach to modelling sea level rise within estuaries can be found in Section 11 and in the individual floodplain reports.

Floodgate locations and geometry

Information on end-of-system floodgates has been collated and collected for this study to assess the vulnerability of key floodplain infrastructure. ‘End-of-system’ denotes structures that discharge directly into tidal waters. In most cases, the relevant local Council has location data for major floodgates (particularly where they are owned and managed by the local government authority). In some cases, information held by local Councils will include the size of the floodgate (e.g. the diameter of the pipe or height and width of a box culvert), but accurate elevation data for the invert (bottom) or obvert (top) was rarely available.

For this study, additional information was collected on floodgate locations from each relevant Council and the information was reviewed to assess gaps in the existing data. Targeted field campaigns were completed to survey as many of the floodgates as practical for this project, with a focus on primary end-of-system infrastructure. Where possible, the survey included information on floodgate:

- Location;

- Dimensions;
- Invert/obvert; and
- Condition.

Data for all floodgates surveyed for this project is presented in appendices of the individual floodplain reports.

2.2.2 Subcatchment delineation

The prioritisation approach requires the delineation of subcatchments within each estuary which are then ranked based on the risk they pose to the estuary in terms of poor water quality relating to acid or blackwater runoff. The delineation of these subcatchments is important as the placement of their boundaries can affect the outcomes of the prioritisation process (as outlined in detail in Sections 4 and 6 for the acid and blackwater prioritisation methods, respectively). Subsequently, great care needs to be taken to determine subcatchment boundaries.

Delineation of subcatchments has been completed considering a number of available data sources, including:

- Topography data (from LiDAR surveys);
- Waterway alignment data;
- Acid sulfate soil risk mapping; and
- Management boundaries (e.g. as specified in CZMP or CMP documentation).

The primary data used for subcatchment delineation was topographical and waterway data which allows for the determination of hydrological flow paths. Using this data allows each subcatchment to be delineated so that it could be defined as an individual hydrological unit. This was deemed the most important factor in the delineation process as it then allows each subcatchment to be managed as a discretised unit. That is, modifications to one subcatchment will not impact or alter the average hydrological conditions to an adjacent subcatchment.

A number of other data sources were also used as secondary factors to delineate subcatchments. Acid sulfate soil risk mapping (Naylor et al., 1998) was used to identify areas where there is a high or low probability of ASS occurring. Areas not identified in this mapping as a risk of ASS occurring were excluded from the subcatchment for the ASS assessment as it is unlikely that they contribute to the overall export of acid from the floodplain. Similarly, floodplain areas mapped as mangroves or saltmarsh (in macrophyte mapping supplied by NSW DPI – Fisheries) were excluded from subcatchments for the blackwater assessment as these areas will not significantly contribute to blackwater generation. Subcatchment delineation areas identified to be managed as discrete hydrological units in coastal zone management plans (CZMPs) or coastal management programs (CMPs) were also considered during the delineation process.

The mechanism by which coastal floodplains were formed was also considered during the delineation process. This includes understanding the geomorphic development of the floodplain and identifying how different landforms can impact water quality of the floodplain. For example, ASS is more likely to occur in Holocene soils than Pleistocene soils (Troadson and Hashimoto, 2008). This approach has previously been effectively utilised in mapping the probability of ASS occurrence (Naylor et al., 1998). While geomorphic settings are important to understanding the development of ASS, poor water quality impacts the wider estuary when it is mobilised and transported from the floodplain. Consequently, the geomorphic setting cannot be considered in isolation without considering subcatchment hydrology when assessing impacts of water quality to an estuary. The subcatchment delineation approach has focussed on catchment hydrology as the primary mechanism that physically transports water of poor quality from the floodplain to the estuary. This methodology also means that management actions for improving water quality can be targeted without impacts to adjacent subcatchments.

2.2.3 Acid sulfate soil prioritisation

The acid sulfate soil prioritisation method developed by Glamore and Rayner (2014) and Glamore et al. (2016a) has been reviewed and updated for this study to ensure applicability over a diverse range of coastal floodplains. The ASS priority assessment is structured around two (2) major factors:

(i) a surface water factor; and
(ii) a groundwater factor.

Each factor is formulated by environmental factors/processes that contribute to the risk of ASS oxidation and acid discharge on downstream sensitive receivers. The risk associated with each factor is determined by a desktop assessment of existing information and combined with a field assessment of onsite environmental conditions. These factors are then combined within a calibrated algorithm to rank each subcatchment. A summary of the risk rating, as applied to each factor, is provided in Figure 2-3. Details on the ASS prioritisation methodology are presented in Section 4.

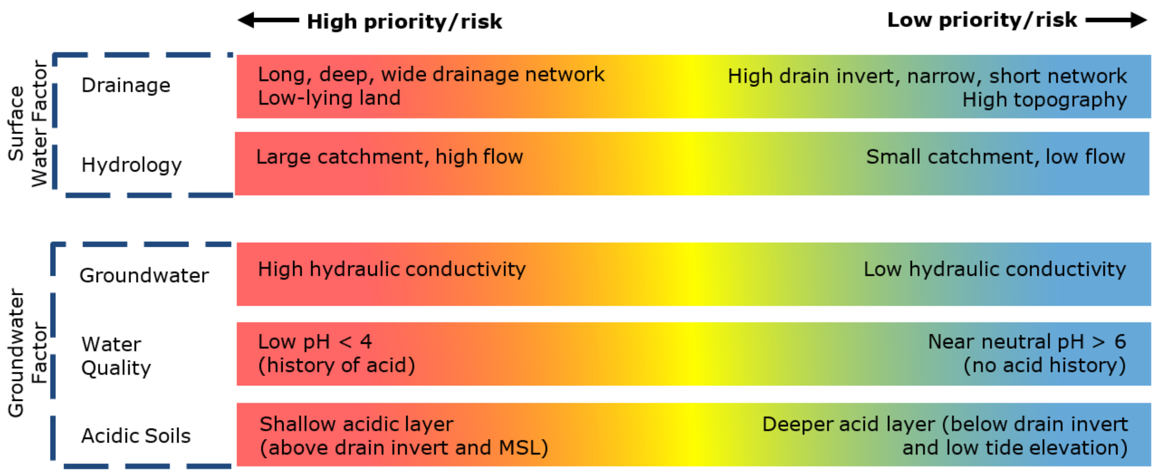


Figure 2-3: Factors influencing ASS discharge from an ASS-affected floodplain in coastal NSW (adapted from Johnston et al., 2003a)

2.2.4 Blackwater prioritisation

In addition to the ASS prioritisation, a second, independent prioritisation has been developed to address the risk of deoxygenated water (often referred to as 'blackwater') to coastal waters. The blackwater priority assessment is structured around two (2) major factors:

(i) an area of the floodplain that contributes to blackwater production; and
(ii) the risk associated with different land uses and vegetation types in each area.

These factors incorporate the key physical attributes that determine the difference in blackwater generation within an individual floodplain. The blackwater prioritisation was completed utilising existing, catchment or state-wide datasets. A summary of how each factor affects the prioritisation is provided in Figure 2-4. Details on the blackwater prioritisation methodology are presented in Section 6.

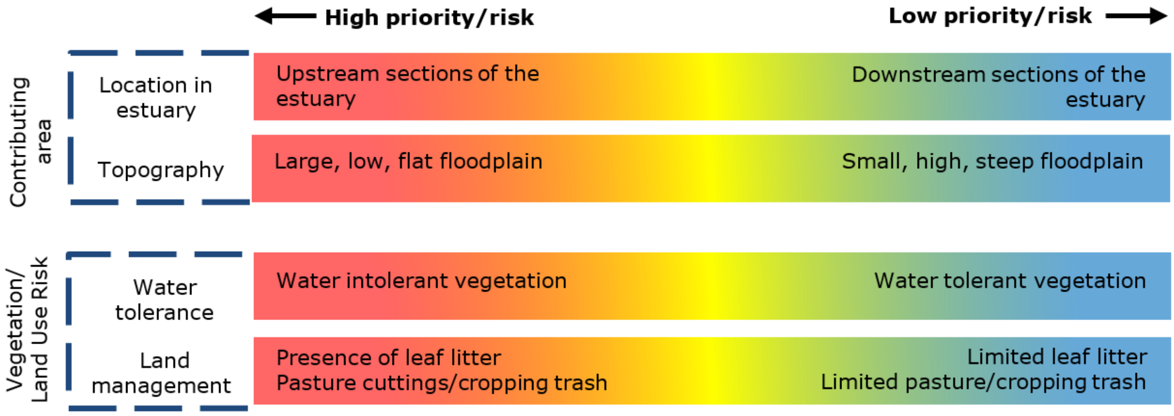


Figure 2-4: Factors influencing blackwater discharge from coastal floodplain in NSW

2.2.5 Sea level rise vulnerability

Future sea level rise in estuaries will result in reduced floodplain drainage and prolonged inundation of connected floodplain areas, with potential impacts on land use and productivity (Oppenheimer et al., 2019). Sea level rise vulnerability has been assessed in detail using numerical hydrodynamic models developed for each estuary. Water levels have been modelled for present day ocean tides, as well as the near future (2050) and the far future (2100), based on a sea level rise of +0.16 m and +0.67 m respectively (see Section 11). This approach provides a first-pass assessment that identifies floodplain areas and infrastructure susceptible to impacts due to sea level rise. Vulnerability has been assessed in two (2) forms:

- Vulnerability of floodgate to sea level rise; and
- Vulnerability of floodplain drainage due to sea level rise.

The vulnerability of floodgates was assessed by determining how frequently the floodgates are able to freely drain based on the downstream water levels and floodgate geometry. Modelled water levels were extracted at each floodgate location, and water level statistics (e.g. the level the water is below

5%, 50% and 95% of the tide record) have been compared to the floodgate obvert (the top of the culvert) to assess vulnerability due to sea level rise. A floodgate is considered most vulnerable to reduced drainage where the obvert is *lower* than the 50th percentile water level (meaning water can freely drain through the floodgate less than 50% of the time) and least vulnerable where the obvert is *above* the 95th percentile water level (meaning the floodgate can freely drain more than 95% of the time). The vulnerability of floodgates based on downstream water levels is shown in the schematic in Figure 2-5. More information of the assessment of floodgate vulnerability is provided in Section 11.4.1.

Floodplains are vulnerable to sea level rise for a number of reasons, including increased flooding due to higher ocean levels and reduced drainage during dry periods. Flood impacts are typically documented in floodplain flood studies, however, reduced drainage resulting in increased inundation durations (particularly during non-flood times) may also have substantial impacts on future land uses and productivity. In this study, floodplain vulnerability has been assessed with respect to the potential impacts of reduced drainage only. The extent of the floodplain impacted by reduced drainage potential due to present day and future sea level rise has been assessed based on the reduction in water level differential between the floodplain and the river. As with the floodgate vulnerability, modelled water levels are extracted from the main river channels at the primary discharge points of floodplain subcatchments and receiving water level statistics are transposed across the floodplain using a GIS ‘bathtub’ approach. Impacts due to flooding or tidal inundation are not incorporated in this assessment. More information of the assessment of floodplain vulnerability is provided in Section 11.

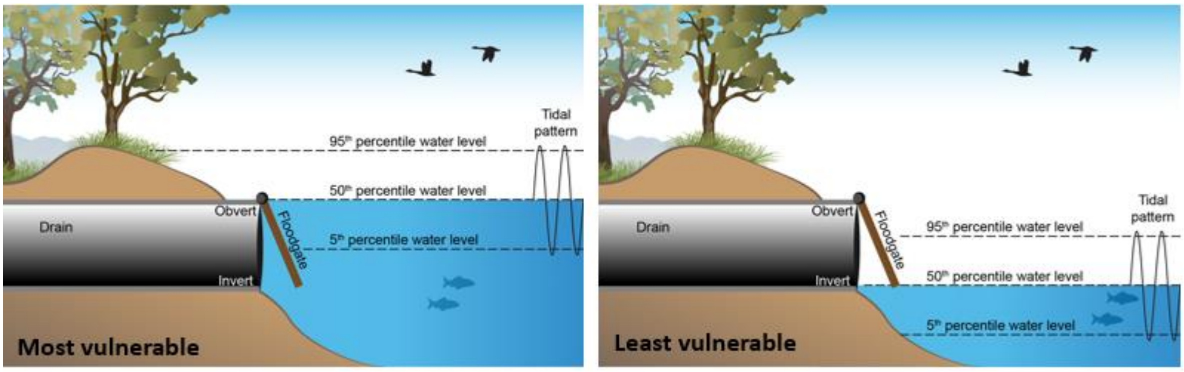


Figure 2-5: Schematic of most vulnerable (left) and least vulnerable (right) floodgates based on downstream water levels

2.2.6 Development of management options

Management options have been developed for each floodplain subcatchment identified in the seven (7) floodplains considered in this study. The management options provide potential short-term (generally implementable without major changes in land uses and typically actionable within a 1 – 10 year time period) and long-term (which often requires changes in existing land uses that may limit implementation in the immediate future) on-ground management actions and remediation measures to mitigate the impacts of acid and blackwater discharges.

Short-term plans were designed with the assumption that existing land use practices were maintained. Long-term plans were developed under the assumption that current land use practices may change to adapt in the future. Future sea level rise was considered when developing long-term management options. Note that the time scale (i.e. short or long-term) for implementation of actions was primarily based upon existing land use. Identified 'long-term' strategies could therefore be potentially implemented immediately if a change in present-day land use were to occur. The management options provided in this study are intended to be a guide only, and no on-ground work is recommended without further studies into the applicability and potential impacts of any changes in management. This will typically include extensive consultation and consideration of the social, cultural and economic impacts on local landholders.

The management options vary in detail depending on the ranking of a subcatchment with respect to acid and blackwater discharges in the estuary. The management options also consider:

- Proximity to sensitive receivers (e.g. macrophytes, oyster leases and key fish habitat);
- Current land uses and productivity;
- Potential cost of changes in land management or remediation (e.g. upfront and on-going costs);
- Potential benefits of changes in land management or remediation (e.g. reduced acid or blackwater discharge, increased aquatic habitat and estuarine connectivity);
- Sea level rise and associated floodplain and infrastructure vulnerability; and
- Types of waterways in the subcatchment, with a particular emphasis on restoring natural flow paths and connectivity.

3 Acid sulfate soil theory

3.1 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 noted causing problems worldwide. Since then, the various manifestations and impacts of ASS have been extensively researched and consequently well understood, 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.

3.2 What are acid sulfate soils?

Acid sulfate soil is the common name given to soils and sediments containing iron sulfides, the most common being pyrite (FeS_2) (DERM, 2019). 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).

3.3 Formation

ASS are predominantly located within 5 m of the surface and are found extensively on Australia's coastline (DERM, 2019). Pyrite is formed in reducing depositional environments where there is a supply of easily obtained, decomposed organic matter, sulfate, iron and reducing bacteria (Figure 3-1). 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 (2019) 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.

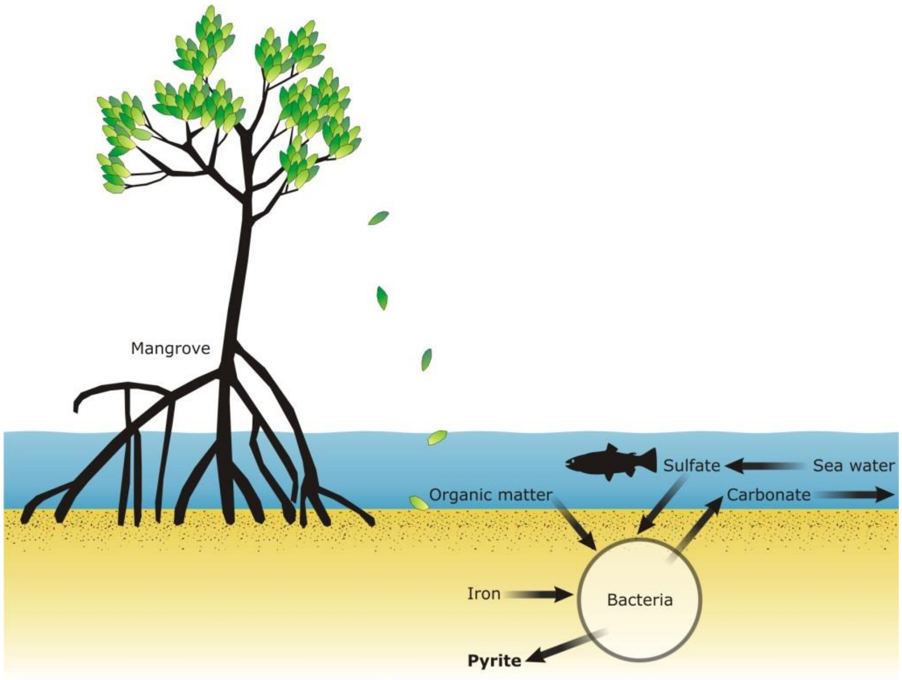


Figure 3-1: Pyrite formation (NRM, 2011)

3.4 Acidification

The pH scale (Figure 3-2) 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).

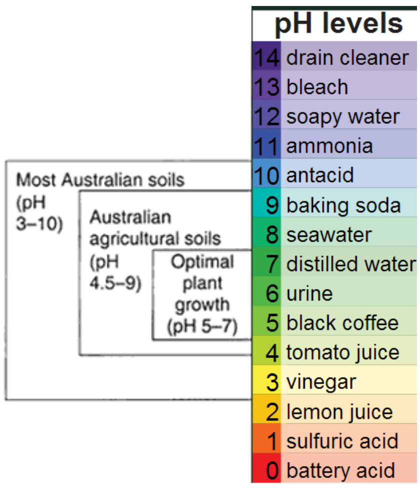


Figure 3-2: pH scale (NRM, 2011)

PASS is oxidised to form AASS when coastal land is cleared and drained which results in a lower groundwater table and introduces oxygen from the air to 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 runoff into the drainage network or other receiving waters (Figure 3-3). 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 (zone 1) exists comprised largely of roots and decomposing matter. This layer transforms into an alluvial/clay zone (zone 2). An AASS layer (zone 3) 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 (zone 4) 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 (zone 5).

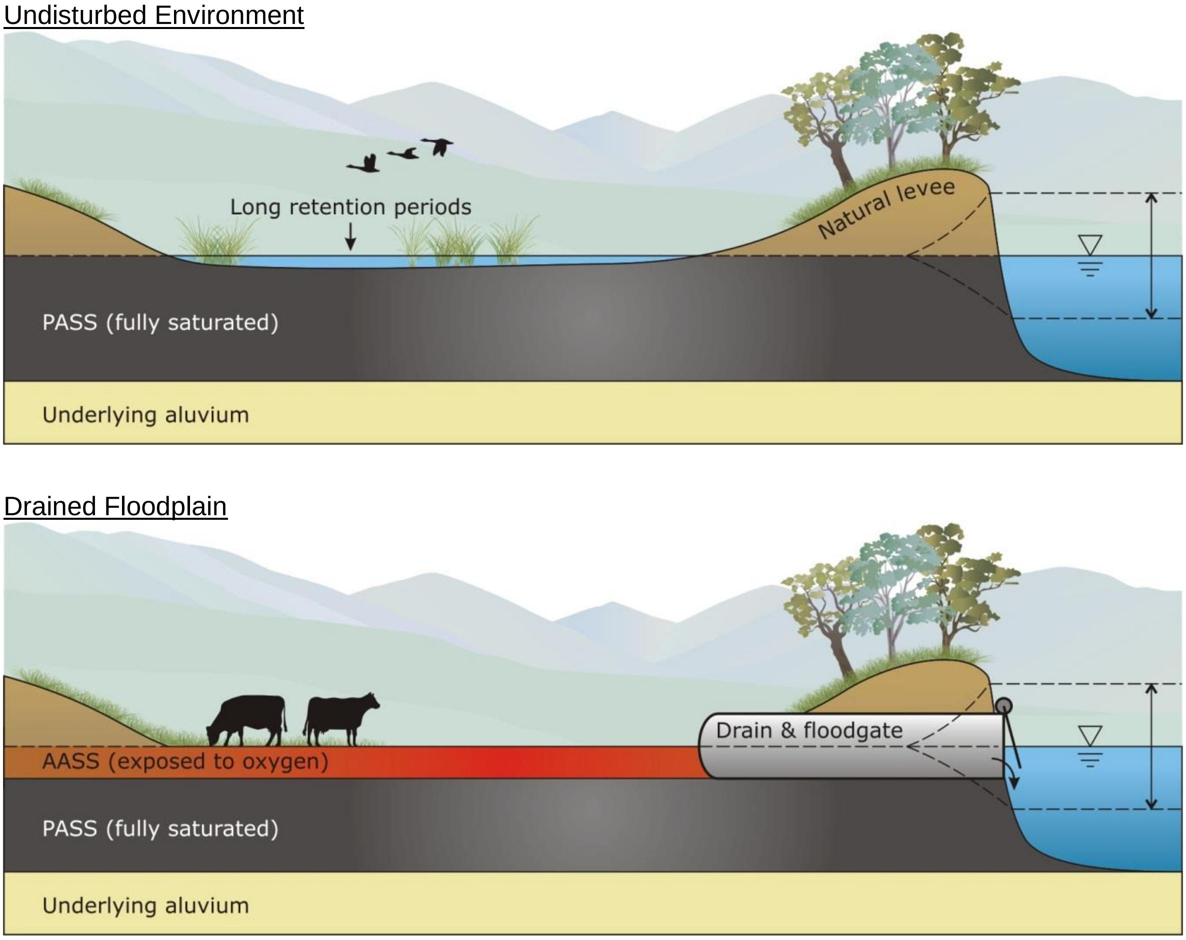


Figure 3-3: Soil acidification by lowering of groundwater levels

3.5 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 3-4.

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 (Glamore, 2003). Floodgates and drainage structures are usually designed to maintain drain levels at the low tide level to drain backswamp areas and reduce pasture water logging. As the pyritic layer is normally situated at the mid-to-high tide level, maintaining drain water elevations under the low tide elevation, allows one-way floodgates to increase the hydraulic gradient between the drain surface water and the surrounding acidic groundwater (Glamore, 2003).

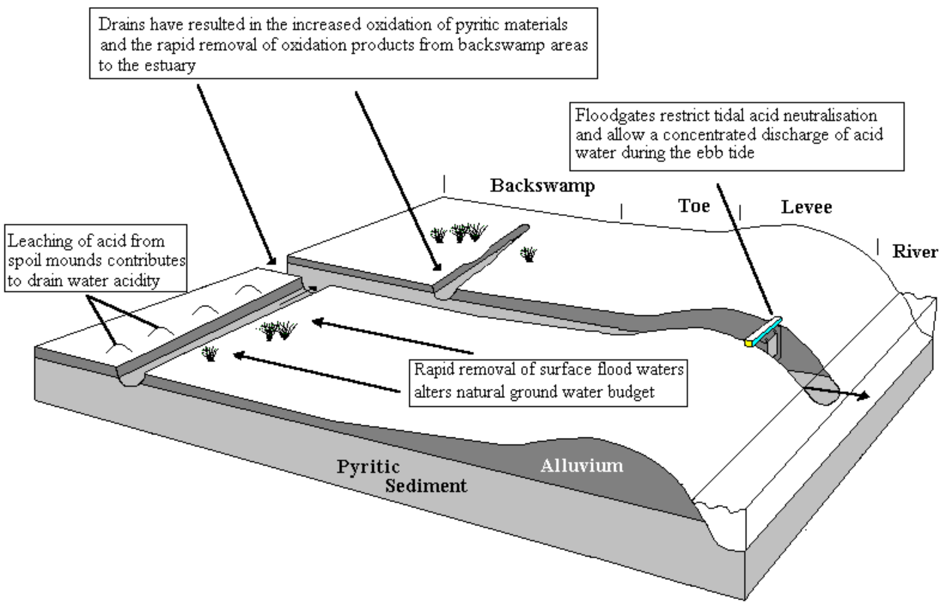


Figure 3-4: Schematic of a backswamp drainage and floodgate network (Naylor et al., 1998)

The difference in hydraulic gradient caused by the tidal floodgates promotes the transport of oxygen into sulfidic subsoil material and the leaching of acid by-products into the drain (Blunden and Indraratna, 2000). This is particularly evident following large rainfall events when receiving water levels drop, groundwater levels remain elevated, and floodgates effectively drain surface waters from the floodplain causing low drain water levels (Glamore and Indraratna, 2001).

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.

3.6 Soil hydraulic conductivity

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. Other factors such as macropores and soil ripening also affect the porosity of soils. The higher the porosity, the greater potential for rapid acid discharge into a drain.

Understanding the saturated hydraulic conductivity (often referred to simply as 'hydraulic conductivity') of drained floodplain soils is an important factor used in assessing the severity of acid sulfate soils (ASS) and the potential risk to estuarine waterways (Johnston and Slavich, 2003). Spatially, the hydraulic conductivity of a soil profile can be highly variable in both the horizontal direction across different field and landscape scales and vertically at different depths (Johnston et al., 2009). This is due to the heterogenic properties of soil, particularly on coastal floodplains (Oosterbaan and Nijland, 1994; Johnston et al., 2009).

In coastal floodplains the spatial variability on a horizontal scale is caused by the intricate development of the floodplain, involving factors such as changing sea levels and human interference (Hirst et al., 2009). Oosterbaan and Nijland (1994) describe how coarser soil particles (e.g. sand and gravel) are deposited as levees near riverbanks and finer particles (e.g. silt and clay) are deposited on the floodplain. Over time, as rivers or creeks meander and vegetation growth changes this creates complex lithological patterns across a floodplain resulting in varying hydraulic conductivity even within a single paddock. Indeed, Gupta et al. (2006) found that there was significant spatial variation in hydraulic conductivity when conducting an experiment testing hydraulic conductivity of adjacent eight metre square plots.

A detailed discussion on hydraulic conductivity is provided in Appendix B .

3.7 Acid discharge

In a similar manner to geographical/geomorphological descriptions of estuaries internationally, Australian estuaries have been classified by Digby et al. (1999). These authors described the 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, salt water 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 bed of the estuary, and the estuary progresses from a highly stratified salt-wedge estuary to a partially mixed estuary and subsequently to a vertically homogeneous estuary.

Estuaries in south-eastern Australia have also been classified by Roy et al. (2001) considering their entrance type and degree of marine influence. The prioritisation assessment in this study only includes mature, wave dominated barrier estuaries with open inlets (Roy et al., 2001). These estuaries have tidal inlets which are inhibited by wave driven sandy beaches and flood-tide deltas that limit the tidal influence. The assessment may need to be reconsidered for estuaries with alternative entrance types.

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 acidic contamination to the estuary is reduced.

Figure 3-5 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 providing low acid risk conditions.

Figure 3-6 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 3-7 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 as shown in Figure 3-8. As the natural buffering capacity of the estuary has been removed by the fresh floodwaters, acidic plumes comprised of low pH water and high soluble metal concentration remain in the open estuary.

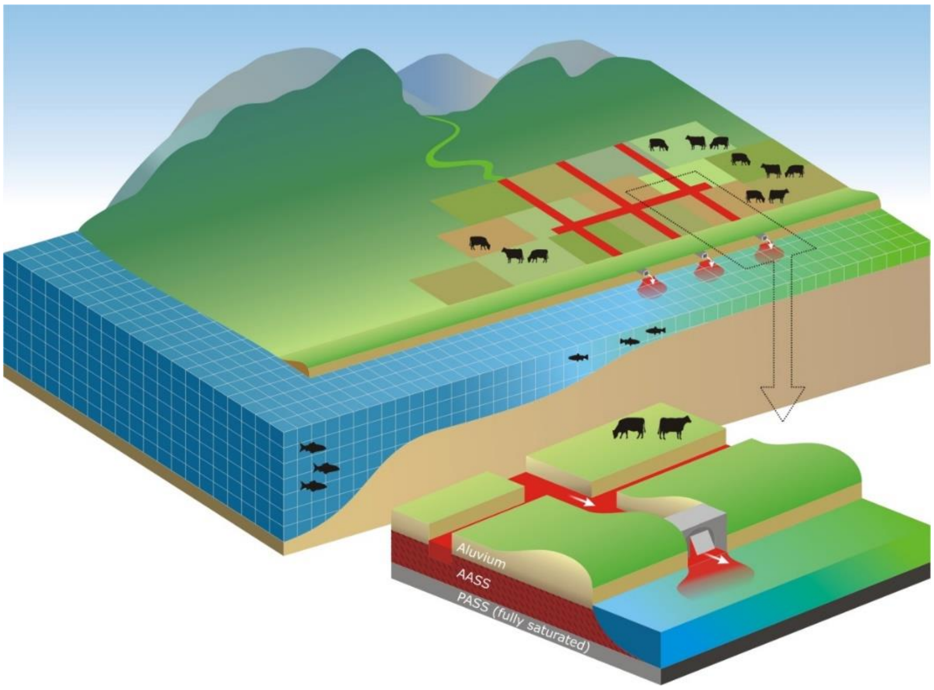


Figure 3-5: Period of tidal buffering and low acid risk (Ruprecht et al., 2018)

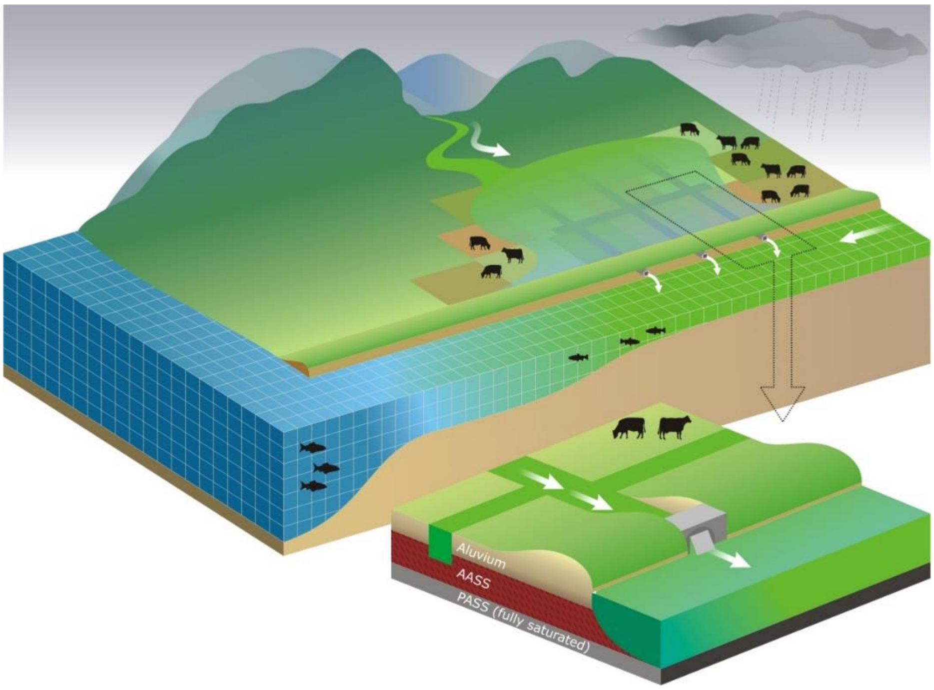


Figure 3-6: Flow dilution period as a result of a large rainfall event (Ruprecht et al., 2018)

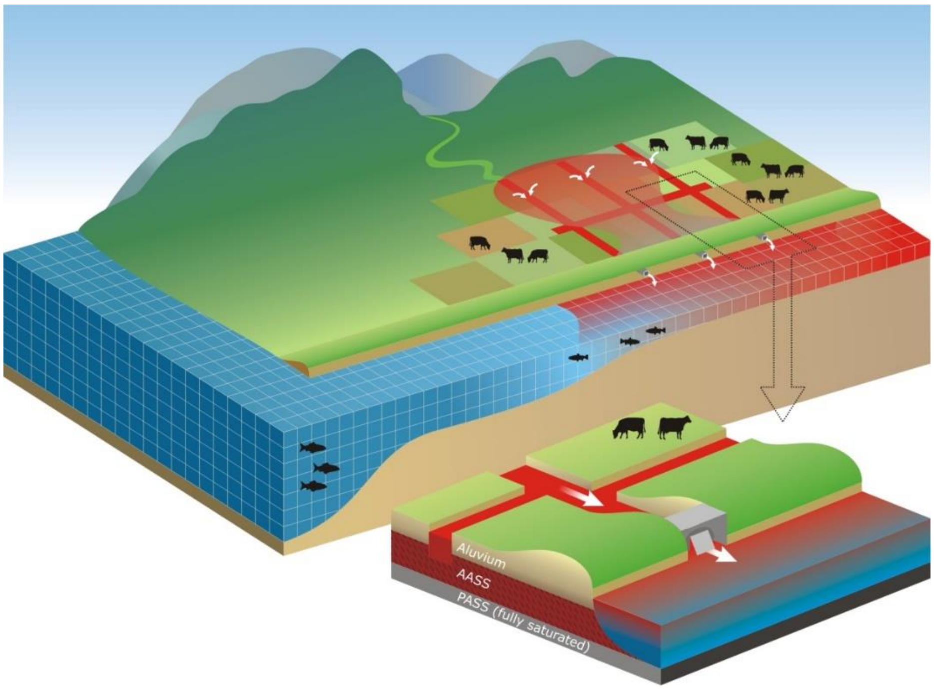


Figure 3-7: Period of acid impact following rainfall event (Ruprecht et al., 2018)

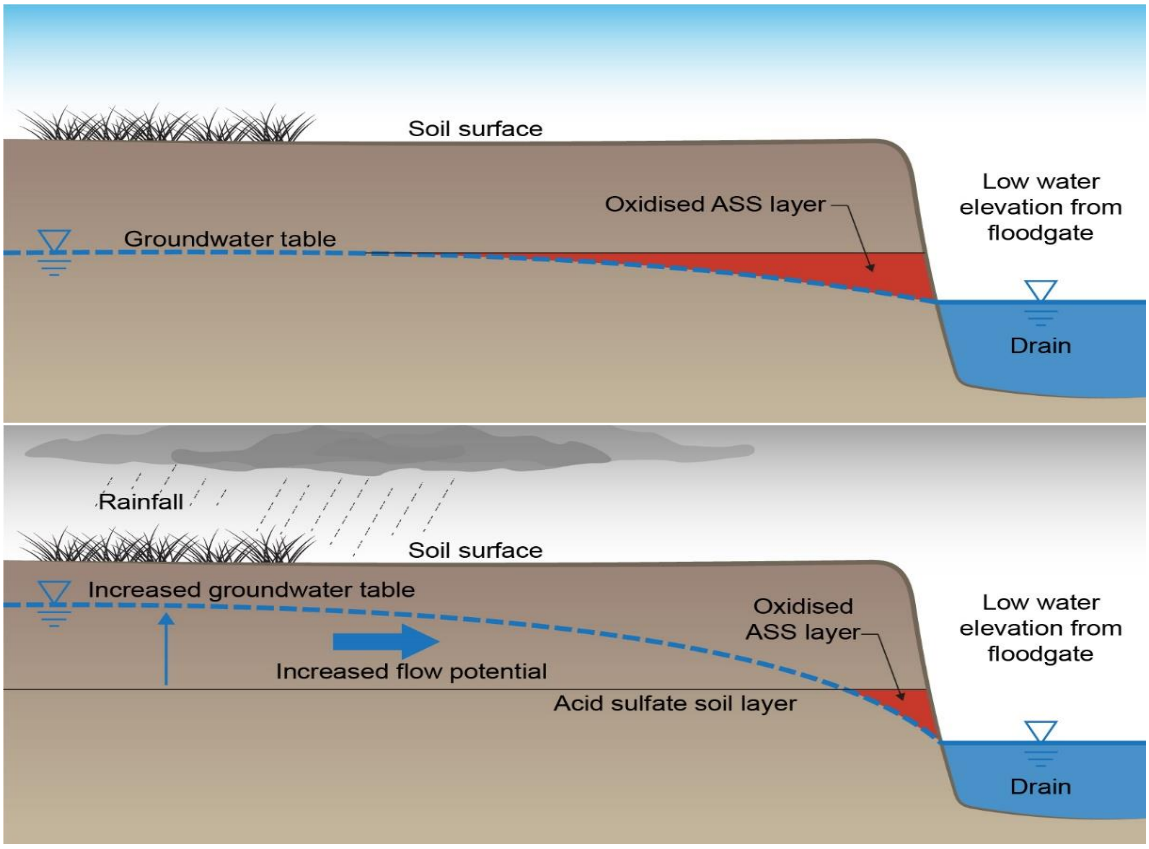


Figure 3-8: Influence of one-way floodgates on groundwater elevation under normal (top) and flood (bottom) conditions

3.8 Environmental impacts

Poor water quality from diffuse agricultural runoff has been identified as the highest priority threat to the environmental assets within estuaries in NSW during the Threat And Risk Assessment (TARA) (Fletcher and Fisk, 2017). Diffuse agricultural runoff was also identified as a significant threat to the social, cultural and economic benefits derived from the marine estate. The TARA highlights the threat posed to estuaries from acid and blackwater discharges associated with modified floodplain uses and drainage. In particular, acid sulfate soil oxidation causes adverse environmental, ecological, and economic impacts, leading to a deficiency in essential plant nutrients and plant base minerals such as calcium, magnesium, and potassium, while at the same time, the concentration of toxic metals such as aluminium, iron, and other heavy metals increases. Furthermore, the release of acidic plumes, containing aluminium and iron flocs, is well known to cause widespread environmental pollution in tidal estuaries resulting in large scale fish kills (Winberg and Heath, 2010), and negatively impacts oyster health (Dove, 2003).

In 2008, the NSW Department of Planning, Industry and Environment (DPIE) (formerly the NSW Department of Environment and Climate Change (DECC)) 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.

Aaso (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.

4 Acid sulfate soil prioritisation method

4.1 Preamble

Section 3 outlines how acid sulfate soils (ASS) were formed and why they are an issue in coastal NSW. This study prioritises subcatchments of coastal floodplains below 5 m AHD based on the risk of acid drainage from ASS and low oxygen blackwater. This section outlines the method developed for the prioritisation of ASS affected subcatchments within coastal floodplains.

The objective ASS priority assessment is structured around two (2) major components:

(i) a surface water drainage factor; and
(ii) a groundwater factor.

Each component is formulated by a range of environmental factors/processes that determines the risk of acid production from an ASS affected floodplain subcatchment. These factors are combined within a benchmarked algorithm to rank each subcatchment in terms of acidic discharge risk within an individual estuarine floodplain. This section details the information and data required to determine each factor used in the ASS prioritisation assessment. The prioritisation method used in this study does not consider improvements made through historical remediation efforts. However, any previous on-ground work is considered in the individual management options.

The methods described in this section have been developed with an understanding of the data available in the seven (7) estuarine floodplains considered in this study. The method was developed to ensure that there was sufficient confidence in the base data in each of the floodplains included in the study.

4.2 ASS Prioritisation factors

The ASS prioritisation methodology is fundamentally based on environmental factors that contribute to acid flux (i.e. discharge x acid concentration) from a drained, ASS-affected floodplain area. The final prioritisation factor is a function of two individual factors – a surface water factor and a groundwater factor, as shown in Equation 4-1.

$$\boldsymbol{Prioritisation\ factor = Surface\ water\ factor \times Groundwater\ factor} \qquad \textbf{Equation 4-1}$$

The surface water factor (Equation 4-2) combines information of how heavily drained the catchment is (drainage density factor) and how large the catchment is that drains through the ASS affected soils (inflow factor). This is a measure of the mobilisation and transport potential of acid leachate from the ground, into nearby receiving waters. The surface water factor is normalised against the largest subcatchment within an individual floodplain via the inflow factor. More information on the computation of the surface water factor is provided in Section 4.3.

$$\textit{Surface water factor} = \textit{drainage density factor} \times \textit{normalised inflow factor} \qquad \textbf{Equation 4-2}$$

The groundwater factor (Equation 4-3) incorporates the hydraulic conductivity of the soils (hydraulic conductivity risk factor) and the acidity of the soils (pH factor). This is an indication of how acidic the soils are, and how easily acid can flow from the ground into surface waters. More information on the computation of the groundwater factor is provided in Section 4.4.

$$\textit{Groundwater factor} = \textit{hydraulic conductivity risk factor} \times \textit{pH factor} \qquad \textbf{Equation 4-3}$$

The final prioritisation factor is used to rank each drainage unit to identify areas with the highest risk of ASS oxidation and mobilisation within an estuarine floodplain.

4.3 Surface water factor

A surface water factor is calculated for each subcatchment or drainage unit within the relevant floodplain. The surface water factor is comprised of:

- Drainage density factor = total drainage length / floodplain subcatchment area; and
- Inflow factor = catchment runoff coefficient x catchment size factor.

4.3.1 Drainage density

The drainage capacity of a floodplain drainage network influences the potential for acid drainage from the floodplain. Drain dimensions (length, width and depth) are critical factors with respect to ASS oxidation and mobilisation. For example, a long, wide drain, that is deeply incised into the acidic soil layers (AASS and PASS), poses a greater potential environmental risk, than a short, narrow drain with a high invert. Similarly, a location that has a larger number of drains (per unit area) has a greater potential for ASS oxidation and mobilisation.

In the prioritisation methodology, drainage density refers to the length of the drainage network relative to the floodplain area which is being drained. A subcatchment with a greater drainage density would have a higher drainage capacity, when compared to a similar sized subcatchment with a lower drainage density. Therefore, a subcatchment with a greater drainage density is associated with a high priority risk rating. The drainage density is expressed in a measurement of metres of drain per square kilometre of floodplain area as shown by Equation 4-4. ‘Floodplain area’ in the equation is defined as the area below the 5 m AHD contour and classified as having a high or low risk ASS (as per Naylor et al., 1995). The data required, data sources and assumptions are summarised in Table 4-1. Note that only drain length is considered; width and depth are not included in the calculation of drainage density.

$$\textit{Drainage density factor} = \frac{\textit{Total drain length } (m)}{\textit{Floodplain area } (km^2)} \qquad \textbf{Equation 4-4}$$

Table 4-1: Inputs and data sources to calculate drainage density factor

Required Input	Data Source	Assumptions
Floodplain catchment area	1 m DEM downloaded from https://elevation.fsdf.org.au/ ASS Risk Maps download from https://data.nsw.gov.au/data/dataset/acid-sulphate-soils-ass-planning-maps	Floodplain area contributing to ASS is bounded by the area below 5 m AHD contour and classified as high or low risk of ASS by risk mapping.
Drainage length	Custom drainage layer, described in detail in Section 12	Only drains falling within the floodplain area (as defined above) are counted. Drainage layer does not capture all drains – particularly smaller paddock scale drains. These are therefore not considered. Both artificial and natural waterways are included in measurement.

4.3.2 Normalised inflow factor

The combination of a runoff coefficient and a normalised catchment size factor is used to estimate the relative water yield of each subcatchment of the floodplain. The inflow factor accounts for the potential runoff from each subcatchment following a rainfall event and is determined by multiplying the runoff coefficient by the catchment size factor as per Equation 4-5.

$$\begin{aligned}&\boldsymbol{Normalised\ inflow\ factor}\\&\quad = \boldsymbol{Runoff\ coefficient} \times \boldsymbol{Catchment\ Size\ Factor}\end{aligned}$$ **Equation 4-5**

The runoff coefficient provides a relationship between rainfall-runoff volumes and allows for varying areas of pervious and impervious surfaces in a subcatchment. The runoff volume (m^3) from a catchment is calculated using the following formula in Equation 4-6.

$$\boldsymbol{V_c = CiA}$$ **Equation 4-6**

Where:

C = runoff coefficient (dimensionless)
i = rainfall depth (mm) equal to rainfall intensity (mm/hr) x storm duration (hrs)
A = area of catchment (m^2).

The runoff coefficient can be determined by comparing the volume of runoff generated by precipitation from incident rainfall with the observed subsequent streamflow data.

WaterNSW operates a network of flow gauges throughout NSW with typically one or two gauges in each of the low-lying coastal floodplain catchments. The upstream contributing catchment for each flow station site can be delineated using standard GIS techniques based on a digital elevation model

(DEM). Long term daily rainfall data relative to each flow gauging station is available from the Bureau of Meteorology (BOM). Required inputs and data sources for the calculation of the runoff coefficients are summarised in Table 4-2.

Table 4-2: Inputs and data sources to calculate runoff coefficient

Required Input	Data Source	Assumptions
Flow data	WaterNSW daily flow data at appropriate locations downloaded from https://realtimedata.waternsw.com.au/	Only gauges near the floodplain were analysed (typically 1 to 2 in an estuary).
Upstream catchment size for flow locations	5 m DEM downloaded from https://elevation.fsdf.org.au/	Delineated using standard GIS techniques.
Rainfall data	BOM daily rainfall data at appropriate locations downloaded from http://www.bom.gov.au/climate/data/	Thiessen polygons encompassing all BOM stations. Where the catchment flowing to the WaterNSW flow gauge falls within more than one Thiessen polygon, rainfall is weighted by area.

When comparing subcatchments of similar ASS potential, a larger subcatchment with larger flows will have a greater potential to discharge more acid than a small catchment with smaller flows. That is, an ASS affected drainage unit with a large catchment area contributing to acid drainage has a greater potential to produce acid flux during a post-flood recession period. Subsequently, accurate estimates of subcatchment areas and the potential discharge from those areas are critical for identifying drainage units that are of high-risk for acid drainage.

The subcatchments of a coastal floodplain are typically comprised of both steep, upland catchments, and flat, low-lying floodplain catchments. For the purpose of this study, the ‘floodplain’ catchments have been defined as areas that are below 5 m AHD and classified as at risk for ASS by Naylor et al. (1995), shown in yellow in Figure 4-1. The whole floodplain area is considered to potentially contribute to acid drainage. As shown in Figure 4-1, upland catchment (above 5 m AHD) has been divided into areas discharging to the estuarine receiving water via an end-of-system floodgate or discharge uninhibited to the estuary. In this study, only upland catchments that are upstream of floodgates are considered to contribute to acid drainage potential. Floodgates artificially lower the surface water table resulting in a greater hydraulic gradient between the groundwater table, thereby exacerbating acid drainage. Waterways that are not floodgated are also likely to be natural waterways and are therefore less likely to be artificially excavated into acid soils. Contributing catchments have been delineated using standard GIS techniques.

To allow comparison of catchment size within an individual estuarine floodplain, the total contributing areas of each subcatchment were then normalised against the subcatchment with the largest total area (i.e. catchment size factor = 1.0). Required inputs and data sources for the calculation of the catchment size factor are summarised in Table 4-3.

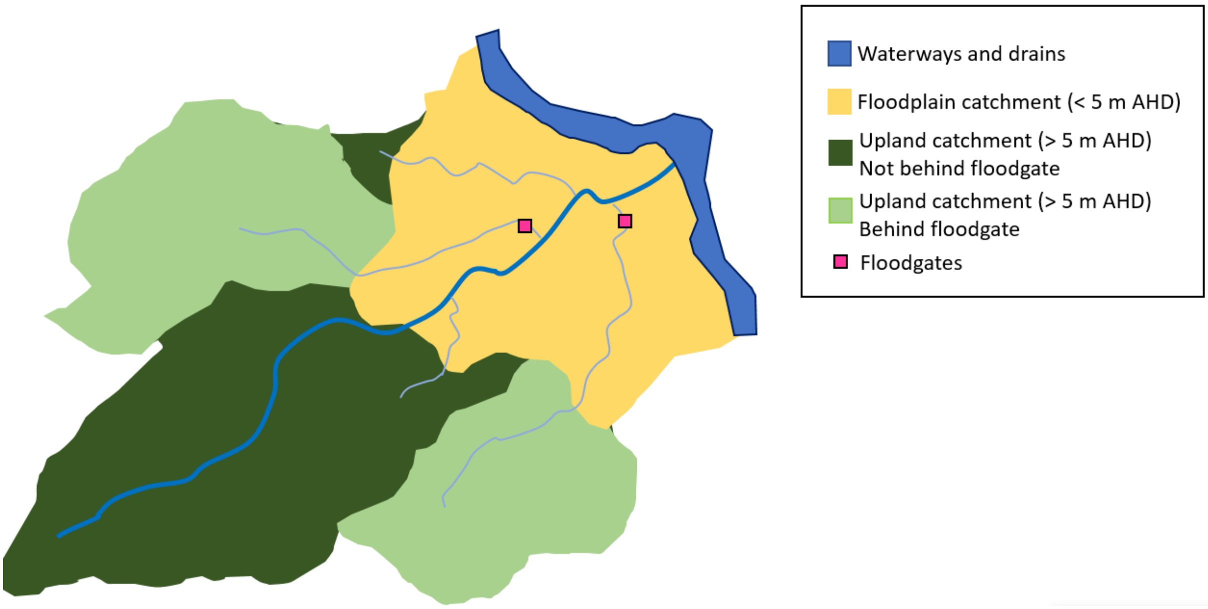


Figure 4-1: Floodplain catchment and upland catchments behind floodgates and not behind floodgates

Table 4-3: Inputs and data sources to calculate catchment size factor

Required Input	Data Source	Assumptions
Floodgate locations	Floodgate locations provided by the responsible agency. Further information on floodplain infrastructure can be found in individual reports.	All floodgates have catchments that could potentially contribute to acid drainage.
Major drainage lines	SixMaps hydrography layer downloaded from https://maps.six.nsw.gov.au/arcgis/rest/services/public/NSW_Hydrography/MapServer/layers	Only drainage lines included in this layer considered.
Upland catchments	30 second DEM downloaded from https://elevation.fsdf.org.au/	Delineated using standard ArcGIS techniques.

4.4 Groundwater factor

The groundwater factor provides a measure of the ASS oxidation and mobilisation potential of a subcatchment. This factor includes:

- Hydraulic conductivity (K_{sat});
- Measured acidity (pH) of the soil, groundwater, and/or adjacent surface water, expressed as hydrogen protons (H+) (µmol/L); and
- Potential acid gradient, or thickness of the acid zone contributing to the risk of acid discharge, between the AASS layer and the lowest drain water level (i.e. mean low water spring tidal level (MLWS)).

The groundwater factor is calculated by multiplying a hydraulic conductivity risk factor by a pH factor (which accounts for acidity, acid soil layer thickness and acid layer elevation with respect to lowest drain water level), as shown in Equation 4-7.

$$\boldsymbol{Groundwater\ factor} \\ = \boldsymbol{hydraulic\ conductivity\ risk\ factor} \times \boldsymbol{pH\ factor}$$

Equation 4-7

4.4.1 Hydraulic conductivity risk factor

The potential for water to flow through the soil matrix in the saturated zone is known as the hydraulic conductivity (K_{sat}) (Dunn, 1980; Dent, 1986). A high hydraulic conductivity implies a greater potential groundwater flow rate. In high-risk ASS-affected floodplains, a high K_{sat} increases the potential for acid to be mobilised from the soil matrix into surface waters (Johnston et al., 2009). The hydraulic conductivity of soils can be determined by standard field and laboratory techniques described in Appendix A, although there can be variability depending on the method used (see Appendix B). Acknowledging the variability of the measurements, hydraulic conductivity has been included as a risk rating (adapted from Johnston and Slavich (2003); Johnston et al. (2003a)), as shown in Table 4-4 (more information is provided in see Appendix B). All available hydraulic conductivity measurements in each subcatchment are collated and averaged, and a subcatchment K_{sat} risk factor is assigned. Required inputs and data sources for the calculation of the hydraulic conductivity risk are summarised in Table 4-5.

In some cases, no available hydraulic conductivity in an individual subcatchment was available, and the risk rating from adjacent subcatchment(s) with similar geology was adopted.

Table 4-4: Approximate K_{sat} ranges and associated risk factor (adapted from Johnston and Slavich (2003))

Hydraulic Conductivity Range (m/day)	Category	Risk Factor
~0	Extremely Low	1
<1.5	Low	2
1.5 – 15	Moderate	3
15 – 100	High	4
>100	Extremely High	5

Table 4-5: Inputs and data sources to calculate hydraulic conductivity risk

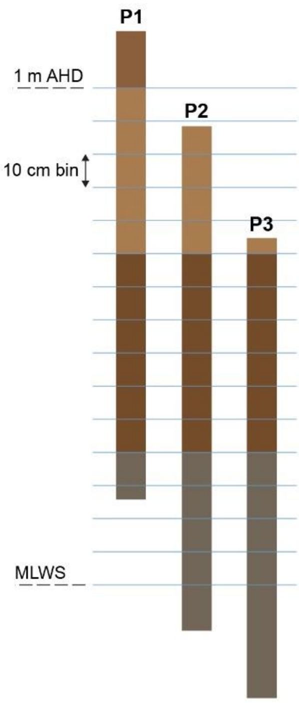
Required Input	Data Source	Assumptions
Hydraulic conductivity measurements	• WRL measurements (methods for measurement summarised in Appendix A and Appendix B). • Field data collected by Hirst et al. (2009) in NSW coastal floodplains. • Other available literature.	To reduce uncertainty related to the method of measurement, hydraulic conductivity is included as a risk factor.

4.4.2 pH Factor

The extent of ASS across a coastal floodplain is a key component of the priority assessment and contributes to the acidity component of the groundwater factor. Soil acidity is an accurate way of identifying the potential risks associated with acid discharges of a subcatchment (Sullivan et al., 2018), and is independent of external environmental factors (e.g. dilution via rainfall, bacterial oxidation causing a drop in pH etc.) that may artificially manipulate the acidity of drain water and receiving waters. Note that since pH is a logarithmic measure of hydrogen protons (H^+), pH values are converted to H^+ concentrations (µmol/L) before being utilised in the priority assessment to determine the groundwater factor.

There are two major components of the pH factor; (i) the depth averaged H^+ concentrations, and (ii) the depth of soil potentially contributing to acid drainage. The depth of soil contributing to acid drainage was considered to be the difference in elevation between the lowest water level in the adjacent surface water drains and 1 m AHD. This 1 m AHD elevation cut-off for ASS contribution was based on the work of Naylor et al. (1998), who established the upper limit for ASS in NSW to be typically around 1 m AHD (i.e. layers between 1 m AHD and the surface topography are typically not ASS). This is consistent with data collected for this project, where only 3.5% of layers, from over 100 samples, collected above 1 m AHD had a pH below 4.5. Adopting this level removes any reliance on the elevation of the soil profiles collected, and accounts for variability in soil profile data between floodplain catchments. In the absence of widespread water level monitoring in all surface drains within the study regions, the mean low water spring (MLWS) tide level in the main river channel was adopted as the lowest surface water elevation in floodplain drainage systems. This provides a lower elevation boundary for potential ASS drainage and the depth of soil that regularly contributes to acidic drainage. As most of the floodplain areas considered in this study have one-way floodgates installed, floodplain surface waters will typically continue to drain until the downstream low tide level is reached. As such, the low tide river levels are a suitable proxy for long-term average water levels within the floodplains. Tidal planes at each of the water level gauges (operated by MHL on behalf of DPIE) in the estuary were adopted based on Couriel et al. (2012) and the MLWS level at the closest level gauge to each subcatchment was adopted.

Soil profile data was used to determine the depth averaged H^+ concentration. The soil data available (both collected by WRL for this project and from existing literature) varied in terms of location, surface elevation and total depth analysed. Ideally, all profiles would include H^+ concentration data (noting that H^+ concentration is equal to 10^{-pH}) for the entire contributing depth (1 m AHD to MLWS), however this is not always the case. To minimise the bias of the particular geometry of any one profile on the representative acidity of a subcatchment, the H+ concentration data was separated into 10 cm bins and then averaged across all profiles collected in a subcatchment to develop a representative soil profile that has data across the elevation range contributing to acid drainage (shown in Figure 4-2 with a three hypothetical profiles).



	pH in bin			H+ concentration in bin (µmol/L)			
Bin height (cm)	P1	P2	P3	P1	P2	P3	Average H+ concentration in bin (µmol/L)
10	5	-	-	10	-	-	10.0
10	5	4.5	-	10	31.6	-	20.8
10	5	4.5	-	10	31.6	-	20.8
10	5	4.5	-	10	31.6	-	20.8
10	5	4.5	5	10	31.6	10	17.2
10	4.5	4	4	31.6	100	100	77.2
10	4.5	4	4	31.6	100	100	77.2
10	4.5	4	4	31.6	100	100	77.2
10	4.5	4	4	31.6	100	100	77.2
10	4.5	4	4	31.6	100	100	77.2
10	4.5	4	4	31.6	100	100	77.2
10	8	6	7	0.01	1	0.1	0.4
10	8	6	7	0.01	1	0.1	0.4
10	-	6	7	-	1	0.1	0.6
10	-	6	7	-	1	0.1	0.6

Figure 4-2: Illustration of the process of establishing a representative H^+ concentration profile from a hypothetical subcatchment with three (3) soil profiles

The depth averaged H^+ concentration is then calculated as per Equation 4-8 and the pH factor calculated as per Equation 4-9. Table 4-6 summarises the required inputs, data sources and assumptions used to calculate the pH factor.

$$\textbf{Depth averaged } H^{+} \textbf{ concentration} = \frac{\sum_{MLWS}^{1\,m\,AHD} \textbf{Bin size} \times \textbf{Ave } H^{+}\textbf{concentration}}{\mathbf{1\ m\ AHD - MLWS}}$$ **Equation 4-8**

$$pH\ factor = Depth\ averaged\ H^{+}\ concentration \times contributing\ depth$$ **Equation 4-9**

Table 4-6: Inputs and data sources to calculate pH factor

Required Input	Data Source	Assumptions
Soil profile acidity	WRL measurements (methods of collection shown in Appendix A . Collated soil profile field data in NSW government database eSpade available at https://www.environment.nsw.gov.au/eSpade2Webapp Other available literature.	Where the surface elevation has not been provided, elevation has been extracted from the 1 m DEM.
MLWS tidal plane	Couriel et al. (2012) provides the analysis of tidal planes at all tidal NSW gauges. All gauges can be viewed at https://www.mhl.nsw.gov.au/data/realtime/WaterLevel	Typically, there are 5 to 8 water level gauges throughout each estuary. The nearest gauge is used for the mean low water spring (MLWS) level.

It should be noted that for the Shoalhaven River floodplain, the pH factor was determined using a separate method due to lack of soil profile data. This is further explained in Section 4.4.3 below and in the individual estuary report.

4.4.3 Water quality pH factor

In the absence of accurate soil profile acidity data, wet weather water quality information can be used in the priority assessment to calculate the acidity component of the groundwater factor. While field measurements of drain water quality (i.e. acidity) during dry periods can provide an indication of the potential risk associated with discharges from a future acid event, the measurement of actual acid flux during and after a wet weather event is preferred. Field measurements of post-flood discharges and water quality enables the total acid flux from a drain to be determined, as well as the contribution of each drain in the drainage network to the overall risk to estuarine water quality.

Wet weather water quality was used for seven (7) flood mitigation drainage areas on the Shoalhaven River floodplain, where the soil profile data was insufficient to calculate the pH factor as described above. In this case, the pH factor was calculated by Equation 4-10.

$$\boldsymbol{pH\ factor} = \mathbf{10^{6}} \times \mathbf{10^{-\,wet\ weather\ pH}}$$ **Equation 4-10**

5 Blackwater theory

5.1 Preamble

Fish kills associated with flooding have been documented in NSW since the start of the 20th century (Moore, 1996). More recently, it has been established that fish kills typically occur due to the discharge of deoxygenated water, often referred to as 'blackwater', from coastal backswamps and floodplains, which is lethal to aquatic fauna (Walsh et al., 2004). This section outlines the key processes relating to the generation of blackwater.

5.2 What is blackwater?

'Blackwater' is dark coloured water that is characterised by high dissolved organic carbon (DOC) and reduced levels of dissolved oxygen (DO) in the water column (Moore, 1996). The discolouring of the water emanates from carbon compounds released into the water column as organic matter decays, which includes tannins (Howitt et al., 2007). It is often associated with flooding, as floods act as a link between the floodplains (rich in organic matter) and the adjacent river channel (where the main impact occurs). Although blackwater events are a natural part of a lowland river ecosystem (Hladyz et al., 2011), the frequency, timing and the magnitude of their occurrence has been exacerbated by anthropogenic alterations of floodplain hydrology and vegetation (Wong et al., 2010).

Blackwater events are categorised by the processes that lead to their formations either as hypoxic blackwater or humic (dystrophic) blackwater (see Figure 5-1). A detailed description of the processes leading to the formation of these two types of blackwater is presented in the following Sections 5.3 to 5.5. For most NSW coastal floodplains, large scale blackwater events are typically associated with hypoxic blackwater generated from organic inputs.

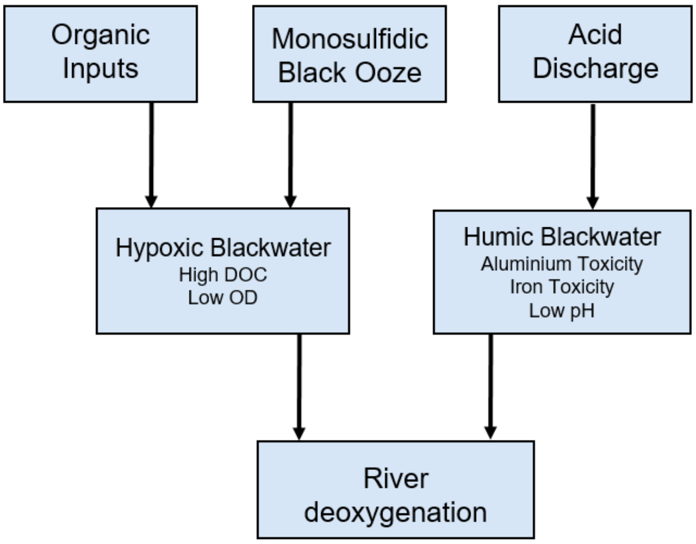


Figure 5-1: Formation of hypoxic and humic blackwaters. Modified from Moore (1996)

5.3 Humic (dystrophic) blackwater

Humic blackwater is not the focus of this study, however it is discussed briefly here for completeness. Low dissolved oxygen blackwater can also be formed when humic acid naturally leaches from decaying organic matter into water bodies (Moore, 1996). The humic acid discharged into the river system may increase aluminium and iron toxicity, which lowers the pH posing a risk to the aquatic organisms. These humic blackwaters are not typically black in colour, but they pose significant threats to the environment. Although, it occurs in streams which have perennial elevated Dissolved Organic Carbon (DOC) characteristics (Kerr et al., 2013), the majority of elevated DOC in these streams/rivers has low bioavailability. Therefore, widespread hypoxia does not generally occur in these kinds of conditions as compared to the case of hypoxic blackwaters (Meyer and Edwards, 1990). Hypoxic blackwater is the primary focus of this assessment and is discussed in detail below.

5.4 Hypoxic blackwater

Hypoxic blackwater is formed when organic matter within the water column is rapidly metabolised, leading to a consumption of dissolved oxygen from the waterbody (Whitworth et al., 2013). Hypoxic blackwater events occur periodically in riverine and estuarine systems that are normally well oxygenated and have low-to-medium DOC (Kerr et al., 2013). Despite being a natural phenomenon, the extensive alteration of floodplain drainage to promote agriculture, and the subsequent changes in vegetation, have exacerbated the frequency, magnitude and impact of hypoxic blackwater events (Kerr et al., 2013; Wong et al., 2010). Hypoxic blackwater produced as a result of decomposition of organic matter, is discussed in detail in Section 5.5 and 5.5.1.

Hypoxic blackwaters can also occur following the mobilisation of Monosulfidic Black Ooze (MBOs) in the waterbody, which results due to deposition of acid sulfate soils by-products in waterway bed sediments. MBOs are discussed in Section 5.5.2.

5.5 Formation of hypoxic blackwater by organic inputs

Kerr et al. (2013) outlined a number of processes that lead to formation of hypoxic blackwater events (see Figure 5-2). These include:

- Accumulation of organic matter between flood events, which supplies DOC for metabolism;
- Inundation of the floodplain during flood events, causing leaching of carbon compounds. DOC in the water column begins to increase;
- Aerobic decomposition of DOC by micro-organisms consumes DO in the water column. This is signified by an increase in the Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) in the water;
- In cases of high DOC concentration, the rate of oxygen consumption may exceed oxygen re-aeration within the water column, which depletes oxygen rapidly causing anoxic conditions (Kerr et al., 2013, Ning et al., 2015); and
- This results in a hypoxic blackwater event, which can be harmful and even lethal to many aquatic biota, including fish and crustaceans (Ning et al., 2015, McCarthy et al., 2014).

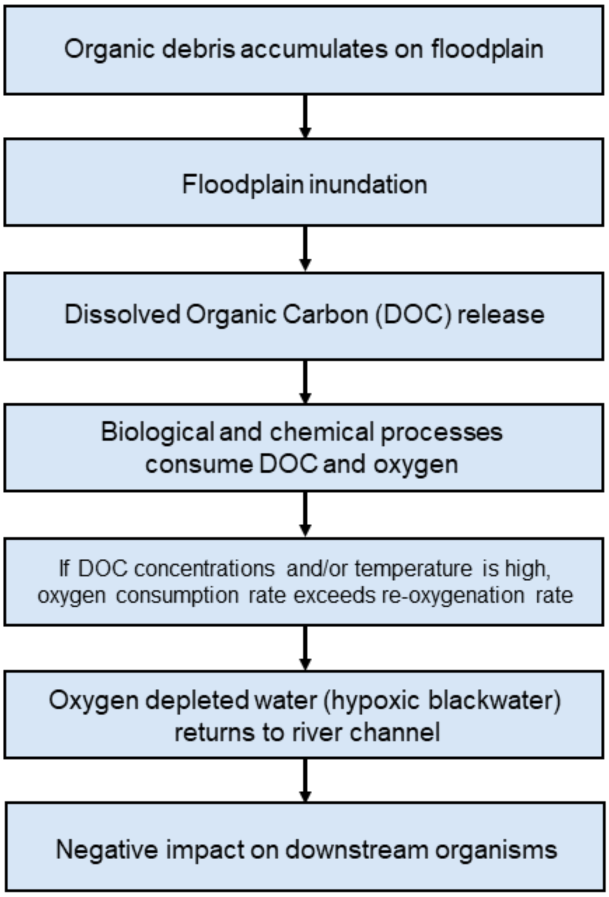


Figure 5-2: Processes leading to formation of hypoxic blackwater (Kerr et al., 2013)

The process of blackwater generation is illustrated in Figure 5-3 and Figure 5-4. Figure 5-3 depicts a period during or immediately following a flood event, whereby floodplain areas are inundated with flood waters. Prolonged inundation can occur due to elevated water levels in the main river channel which can lead to the decay of organic matter and to the production of blackwater. During this period, large freshwater flows in the main river channel keep water levels in the main river high, preventing discharges from the backswamp.

Figure 5-4 depicts the discharge of standing waters, including blackwater, into the receiving water. Once water levels in the main river channel have lowered below backswamp levels, floodwaters begin to drain. The timing and rate of drainage are strongly dependent on the flood behaviour in the main river, as well as the overall efficiency of the floodplain drainage system. Depending on the site-specific geometry of the receiving waters, blackwater discharges can be quickly flushed and mixed with main river flows, or persist in the receiving water as large plumes. If the blackwater has a sufficiently high deoxygenation potential (i.e. high DOC and BOD), it will also continue to reduce dissolved oxygen in the receiving water. In cases where the assimilation capacity (discussed in Section 5.5.3) of the receiving waters is limited, this can result in large scale deoxygenation of the receiving water body and impact downstream organisms (Wong et al., 2011b).

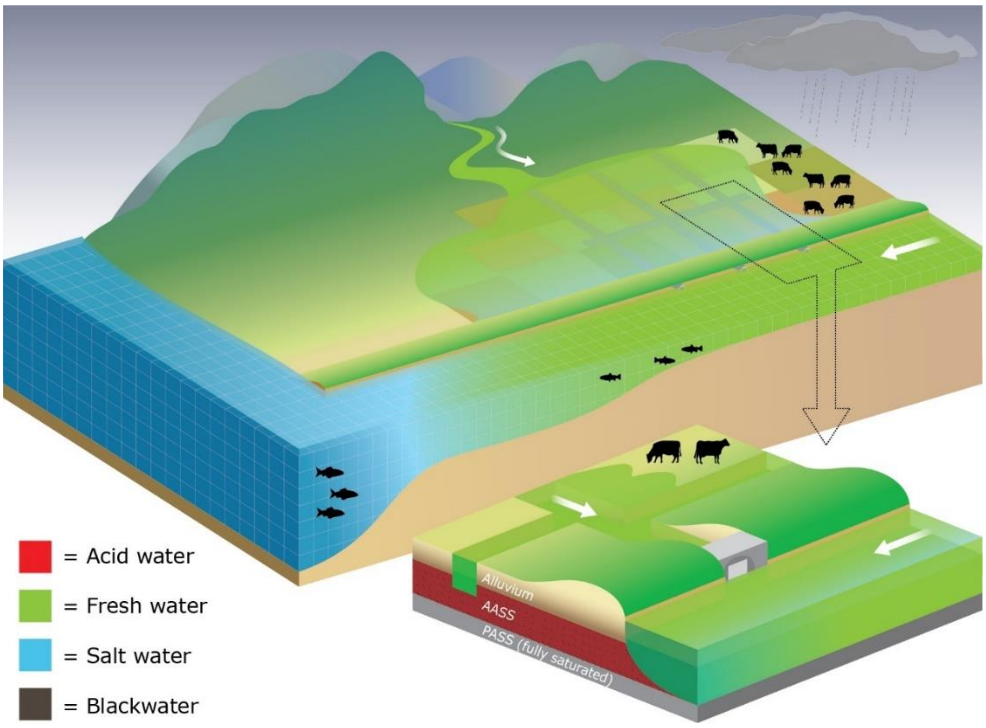


Figure 5-3: Catchment inflows or river flooding inundates floodplain areas, with elevated receiving water levels restricting drainage, resulting in prolonged floodplain and the formation of low DO blackwater

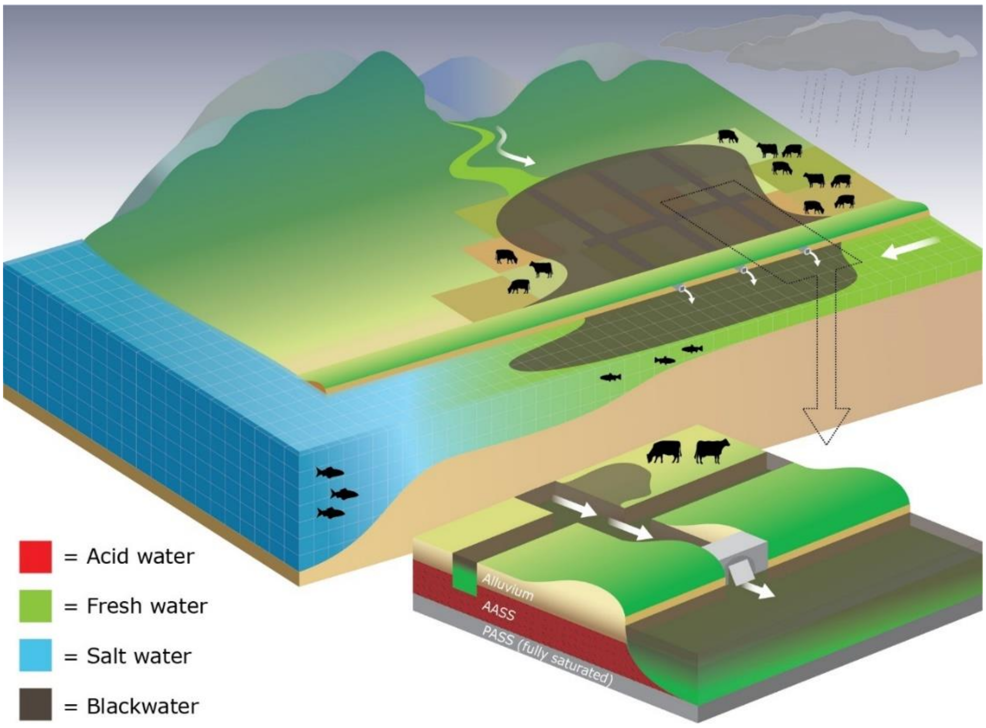


Figure 5-4: Blackwater discharging to receiving waters

5.5.1 Main factors and processes in the formation of hypoxic blackwater by organic inputs

Figure 5-2 shows the processes that lead to the formation of hypoxic blackwaters from the decomposition of organic material. Each one of these steps is associated with a number of physical factors that control the magnitude of a potential blackwater event. This section provides a breakdown of the factors that impact hypoxic blackwater formation in coastal floodplains.

i. Antecedent weather conditions

Antecedent weather conditions are important in considering the potential for blackwater generation, as it influences the accumulation of organic matter on the floodplain. This is relevant mainly during extreme climate conditions, such as prolonged drought followed by significant floods. During long droughts (or between floods), organic matter builds up on the floodplain and in dry channels. Typically, the mass of litter on floodplains increases the longer the period since the last flood event (Xiong and Nilsson, 1997).

Wong et al. (2018) assessed the influence of antecedent weather conditions on the likelihood of a blackwater-induced fish kill event in the Richmond River catchment during the past 100 years. The study found that fish kills were more common when the previous six (6) months had been drier than usual prior to the flooding event. The main contributing factors were:

1. A greater accumulation of organic material on the floodplain; and
2. Increased litterfall as a stress response by the riparian and floodplain vegetation under extended periods of drought (Whitworth et al., 2012).

While drier than average conditions are favourable for accumulation of organic matter on the floodplain, wetter than average conditions act in the opposite way, reducing the amount of DOC that is available, thereby lowering the risk of blackwater generation (Hladyz et al., 2011). The amount of carbon leached from organic matter also reduces when the litter has been previously inundated. Therefore, extended periods of dry weather prior to a flood event increase the likelihood and severity of a potential blackwater event in the affected water body.

ii. Inundation of floodplain vegetation

Inundation of floodplain vegetation is a primary driver of the release of DOC after a flood event, and subsequently increases the BOD that depletes dissolved oxygen in the water column. The importance of vegetation as a source of carbon for microbial respiration with respect to the deoxygenation potential of landscapes was established by the results of mesocosm experiments in the Richmond River (Eyre et al., 2006) and in the Edward-Wakool River system (Hladyz et al., 2011). Both experiments determined the BOD of a variety of representative vegetation types and confirmed the potential for the process of microbial decomposition of inundated floodplain vegetation alone to deplete oxygen levels sufficiently to trigger a blackwater event.

Numerous studies have shown with inundation experiments that DO in standing water can reach near 0 mg/L within a relatively short period of time, often after less than 24 hours (Eyre et al., 2006; Johnston et al., 2005b; Liu et al., 2019). However, the deoxygenation potential (DOP) of the water is also an important consideration (Eyre et al., 2006; Wong et al., 2011b). Even when DO in the standing water on backswamps reaches zero, the decomposition of organic matter continues to occur. This microbial activity has the potential to deoxygenate substantial volumes of water once released into the wider estuary (Eyre et al., 2006). DOP is a combination of several factors, including labile carbon concentration (often measured by DOC as a proxy) and temperature (Wong et al., 2011b; Wong et al., 2011a) which can continue to rise even after the DO in the immediate water column is stripped.

An indication of the potential oxygen consumption by various vegetation types can be found in the results of leaf litter decomposition experiments completed to examine the processes of nutrient cycling in streams. These studies often refer to the lability of the vegetation. Labile carbon is the carbon that is readily available for use by micro-organisms and a higher lability is associated with faster decomposition. Labile carbon content is therefore an appropriate measure for comparing the impact of various vegetation types on blackwater generation.

Globally, litter from evergreen conifer forests displayed much lower decomposition rates than that from deciduous or evergreen broad-leaf forests (Zhang et al., 2019). This was attributed to lower nutrient content and more recalcitrant structural (lignin and cellulose) and aromatic (tannin and polyphenols) compounds. This is consistent with the conclusions made by Johnston et al. (2003b) regarding the impacts of flooding observed in the Clarence River in 2001. The relatively high oxygen demand from the Everlasting Swamp subcatchment was attributed to the dominance of labile dryland pasture species compared to the Shark Creek subcatchment which is predominately vegetated by recalcitrant *Melaleuca quinquenervia* forest. Wong et al. (2011b) consequently suggested that a change in land use from native forest to more labile dryland pasture or an increase in the biomass of pasture species would increase the deoxygenation potential of a landscape. Floodplains dominated by endemic wetland plant species are therefore generally considered to be less likely to develop anoxic floodwaters than those that have been drained and replanted with pasture grasses or crops that are less tolerant of inundation (Vithana et al., 2019). Five (5) Australian studies have assessed the impact of different vegetation types on the creation of blackwater and are summarised in Table 5-1.

Beyond the vegetation type, land practices also have an impact on availability of carbon on the floodplain. While most living, rooted plants will eventually start to decompose when subjected to sustained inundation, the presence of organic debris (e.g. leaf litter, slashed pasture or non-harvestable trash from crops) on the floodplain floor provides significant, more readily available carbon once inundated (Eyre et al., 2006) and can result in a higher deoxygenation potential (Lin et al., 2004). The current literature suggests that various vegetation and land cover types all have the ability to deoxygenate a body of water. The use of discrete vegetation types or land use categories as a means of differentiating the potential for blackwater generation over various subcatchments is limited by differences in land management (both historic and current) and intensity of use.

Table 5-1: **Brief summary of Australian literature on quantifying the effect of vegetation type on blackwater generation**

Reference	Experiment Type and Location	Vegetation Types	Comments/Conclusions
Eyre et al. (2006)	Laboratory tests measuring DO consumption of inundated, dried vegetation. Richmond River, NSW	Pasture grass Smartweed Canetrash Wheatstraw Paperbark leaf Grey rush Cane stem Cane billets	Pasture grass consumed oxygen substantially quicker than other vegetation types. Grey rush consumes oxygen relatively slowly. Cane trash consumes oxygen more quickly than paperbark or grey rush, but cane stems have a very low consumption rate.
Eyre et al. (2006)	Field mesocosm, 300 mm inundation experiments measuring DO level over 10 hours. Richmond River, NSW	Slashed pasture Dropped tea tree Harvested cane	Slashed pasture consumes oxygen most quickly. Tea tree consumes oxygen quickly initially but tapers off relatively quickly.
Johnston et al. (2005a)	Laboratory mesocosm experiments with 200 mm inundation, measuring DO. Clarence River floodplain, NSW	Grass – pennisetum Grass – cynodon dactylon Melaleuca	DO depletion was notably slower in melaleuca than the grasses.
Liu et al. (2019)	Mesocosm experiments with 450 mm inundation, measuring BOD/DOC/DO over 16 days Murray Darling Basin	Paddock soil + wheat Forest soil + leaf litter Forest soil + wallaby grass Paddock soil + ryegrass Bare paddock soil Bare forest soil	DOC concentrations in leachate derived from inundated floodplain soils with vegetation were similar, regardless of the vegetation type or whether it was from forests or paddocks. There are some differences in DOC over the 16 day period, with forest soil + leaf litter having the highest DOC on days 8 and 16.
Whitworth and Baldwin (2016); Whitworth et al. (2013)	DOC leaching at 20°C Ovens River, Victoria	Leaves Grass Bark Soil Twigs	DOC leeching was greatest in leaves (approximately double grass). Contribution of twigs and soil is comparatively small.

iii. Temperature

Temperature is a key factor in the development of hypoxic blackwater and its role has been investigated extensively (Mallin et al., 2006; Howitt et al., 2007; Whitworth and Baldwin, 2016). Although Australian coastal floodplains experience flooding during both winter and summer seasons, the role of temperature in the development of hypoxia results in blackwater events being more frequent and severe during summer months (Wong et al., 2010).

Temperature influences the generation of blackwater via three (3) main mechanisms:

1. affecting the leaching of DOC;
2. affecting the decomposition of DOC; and
3. affecting the DO saturation in the water bodies.

Temperature influences the amount of carbon leaching from inundated vegetation and consequently increases the consumption of oxygen (Whitworth et al., 2012). In a series of laboratory experiments, these authors investigated the temperature dependence of carbon leaching and decomposition, specifically from leaves of the river red gum *Eucalyptus camaldulensis.* The experiments showed that the leaching rates as well as DOC consumption by microbiota increased with temperature.

The accelerated microbial decomposition of inundated organic matter then causes rapid consumption of the DO in floodwaters (Hladyz et al., 2011). Vithana et al. (2019) completed inundation experiments of water intolerant pasture grass from the Richmond River floodplain incubated at three different temperatures (20°C, 27.5°C and 35°C) for 20 days. This study showed that higher temperatures (27.5°C and 35°C) resulted in more rapid development of hypoxic conditions than the lower temperature tested (20°C). The influence of temperature was particularly evident for inundation times of less than seven (7) days. However, the study also showed that hypoxia would occur at the lower temperature (20°C) when inundation persisted for more than seven (7) days.

In addition to the effects of temperature on microbial processes, the actual amount of DO (mg/L) in the water varies naturally with temperature. In aquatic environments, oxygen saturation is measured by the ratio of the concentration of DO to the maximum amount of oxygen that will dissolve in that water body at the current temperature, pressure and salinity levels. Dissolved oxygen saturation potential decreases with increasing temperature, lowering the concentrations of DO in surface waters during warmer months (Conley et al., 2007). This further reinforces the impact of temperature on increased risk of blackwater generation.

iv. Floodplain inundation duration and drainage

The prolonged inundation of vegetation will drive the generation of blackwater on a floodplain. However, the size and spatial extent of rainfall and flooding influences floodplain inundation duration, blackwater formation and therefore the subsequent impact on the downstream waterway. Literature suggests that decomposition of organic matter can result in total deoxygenation of standing water on the floodplain in a period of less than one day under certain circumstances (Eyre et al., 2006), although it may take longer for the deoxygenation potential (DOP) of the water to be sufficiently high to also deoxygenate the receiving waters (Johnston et al., 2003b). While the optimum time of inundation taken to maximise the DOP is not well documented, Vithana et al. (2019) and Liu et al. (2019) suggest that both DOC and BOD (which both relate to DOP) can continue rising more than two (2) weeks after the initial inundation event began. Similarly, Wong et al. (2011b) showed that COD (chemical oxygen demand) peaked approximately 15 to 20 days after the flood peak in a backswamp on the Clarence River. This suggests that for floodplain inundation times of less than 14 days (approx.), DOP is likely to be increasing with time.

Given duration of inundation is a significant determining factor in blackwater generation, the following aspects are important to consider:

- In general, a higher magnitude flood event is likely to inundate a greater area over a longer period of time;
- A lower elevation and/or larger backswamp is likely to be inundated over a larger area;
- A backswamp located near the ocean entrance is likely to be inundated to a lower level and for a shorter period time due to flood gradients in estuaries; and
- Conversely, a backswamp located upstream is likely to be inundated to a higher level for a longer period.

Broadly speaking, there are two (2) types of events that can cause floodplain inundation:

1. Widespread rainfall across the whole catchment of the river, resulting in widespread flooding and prolonged river level elevations throughout the estuary; and
2. Localised rainfall in a small portion of the estuary, resulting in localised flooding with minimal or confined impacts on wider river levels.

While both types of events can lead to the generation of anoxic conditions, studies in the Richmond River estuary by Moore (1996) suggest large scale impacts from blackwater (such as mass fish kills) are more likely during whole-of-catchment events from widespread rainfall. During these events, there can be numerous backswamps discharging water with a high DOP at multiple points throughout an estuary. This leaves aquatic life with limited refuge from poor water quality, which might be more readily available if rainfall and high DOP discharges are localised.

The other aspect of localised rainfall that reduces the risk of blackwater generation is efficient drainage. In general, coastal floodplains throughout NSW have been artificially drained to allow for viable agriculture in some of the lowest lying areas (Johnston et al., 2003a). While altering the hydrology has increased the frequency and severity of blackwater events during large floods (discussed in detail in the following section), it does allow for efficient drainage during localised flood events. Without restrictions in drainage from elevated receiving water levels, localised flooding tends to be less prolonged and the risk of blackwater is reduced.

v. *Modified Floodplain Hydrology (Altered Drainage)*

The drainage of floodplains during larger, widespread flood events is ultimately determined by the rate of floodwater recession in the main river channel. While receiving water levels remain elevated, the floodplain cannot drain regardless of the efficiency and scale of drainage infrastructure. Consequently, low-lying backswamps are typically the first areas of the floodplain to be inundated and the last areas to drain.

However, once the floodwaters in the receiving waters begin to recede, drainage efficiency becomes more significant. According to Johnston et al. (2003b), the natural drainage rate of inundated backswamps was often slow due to low outlet channel density, high channel roughness and sinuosity, low hydraulic gradients, and tidal depositional barriers that were found at the mouth of backswamps. Prior to the construction of extensive artificial floodplain drainage, backswamps used to be frequently or permanently inundated and often supported water tolerant vegetation. While blackwater would have naturally been produced on these backswamps historically, the labile carbon content was typically lower (due to water tolerant vegetation) and the backswamps were poorly connected to the river, resulting in relatively minor impact to biota in the main estuary.

However, artificial drainage systems and flood mitigation works were designed to alter the natural drainage of floodplains. The purpose of these drainage systems (Johnston et al., 2003a) was to:

- Reduce the impact of major floods, by promoting rapid removal of floodwaters when the river levels recede;
- Convert natural swamp/wetland area to agricultural dryland by reducing nuisance flooding. It is common for the artificial drainage network to intersect natural levee systems, allowing for drainage beyond the minimum levee height, shown in Figure 5-5; and
- Remove stormwater from agricultural land.

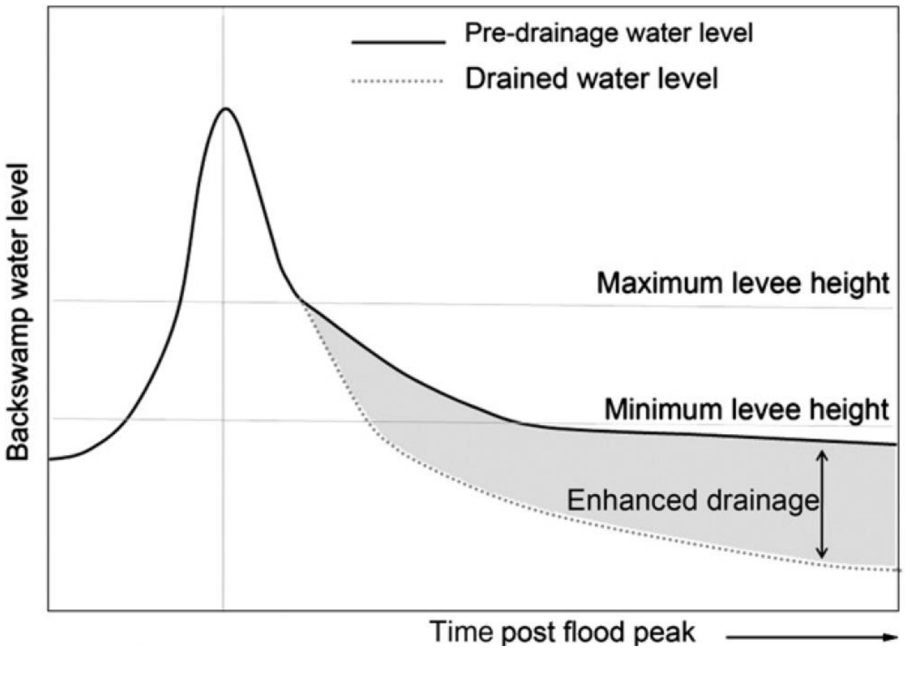


Figure 5-5: Backswamp drainage enhanced through artificial drainage (Wong et al., 2011b)

As discussed in the section above, artificial drainage allows localised floods to drain efficiently. However, during larger widespread flood events, this resulted in substantially modified connectivity of the backswamps with the main river during the flood recession. There are four (4) major effects on blackwater generation in coastal floodplains from improved drainage efficiency:

- A change in vegetation from water tolerant wetland species to dryland agricultural species (pastures and crops) due to improved removal of floodwaters during smaller rainfall events (Eyre et al., 2006; Johnston et al., 2003a);
- Through the same mechanisms, decreases in floodplain inundation frequency due to artificial drainage systems, have allowed increased organic matter (most as plant litter) to accumulate between floods. This has led to an increased concentration of DOC when the next flood inundation occurs (Ning et al., 2015);
- Allowed floodwaters to leave low lying backswamps more rapidly once flood levels in the main river begin to fall. This prevents carbon processes from completing their cycle and transfers the deoxygenated water with high BOD into the greater estuary, causing impacts downstream; and
- The timing of the discharge coincides with when flows are abating in the receiving waters, so the dilution capacity is limited (Johnston et al., 2003b). Receiving waters can be readily impacted by high DOC and BOD discharges from the backswamp, resulting in widespread deoxygenation, shown in Figure 5-6.

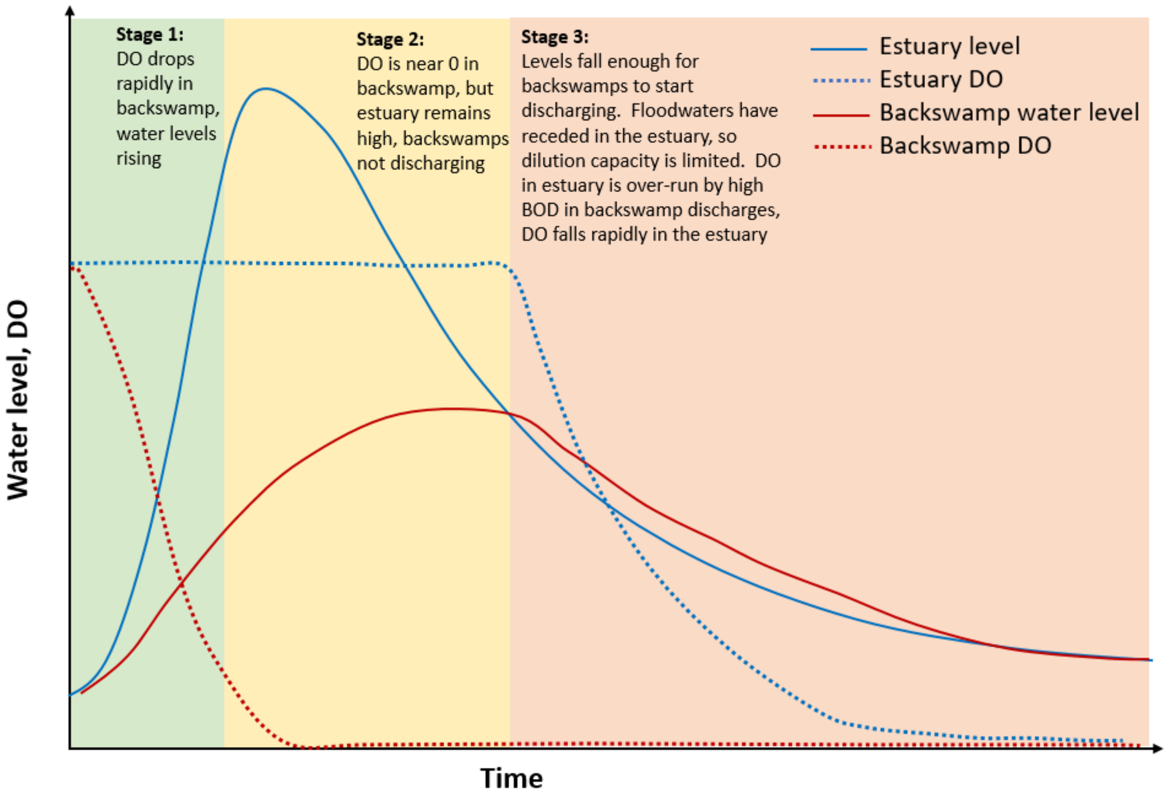


Figure 5-6: Impact of backswamp discharges on estuary DO (adapted from Johnston et al. (2003a))

5.5.2 Formation of hypoxic blackwater by Monosulfidic Black Ooze (MBO)

Monosulfidic black oozes (MBOs) are organic oozes rich in iron monosulfides frequently found in coastal floodplain drain sediments (Moore, 1996). They are formed when organic matter is reduced by sulfate-reducing bacteria in sediments which produce hydrogen sulfide. The hydrogen sulfide reacts with soluble iron and precipitates.

In many coastal drains, the excess supply of carbon from aquatic vegetation and terrestrial inputs may outweigh the aerobic decomposition potential of the system. This excess organic carbon along with abundant iron from surrounding acid sulfate soils landscape produce reducing conditions favourable for the formation of MBOs (Moore, 1996).

MBOs are likely to continue accumulating within the drains until flood events with sufficiently high velocity scour the bottom of the drain and mobilise the sediments, which become suspended and transported to river system. When brought into suspension by high velocities, they immediately begin to oxidise, consuming oxygen from the water column. This is a rapid chemical reaction, which has the potential to consume a significant amount of dissolved oxygen in the water column, and leads to the creation of blackwater.

MBOs generate locally significant blackwater that contribute to blackwater events in coastal estuaries. An example of a blackwater event where MBOs contributed was on the Richmond River in February 2001 when MBOs from Tuckean Swamp were found to contribute to the deoxygenation of 4% of the daily river flows (Moore, 2007). In comparison to hypoxic blackwater events caused through the breakdown of organic matter, MBOs only have a small contribution to the deoxygenation of waterways and generally only affect waterways on a localised scale. Subsequently, they are considered to be secondary to blackwater events caused by the breakdown of organic matter (Moore, 2007).

5.5.3 Assimilation capacity of receiving waters

The assimilation capacity of receiving water refers to the capacity of the river or creek to mitigate the impacts of contaminants entering the system without unacceptable detrimental impacts on the environment (Masini et al., 1992). Assimilation occurs through mixing processes in the river channel such as dilution, flushing or buffering. The sections above largely focus on the mechanisms relating to the formation of blackwater, however it is also important to consider the impact of the discharges when they are flushed into the wider estuary.

The lower estuary generally has a greater assimilation capacity compared to the upper estuary as the proximity of waters within the estuary to the ocean typically results in greater tidal flushing and shorter residence times, as estuarine waters are replaced with a greater volume of ocean water each tidal cycle. As a result of this, blackwater discharges in the lower estuary are generally more diluted and impact the environment less than similar discharges further upstream (Johnston et al., 2003a). Eyre and Twigg (1997) sampled water quality in the Richmond River in the days, weeks, and months after a flood event. They showed that dissolved oxygen saturation was higher in parts of the estuary with higher salinity (e.g. the lower estuary closer to the ocean) for at least the first seven (7) weeks after the flood event.

As illustrated in Figure 5-6, discharges from artificially drained backswamps after flood events tend to occur well after the peak of the flood, when flows in the main river channels are dissipating, reducing the assimilation capacity. If the blackwater discharges from the floodplain are of sufficient volume and severity, they can be enough to overwhelm the receiving water (Moore, 1996). This is more likely to occur when the volume of water held on the backswamp is greater (i.e. the area of the backswamp is larger), and when the volume of the receiving water is smaller, such as a for a minor tributary. Numerous studies have suggested that modifying outflows from backswamps to occur over a longer time period may mitigate some of the environmental impacts of blackwater discharges.

Many of the coastal floodplains in NSW have multiple backswamps that are known for producing blackwater. Water quality data from Rous County Council during a number of different flood events shows that a substantial portion of the mid-to-upper Richmond River estuary can simultaneously become deoxygenated (Rayner et al., 2020). There are a number of backswamps in the Richmond River that are known for high blackwater risk, including Tuckean Swamp, Rocky Mouth Creek and Sandy/Bungawalbin Creeks (Moore, 1996). While any one of these areas has the capacity to impact the river, the catchment wide deoxygenation tends to happen when blackwater is being discharged from all of these areas at the same time, often resulting in catastrophic impacts (Moore, 1996). Plumes of blackwater with low DO and high DOP from each backswamp can join together, well in excess of the assimilation capacity of the river. Widespread deoxygenation leaves few refuges for aquatic life and has been known to result in mass fish kills throughout large portions of estuaries.

6 Blackwater generation prioritisation methodology

6.1 Preamble

Section 5 outlined how blackwater is formed, its impact on estuaries, and why it is an issue in low-lying coastal backswamps. A key outcome of this study is to prioritise drainage subcatchment areas of coastal floodplains to identify locations where the risk of blackwater generation is most prevalent. This section outlines the objective method that has been developed for prioritisation of blackwater areas on the subject coastal floodplains. The prioritisation method only considers hypoxic blackwater generated through the decomposition of organic matter (i.e. it does not consider humic blackwater).

The blackwater priority assessment is structured around two (2) major factors:

1. A contributing area of the catchment that contributes to blackwater production; and
2. The blackwater generation potential associated with different land uses and vegetation types.

These factors have been combined to assess the relative contribution of a subcatchment to the production of hypoxic blackwater in the wider estuary. This section provides detailed information describing the data required to determine each factor used in the priority assessment.

This section includes a brief summary of the methodology used for the quantitative prioritisation (Section 6.2, Section 6.3 and Section 6.4) and a summary of the floodplain characteristics acknowledged to affect blackwater, but are not included in the prioritisation (Section 6.5). The blackwater priority assessment provides a relative quantification of blackwater production but does not incorporate likely impacts, such as proximity to sensitive receivers or the assimilation capacity of the receiving water.

6.2 Contributing area

A primary contributor to blackwater generation is the prolonged inundation of non-water tolerant vegetation following moderate to large rainfall events. Therefore, the larger the area potentially inundated, the greater the potential for detrimental blackwater generation. There are two (2) aspects to consider when estimating the floodplain area that regularly contributes to blackwater generation:

1. Location in the estuary – typically water levels remain elevated at higher levels and for a longer period at locations further upstream from the ocean; and
2. Catchment topography – all else being equal, the lower and flatter the topography, the larger the potential area of inundation and therefore the area that can contribute to blackwater generation.

6.2.1 Prolonged inundation

Unlike flood impacts, blackwater generation is not necessarily driven by peak water levels during a flood event. Instead, sustained inundation over an extended period of time is required for significant, large scale deoxygenation and generation of biological oxygen demand (BOD) in the water column. The hydrograph shape of a flood event (time taken for water levels to rise and fall) is important when considering blackwater generation potential. Figure 6-1 illustrates the effect of flood hydrograph shape on inundation duration. Considering two floods with approximately the same flood flow volume; Event 1 has a high peak water level but is relatively short in overall duration, whereas Event 2, by comparison, reaches a lower peak level, but water levels remain elevated over a longer period of time, creating conditions more favourable to the generation of blackwater.

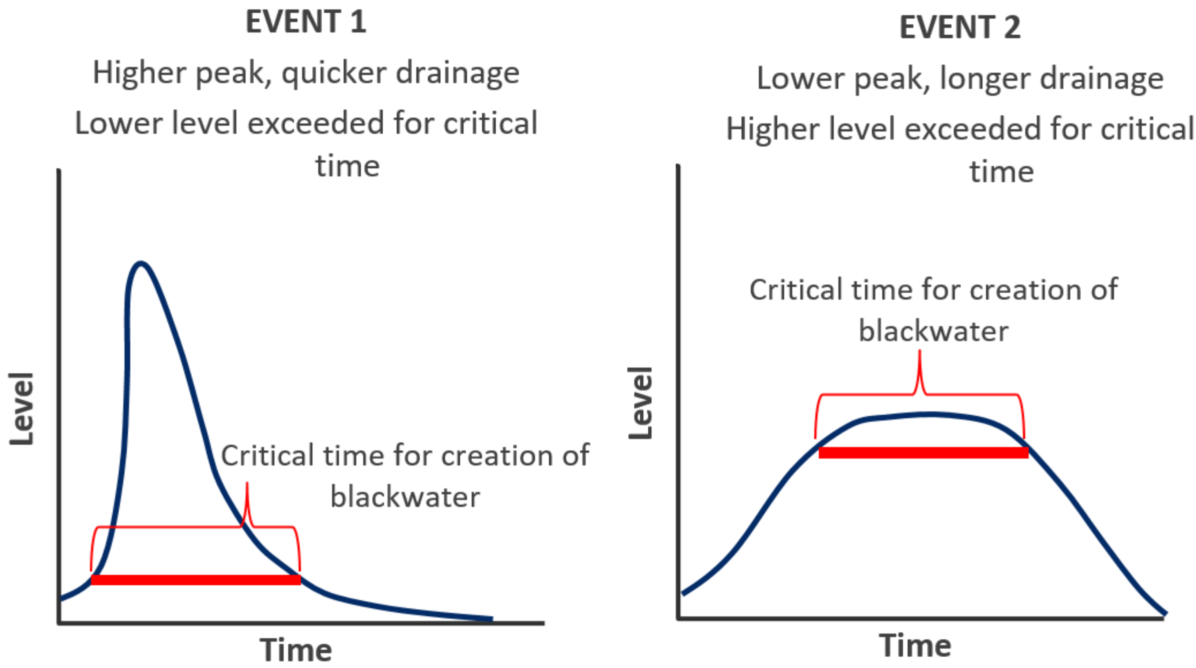


Figure 6-1: Impact of the shape of a flood event on the potential for blackwater

To be able to assess the potential for blackwater generation across a floodplain, it is important to quantify the 'critical time for creation of blackwater' (as shown in Figure 6-1). The critical time for the creation of blackwater has been noted to be dependent on a number of variables, with vegetation type being recognised as a significant contributing factor (Eyre et al., 2006; Johnston et al., 2005a; Liu et al., 2019; Vithana et al., 2019). Research on the Richmond River floodplain showed that in small scale mesocosm experiments, slashed pasture grass can deoxygenate a 300 mm deep water column almost completely (DO < 1 mg/L) in 10 hours, while the deoxygenation was slower in the same experiment on harvested sugar cane and dropped tea tree leaves (DO dropped to 3 – 4 mg/L in 10 hours in both cases) (Eyre et al., 2006). Numerous other Australian studies (e.g. Liu et al. (2019), Johnston et al. (2005a), Vithana et al. (2019)) have shown that DO in similar experiments fell to near 0 mg/L over a period of 2 – 3 days for a variety of vegetation types.

However, while DO can drop very rapidly, oxygen demand (BOD and COD) can continue to increase over a period of approximately two (2) weeks (Wong et al., 2011b; Wong et al., 2011a) and mass deoxygenation of coastal estuaries in NSW is typically observed 4 – 6 days after the peak of a flood event (Johnston et al. (2003b); Southern Cross GeoScience (2019); Wong et al. (2010)). While mesocosm experiments indicate small scale blackwater events may occur with an inundation period of 1 – 3 days, to account for extreme events, sensitivity to the critical time for blackwater generation includes periods of up to five (5) days (Eyre et al., 2006; Johnston et al., 2005a; Liu et al., 2019; Vithana et al., 2019).

6.2.2 Location in the estuary

The rate of recession of floodwaters from a backswamp depends on a number of factors. During localised floods, when local catchment rainfall results in subcatchment inundation, river levels are unlikely to be elevated. During subcatchment based rainfall events, the backswamp drainage time (during regular tide fluctuations) is primarily determined by drainage infrastructure efficiency (floodgates, culverts and drains) and hydraulic gradients from the floodplain to the receiving waters. During these smaller local catchment-based events, drainage efficiency is typically sufficient to limit prolonged floodplain inundation and therefore the risk of blackwater generation.

Flood events that more commonly result in widespread blackwater generation on floodplains occur when widespread rain falls over the greater river catchment. This results in elevated water levels both on coastal floodplains and throughout the entire main estuary channel. During estuary wide flood events, the drainage of an individual floodplain subcatchment is primarily determined by the flood hydrograph and the level/rate of floodwater recession in the main river channel. Figure 6-2 shows a typical water level response in the main waterway in the lower, middle and upper estuary after a catchment wide flood event. The following observations can be made from Figure 6-2:

- In the lower estuary:
  - Maximum water levels are relatively lower than elsewhere in the estuary;
  - Water levels do not rise particularly quickly;
  - Water levels do not remain significantly elevated for an extended period of time;
  - The tidal influence often remains evident throughout the flood event; and
  - The return to normal tidal levels is relatively rapid.
- In the mid estuary:
  - Water levels rise far more significantly than in the lower estuary;
  - Water levels remain elevated for a prolonged period; and
  - The return to normal tidal levels is much slower than the lower estuary.
- In the upper estuary
  - Water levels can rise rapidly;
  - Maximum water levels are often substantially higher than the lower or mid estuary; and
  - Water levels remain elevated for the longest duration.

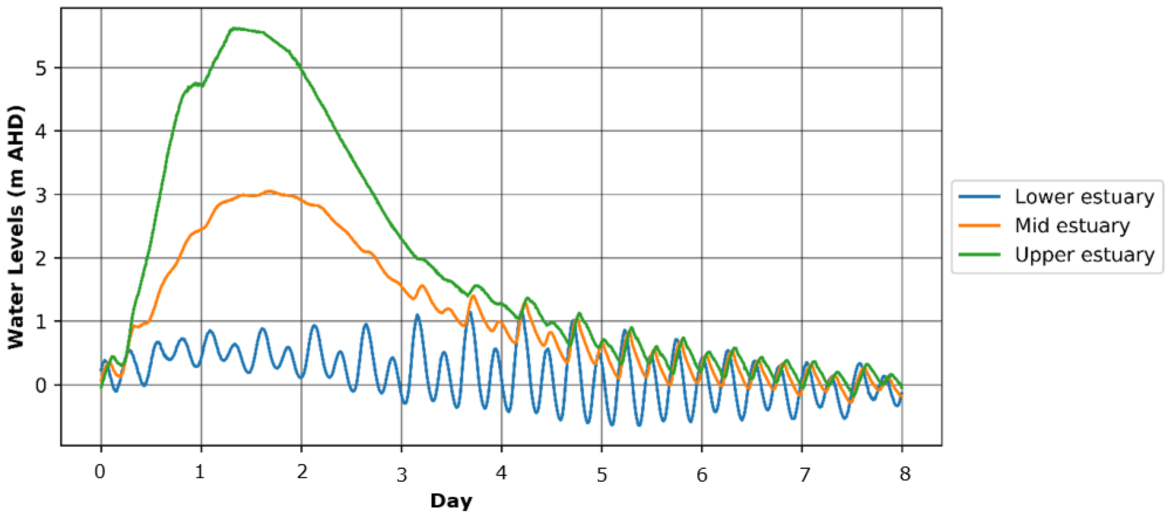


Figure 6-2: Illustration of typical water level response to rainfall in the lower, mid and upper estuary

As discussed in Section 6.2.1, vegetation is typically required to be inundated for 1 to 5 days for substantial deoxygenation of the water column to occur. Therefore, it is not the maximum water level that drives the production of blackwater, but the level that the water remains above a critical level for an extended period of time (i.e. inundation duration). Based on the illustration in Figure 6-2, this level and duration varies throughout the estuary.

Available water level records can be interrogated to assess the inundation level and duration for each floodplain subcatchment throughout an estuary. There are typically between five (5) and eight (8) water levels gauges in the main channels of each study estuary operated by Manly Hydraulics Laboratory (MHL) on behalf of the NSW Department of Planning, Industry and Environment (DPIE). To account for the difference in water levels throughout the estuary, long-term water level records were analysed to assess how often levels remained elevated for a given period of days for a range of different level thresholds. This analysis is then used as a proxy for elevated water levels in floodplain subcatchment areas. As the literature and analysis presented in Section 6.2.1 suggests, the minimum period of inundation that will generate blackwater is variable (depending on a range of contributing factors). To account for this uncertainty, this analysis has been completed five (5) times for a series of inundation durations of: 1 or more days, 2 or more days, 3 or more days, 4 or more days and 5 or more days (noting that the longer the inundation duration, the lower the threshold level reached at each location).

All available water level records within the tidal extent of the study estuaries were analysed for water level thresholds ranging from 0.1 m AHD to 5 m AHD (in 0.1 m increments) for each inundation duration. Figure 6-3 illustrates how this analysis was completed for each water level threshold. The analysis provides a count of the number of flood events throughout the period of record that meet the specified criteria. A single water level gauge is analysed for each of the thresholds between 0.1 to 5 m AHD, noting that a flood event will typically be counted for several thresholds (e.g. an event that counts for a threshold of 2 m AHD will always also be counted for every threshold below 2 m AHD). Using this approach, the analysis will show that lower water level thresholds occur more frequently than higher water level thresholds. Table 6-1 illustrates how this analysis may provide different results for the lower, mid and upper estuary (for a truncated number of thresholds).

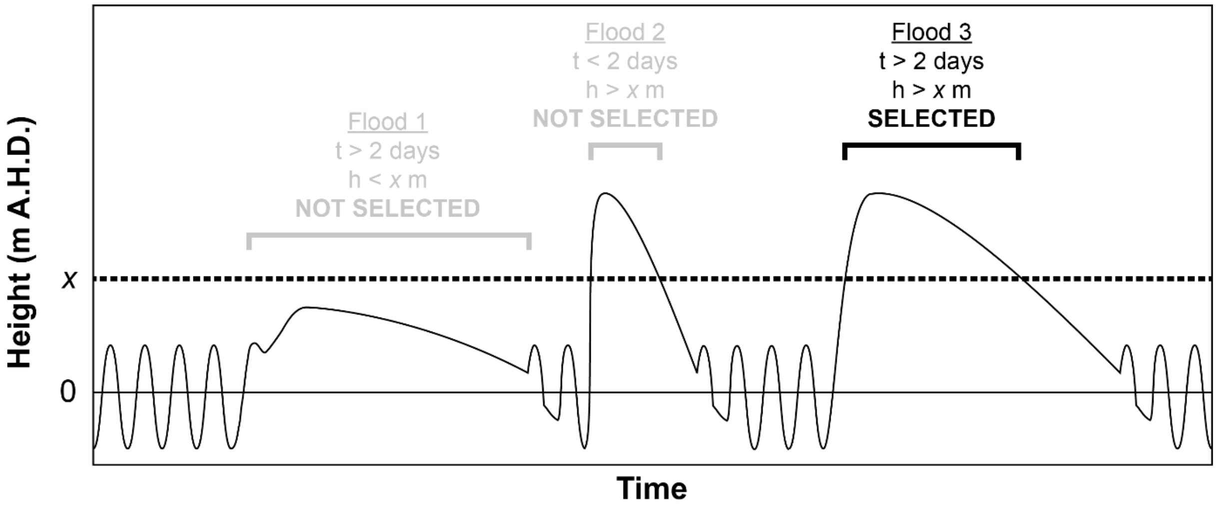


Figure 6-3: Counting events over thresholds in long term water level records, based on a threshold of x and a critical time for blackwater creation of 2 days

Table 6-1: Example of truncated results for the lower, mid and upper estuary water levels over a 2-day inundation duration

Water level threshold (m AHD)	Count over threshold		
	Lower Estuary	Mid Estuary	Upper Estuary
0.1	14	52	198
0.5	0	21	61
1	0	13	42
1.5	0	8	31
2	0	5	28
2.5	0	1	19
3	0	0	14
3.5	0	0	10
4	0	0	5
4.5	0	0	3
5	0	0	2

The water level gauges available typically have data every 15 minutes over a period between 10 and 35 years, with intermittent gaps in the data. Where there is a gap in data of greater than 6 hours (a quarter of a day), any events spanning the gap in data are disregarded. As such, it is difficult to establish a standardised period for the analysis without significantly reducing the amount of data available. To maximise the use of the available data, the full data record has been analysed for each water level monitoring station.

The data was normalised by the length of the data record to provide an estimate of the average recurrence of an extended inundation event to account for the differences in record lengths of the different water level gauging stations. For example, if the water level gauge associated with the 'Upper Estuary' in Table 6-1 had a record length of 10 years, the 5 m AHD level is exceeded twice and therefore this level can be expected to occur approximately every five (5) years. Similarly, the level that is exceeded ten times (3.5 m AHD) can be expected to occur approximately once every year. To assess the sensitivity of the method, the analysis has been completed for five (5) recurrences of 1, 2, 3, 4 and 5 years.

As shown in Table 6-1, water levels in the lower estuary do not typically remain elevated for consecutive days due to the proximity of the ocean. However, water levels in the backswamps near the entrance of the river can still remain elevated during periods of heavy and extended rainfall. In these areas, normal tidal water fluctuations will prevent rapid drainage of floodwaters. To reflect the impact of the tides in the flood recession in lower estuary backswamps, the minimum allowable level at any gauge will be the long-term average mean high water (MHW) level as documented in Fitzhenry et al. (2012). This minimum level is the same regardless of recurrence or critical time for blackwater generation.

6.2.3 Catchment topography

Having established a critical elevation for blackwater generation, the other consideration for the contributing area is floodplain topography (defined using a 5 m DEM). The area of a subcatchment below a specified inundation level can be established using topographic data and considered to be the area that can potentially contribute to the production of blackwater.

The required inputs, data sources and assumptions required to establish the area contributing to blackwater generation is summarised in Table 6-2.

Table 6-2: Inputs and data sources to contributing blackwater area

Required Input	Data Source	Assumptions
Elevation that contributes to blackwater throughout the estuary	All MHL gauges can be viewed at https://www.mhl.nsw.gov.au/data/realtime/WaterLevel	Typically, there are 5 to 8 water level gauges throughout each study estuary. The nearest gauge is used to assign the level that contributes to blackwater.
Area below a specified elevation	5 m DEM downloaded from https://elevation.fsdf.org.au/	Area below specified level delineated using standard GIS techniques.

6.3 Land use and vegetation type

6.3.1 Vegetation type

Section 5.5.1 provides a summary of the present understanding of the influence of vegetation type on the consumption of dissolved oxygen and production of blackwater. There are two (2) aspects of the vegetation type that are relevant to blackwater generation:

1. Water tolerance of the vegetation – some vegetation types can tolerate longer periods of inundation. Vegetation with a greater water tolerance presents a lower risk of blackwater generation; and
2. Deoxygenation potential once the vegetation begins to decompose, which is a function of:
    - Lability – which refers how readily the vegetation breaks down. A more labile vegetation type is associated with faster decomposition and greater deoxygenation potential. This can be measured by the ratio of carbon to nitrogen in a plant, where a higher C:N ratio is more labile; and
    - Carbon volume available – this is a measure of litter or leaf density, where a higher carbon volume will result in a greater blackwater generation potential.

The drainage of coastal floodplains in NSW to facilitate agriculture has caused a change in the types of vegetation that populate low-lying floodplain areas. Where wetland flora would have once flourished, dry land crops or grazing grasses now dominate, enabled by extensive drainage infrastructure and lower subsequent water tables. As a result, these areas are now colonised by vegetation species that are less tolerant to prolonged inundation.

The rate at which vegetation decays and deoxygenates water during periods of prolonged inundation differs depending on the vegetation type (Johnston et al. (2005a); Eyre et al. (2006); Whitworth and Baldwin (2016)). Different types of vegetation will result in different blackwater production potential. However, there is a significant variation between experimental methodology and what was measured (e.g. DO consumption, DO depletion, DOC concentrations, or DOC leeching), how the experiment was undertaken (e.g. field based mesocosm or laboratory experiments with cuttings/litter), as well as the species/types of vegetation studied.

6.3.2 Vegetation and land use risk ranking

Given the different experimental methodologies and study vegetation, direct comparison of data between studies is difficult. Subsequently, experimental results from relevant literature have been separated into five (5) broadscale categories of vegetation or land cover types:

- Dryland grasses;
- General forestry and leaves;
- Tea tree leaves;
- Sugar cane; and
- Freshwater wetland grass.

These categories have been chosen based on available literature and applicability to coastal floodplains in NSW. For each of these categories, the water tolerance and deoxygenation potential has been assigned a qualitative rank based on Australian literature (Table 6-3). The deoxygenation potential is a comparative measure within each individual study and may differ between studies.

Table 6-3: Qualitative rank of vegetation

Vegetation Type	Water Tolerance	Comparative Deoxygenation Potential
Dryland Grasses (e.g. Pasture Grasses)	Low	High (Eyre et al., 2006) Medium (Whitworth and Baldwin, 2016) High (Liu et al., 2019)
Forestry and Leaves (other than tea tree)	Low*	High (Whitworth and Baldwin, 2016) High (Liu et al., 2019)
Tea Tree Leaves	Low*	Low (Johnston et al., 2005a) Low – Medium (Eyre et al., 2006)
Sugar Cane	Medium#	Low – Medium (Eyre et al., 2006)
Freshwater Wetland Grasses (e.g. Grey Rush)	High	Low (Eyre et al., 2006) Medium (Johnston et al., 2005a)

*Forestry and leaves are classified as low tolerance due to the presence of readily available leaf litter, rather than the likelihood of plants dying.

#Sugar cane is relatively tolerant to water, but the presence of waste after harvest increases the deoxygenation potential.

The existing literature considers a narrow range of vegetation types and experimental methods that are inconsistent between studies and make direct comparison difficult. As such, it is not possible to assign consistent blackwater generation rates across all vegetation types commonly found on NSW coastal floodplains. It is however possible to assign a relative risk ranking to acknowledge some vegetation types that present a higher risk to blackwater generation than others. Based on the information in Table 6-3, risk rankings have been assigned in Table 6-4.

Table 6-4: Blackwater risk ranking associated with vegetation types

Vegetation Type	Water tolerance (high tolerance = 0)	Deoxygenation potential (low potential = 0)	Final Risk Ranking (low risk = 0)
Dryland Grasses (e.g. Pasture Grasses)	3	3	3
Forestry and Leaves (other than tea tree)	3	3	3
Tea Tree Leaves	3	1	2
Sugar Cane	2	2	2
Freshwater Wetland Grasses (e.g. Grey Rush)	1	1	1
Permanent water bodies	0	0	0

There is limited data available that maps the spatial vegetation distribution on coastal floodplains in NSW. As such, the land use within the study floodplains has been used as a proxy for vegetation type. For the purpose of this project, the 2017 ALUM land use classifications have been used (see Section 9.2 for more information on the land use categories) and have been assigned a vegetation type based on Table 6-4. Table 6-5 summarises the secondary land use types, assumed vegetation coverage and associated risk ranking. Note that while tea tree is seen to be of lower risk than general forestry (Johnston et al. (2005); Eyre et al. (2006)), there is no way to distinguish tea tree areas through the 2017 ALUM land use categories, so any land use assumed to be forestry/leaves was conservatively given the higher risk rating in Table 6-5. Floodplain areas mapped as mangroves or saltmarsh (in macrophyte mapping supplied by NSW DPI – Fisheries) were excluded from blackwater subcatchments as these areas will not significantly contribute to blackwater generation as they are frequently inundated by tide. The required inputs, data sources and assumptions required to establish the vegetation risk ranking is summarised in Table 6-6.

Note that none of the available literature directly addresses the impact of urban or industrial areas on blackwater risk. These land uses typically have a high degree of impervious areas and are not heavily vegetated and therefore are unlikely to contribute to blackwater through the same mechanisms as agricultural or nature conservation areas. However, the runoff from these areas is often associated with high BOD (USEPA, 2001). The contribution of impervious areas is unlikely to build significantly with time inundated as it would on agricultural land. Runoff from these areas may result in low dissolved oxygen, although the impact on water quality is more likely to be seen during smaller flood events, or with the first flush early in the initial stages of a flood. It is also important to recognise that these areas account for a relatively small portion of the floodplain areas considered in this study, and the results of the blackwater prioritisation is not particularly sensitive to the risk ranking assigned to industrial or residential areas. To acknowledge the initial contribution of high BOD water in the estuary, any land uses identified as built-up/urban, have been assigned a risk ranking of one (1) for contribution to blackwater. However, if this method was used in an estuary with a greater portion of the floodplain being highly developed, this assumption may need to be refined.

Table 6-5: Blackwater risk rating associated with 2017 ALUM land use classifications

Secondary Land Use Type	Assumed Vegetation Coverage	Risk Ranking
1.1.0 Nature conservation	Forestry	3
1.2.0 Managed Resource Protection	Forestry	3
1.3.0 Other minimal use	Forestry	3
2.1.0 Grazing native vegetation	Dryland Grasses	3
2.2.0 Production forestry	Forestry	3
3.1.0 Plantation forestry	Forestry	3
3.2.0 Grazing modified pastures	Grass	3
3.3.0 Cropping	Sugar Cane	2
3.4.0 Perennial horticulture	Forestry	3
3.5.0 Seasonal horticulture	Forestry	3
3.6.0 Land in transition	Forestry	3
4.1.0 Irrigated plantation forestry	Forestry	3
4.2.0 Grazing irrigated modified pastures	Dryland Grasses	3
4.3.0 Irrigated cropping	Sugar Cane	2
4.4.0 Irrigated perennial horticulture	Forestry	3
4.5.0 Irrigated seasonal horticulture	Forestry	3
4.6.0 Irrigated land in transition	Forestry	3
5.1.0 Intensive horticulture	Forestry	3
5.2.0 Intensive animal husbandry	Built-up/Urban	1
5.3.0 Manufacturing and industrial	Built-up/Urban	1
5.4.0 Residential and farm infrastructure	Built-up/Urban	1
5.5.0 Services	Built-up/Urban	1
5.6.0 Utilities	Built-up/Urban	1
5.7.0 Transport and communication	Built-up/Urban	1
5.8.0 Mining	Built-up/Urban	1
5.9.0 Waste treatment and disposal	Built-up/Urban	1
6.1.0 Lake	Water	0
6.2.0 Reservoir/dam	Water	0
6.3.0 River	Water	0
6.4.0 Channel/aqueduct	Water	0
6.5.0 Marsh/wetland	Freshwater Wetland Grasses	1
6.6.0 Estuary/coastal waters	Water	0

Table 6-6: Inputs and data sources to contributing area

Required Input	Data Source	Assumptions
Vegetation throughout the estuary	ALUM land use downloaded from https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017-v1p2-f0ed	In the absence of widespread vegetation mapping, land use has been used as a proxy for vegetation type. A risk rating has been associated with each secondary land use type.

6.4 Combining contributing area and land use

As discussed in Section 6.2, the area which can contribute to blackwater generation is delineated based on elevations from analysis of long-term water level monitoring within an estuary and applied across floodplain topography (on a 5 m grid) using a GIS 'bathtub' approach. The ALUM land use layer was converted into a 5 m grid for each subcatchment and assigned the corresponding risk ranking (as per Table 6-4). For all grid cells below the appropriate elevation threshold (i.e. inundation level), the area was multiplied by the risk rating and then summed, as per Equation 6-1. This is approach is shown graphically in Figure 6-4.

$$\textit{Blackwater factor} = \sum \textit{Count of grids} \times \textit{risk rating} \times \textit{grid area} \qquad \textbf{Equation 6-1}$$

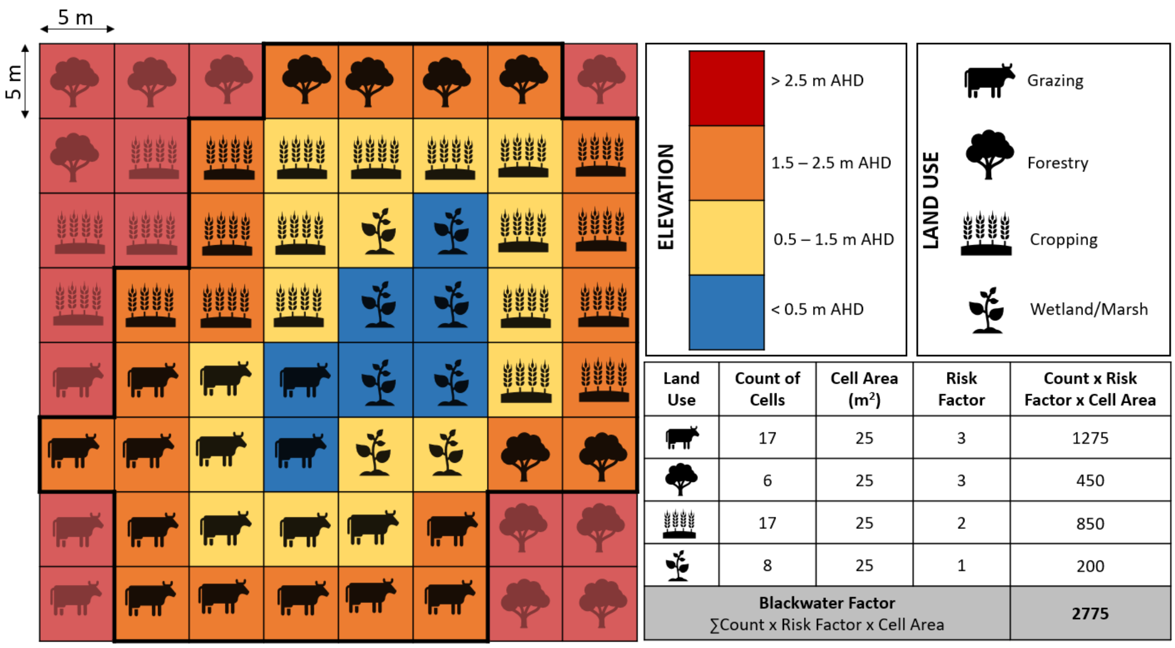


Figure 6-4: Example of calculation of blackwater factor with an example elevation threshold of 2.5 m AHD on a 5 m DEM grid

6.4.1 Sensitivity and final ranking

The inundation elevation threshold, and how it varies across the length of an estuary, is essential to the analysis of comparative blackwater generation potential. It was acknowledged in Section 6.2.2 that using the water level gauges in the main river channels is merely a proxy for levels within the backswamps where blackwater is actually generated. In addition, there is significant variation in the literature in the critical time of inundation for blackwater creation (which varies with vegetation water tolerance) but remains static in the analysis. To account for the impact on this uncertainty, a sensitivity analysis was completed by varying the assumed critical time of inundation and average recurrence. The analysis of the water level gauges has been undertaken 25 times for all combinations of:

- Critical time of inundation: 1, 2, 3, 4 and 5 days; and
- Average recurrence: 1, 2, 3, 4 and 5 years.

For each iteration of the water level analysis, a blackwater factor was calculated at each subcatchment as described by Figure 6-4. The final blackwater factor was an average of the factors calculated for the matrix of inundation thresholds. Subcatchments were then ranked throughout the floodplain (where the first rank is associated with the highest blackwater factor).

For reporting purposes, the median elevation of the 25 iterations of analysis of water level gauges was used to show the indicative area that commonly contributes to blackwater generation.

6.5 Factors omitted from blackwater prioritisation

6.5.1 Temperature

As discussed in Section 5.5.1 it is well understood that higher temperatures promote the generation of hypoxic blackwater. As a result, blackwater events are more likely to occur during warmer summer periods (Wong et al., 2018) than the cooler winter periods. However, the purpose of this prioritisation is to differentiate between the likelihood of blackwater generation for subcatchments across a single coastal floodplain, so it is important to assess whether there is likely to be significant temperature gradients during the months when blackwater is most likely to occur.

BOM analyses average maximum temperatures across the country from October to April, which is shown in Figure 6-5 to Figure 6-11 for each of the seven (7) study estuaries. Average maximum summer temperatures across the floodplains typically vary within 2℃ - 4℃ with all average maximum temperatures being below 30℃. Eyre et al. (2006) showed that the dissolved oxygen consumption rate of dried grass increases with temperatures (DO consumption of 0.65, 1 and 2.2 mg/L/hr for temperatures of 20℃, 30℃ and 40℃ respectively). However, this does not support a strong gradient in oxygen consumption in a 2℃ - 4℃ difference in temperature range, particularly below 30℃. Eyre et al. (2006) observed a much larger increase in DO consumption between 30℃ and 40℃, as opposed to between 20℃ and 30℃.

This temperature gradient is unlikely to be a primary factor driving differences in the blackwater generation across these NSW coastal floodplains. Temperature has therefore been excluded from the prioritisation methodology. However, this assumption means that results are not comparable between catchments, where significant temperature variations across NSW may occur throughout the year.

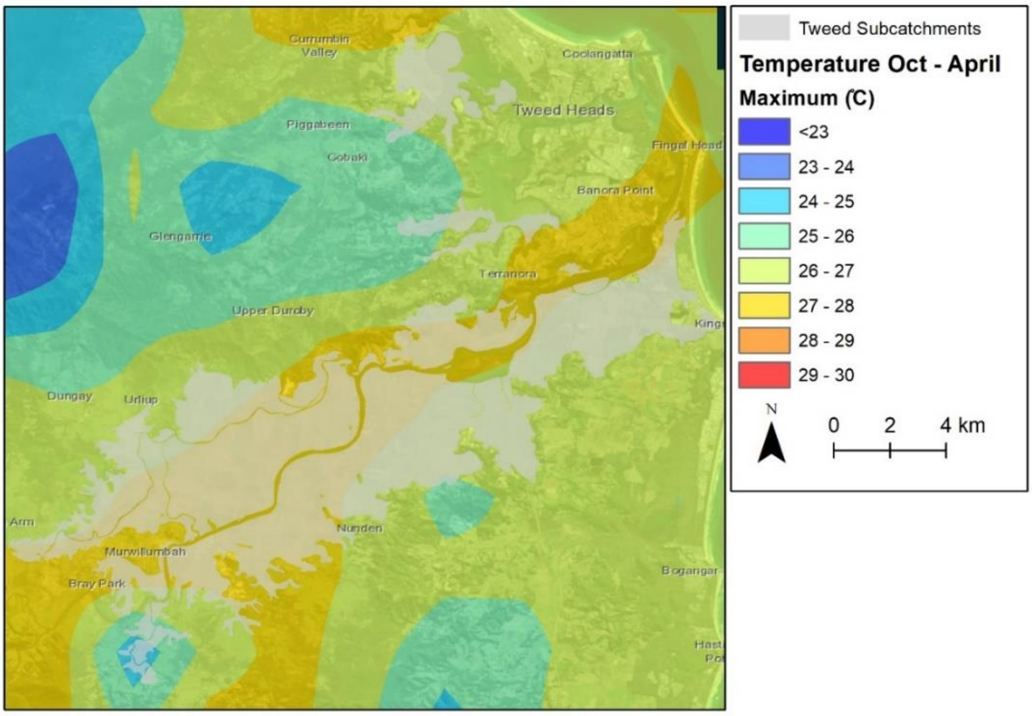


Figure 6-5: Average maximum temperatures during October to April in the Tweed River floodplain

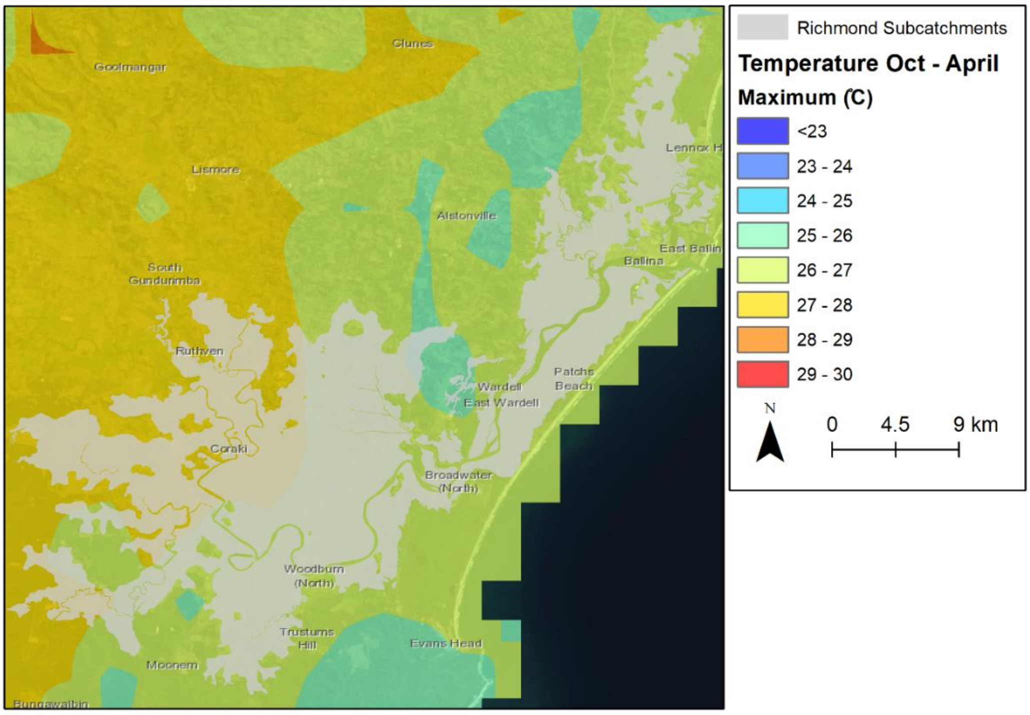


Figure 6-6: Average maximum temperatures during October to April in the Richmond River floodplain

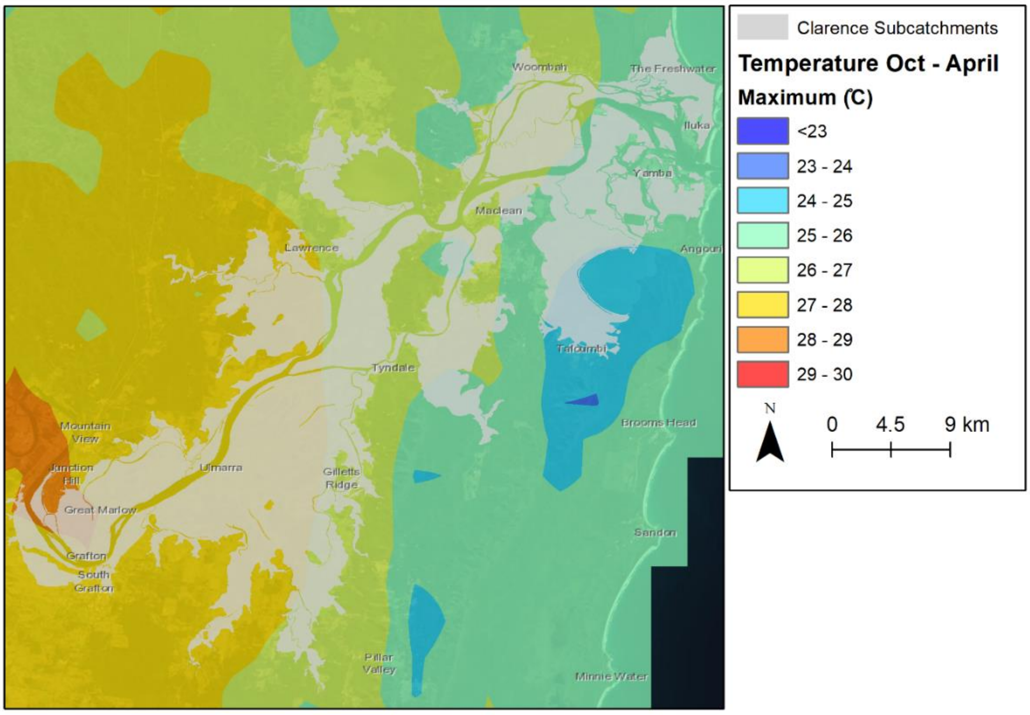


Figure 6-7: Average maximum temperatures during October to April in the Clarence River floodplain

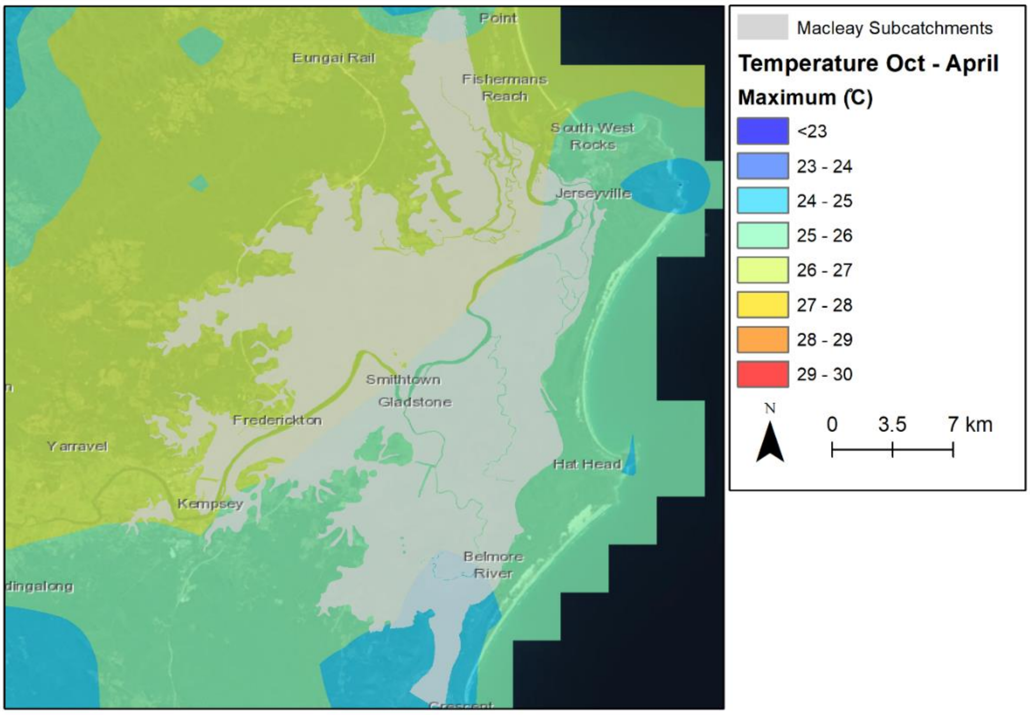


Figure 6-8: Average maximum temperatures during October to April in the Macleay River floodplain

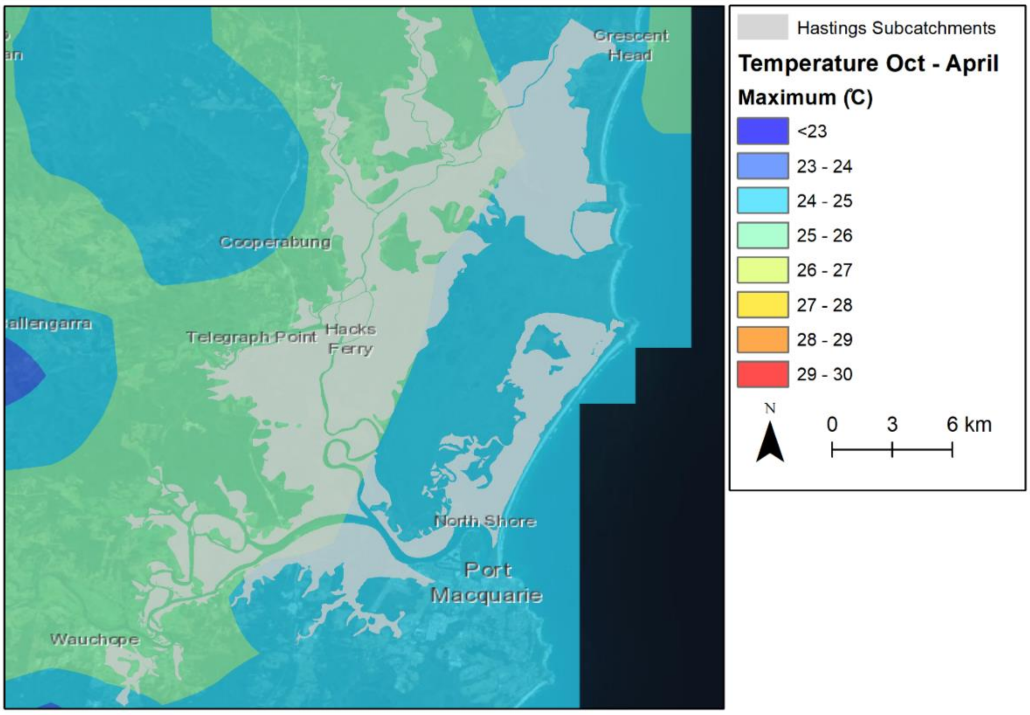


Figure 6-9: Average maximum temperatures during October to April in the Hastings River floodplain

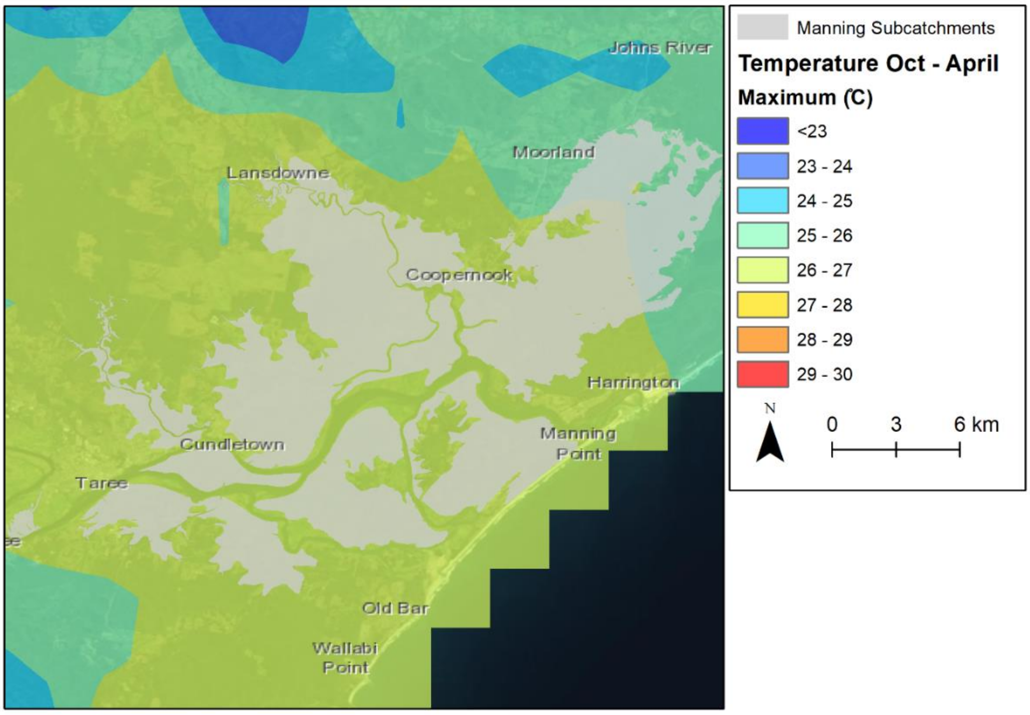


Figure 6-10: Average maximum temperatures during October to April in the Manning River floodplain

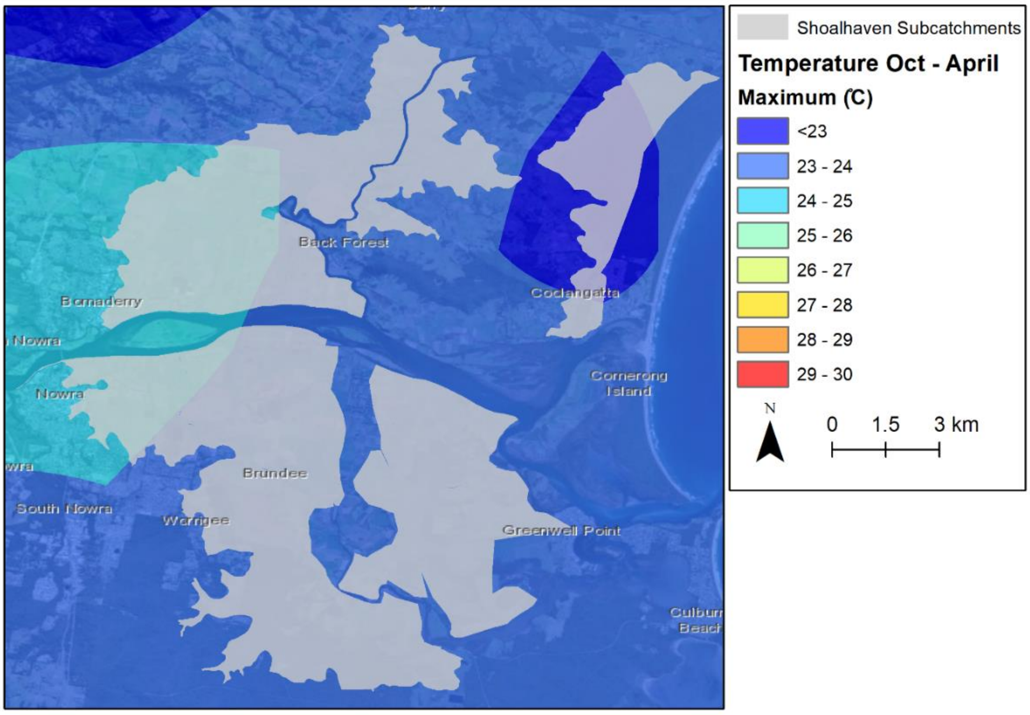


Figure 6-11: Average maximum temperatures during October to April in the Shoalhaven River floodplain

6.5.2 Antecedent conditions

Antecedent conditions can influence the severity of a blackwater event. Extended droughts are associated with a build-up of organic material available, which can lead to worse blackwater events when inundation finally occurs (Wong et al., 2018). However, this study does not aim to provide an assessment of how likely a single flood event is to produce blackwater in a catchment, but rather to provide an assessment of where blackwater is likely to be generated over an extended period of time over multiple events. While antecedent conditions may vary throughout a catchment during any single flood event, for the purpose of this project, it is assumed that any antecedent condition is equally likely across a floodplain and does not factor into the blackwater prioritisation methodology.

6.5.3 Land management practises

The timing of flooding events with respect to different land management activities can be significant to the production of blackwater. Eyre et al. (2006) suggested that, for example, removal of cuttings from slashed pasture may be an effective way to reduce the oxygen depletion potential of an area. Similarly, on a cane farm, whether cane leaves are burnt before harvest or stockpiled can impact the amount of organic material facilitating the consumption of oxygen after a flood event.

However, including land management practices as a factor in this prioritisation presents practical challenges on a broad scale. Consistent and relevant information on the management practises is not widely available and cannot be readily incorporated. Available information on land management practises that may mitigate the impact of the blackwater was considered in the individual subcatchment plans.

6.5.4 Altered floodplain drainage

Decomposition of organic material resulting in anoxic conditions is a natural function of a floodplain that pre-dates European settlement in coastal NSW. However, there is evidence that enhanced drainage and drainage infrastructure has increased the frequency and the severity of the impacts of blackwater in NSW estuaries (e.g. Johnston et al. (2003b), Eyre et al. (2006) and Wong et al. (2010)). Most forms of terrestrial vegetation will die, decompose, and consume oxygen from the water column during periods of prolonged inundation (Southern Cross GeoScience, 2019). Many of the considered coastal backswamp systems were likely to have been inundated historically during flood events. However, most backswamps were historically poorly connected to the main estuary via natural waterways (e.g. creeks). When inundation events did occur in the past, bacterial decomposition would have created anoxic conditions, however, limited pathways for this anoxic water to interact with other water bodies would have reduced the impacts of blackwater production.

By improving floodplain connectivity via the construction of extensive drainage channels and the installation of one-way floodgates, the inundation of much of the lower parts of coastal floodplains has become less frequent. This has allowed for the proliferation of water intolerant vegetation (i.e. pasture grasses) in areas that would once have only supported water tolerant species (i.e. wetland grasses). However, during larger flood events, this vegetation can still be inundated for a prolonged period and will begin to decompose.

Some of the drainage networks constructed in NSW coastal floodplains were built as flood mitigation drains to reduce the impact of flooding, however Tulau (2011) highlighted that swamp drainage was also an objective of the flood mitigation scheme. While these drains have been effective in reducing nuisance flooding (e.g. high frequency flood events), they do not prevent flood inundation when downstream river water levels are sufficiently high to prevent drainage through any drainage paths. Severe blackwater events are most common during widespread flood events, where river water levels remain elevated for days at a time. Increasing the drainage density does not reduce the risk of blackwater generation.

The floodplains that are considered in this study have been extensively drained throughout the last century, promoting agricultural productivity on low-lying floodplain areas. The resulting change in vegetation (and the subsequent effect on blackwater generation) is captured through the vegetation risk rating. For the purpose of the quantitative prioritisation, it is assumed that all the backswamps in this study are all sufficiently connected to main waterways to allow for adequate drainage once river flood levels recede. This is consistent with the purpose of the quantitative prioritisation focusing on blackwater generation and only qualitatively assessing the downstream impacts. Subcatchment drainage connectivity is considered within the management actions plans, where applicable. More comprehensive drainage survey (including smaller scale paddock drains) would be required to improve this assumption and was beyond the scope of this study.

7 Floodplain management options

7.1 Preamble

Acid and blackwater discharges from coastal floodplains and backswamps have a range of environmental impacts including poor water quality, fish kills, and habitat degradation. While identifying the highest priority catchments that discharge poor water quality is an important step in managing the issues associated with ASS and blackwater, this study also provides high level guidance on potential on-ground management options that could be pursued to address the water quality issues.

The management options provided in this study are intended to be a guide only, and no on-ground work is recommended without further studies into the applicability and potential impacts of any changes in management. This will typically include extensive consultation and consideration of the social, cultural and economic impacts on local landholders.

A range of management options exist for the remediation of drains and floodplains affected by ASS and/or blackwater (Table 7-1). The applicability of each option is highly dependent on-site specific factors such as catchment topography, drain condition, tidal amplitude, hydraulic conductivity, acid layer depth, climate change, land use and landholder willingness.

Some options include interim actions for limiting acid or blackwater production and discharge, whereas other options aim to permanently reduce acid and blackwater production and export via remediation. In recent years, the greatest improvements in water quality have occurred where a change in land use has occurred, enabling significant remediation of drainage and hydrology to reduce the impact of acid discharges and blackwater runoff.

Examples where this approach has been implemented include: Yarrahapinni Wetlands (Macleay River), Everlasting Swamp (Clarence River), Partridge Creek (Hastings River) and Darawank Nature Reserve (Wallamba River).

Table 7-1: Potential effectiveness of management options

Option	Potential effectiveness at reducing acid export	Potential effectiveness at reducing blackwater export
Drain infilling	Good	Moderate
Drain reshaping	Good	Limited
Groundwater manipulation(in-drain only)	Moderate	Limited
Groundwater manipulation (floodplain inundation)	Moderate	Moderate
Land raising	Good	Good
Liming	Good, on a small scale	None
Management of cuttings	None	Moderate
Partial retention of floodwater	Low	Good
Permeable Reactive Barriers	Good, on a small scale	None
Relocating floodgates	Good	Limited
Tidal/saline manipulation	Good	Limited
Wet pasture	Good	Good
Wetland remediation	Excellent	Excellent

This section provides a brief description of management strategies for high-priority ASS and/or blackwater affected areas.

7.2 Management options

7.2.1 Drain infilling

Infilling drains effectively reduces the drainage density of floodplains, shown Figure 7-1. By reducing the number of surface water drains on a floodplain, the groundwater table will typically increase preventing acid production and transport from areas away from the remaining drains. Southern Cross GeoScience (2019) also stated reducing drainage density may help manage the generation of blackwater as water tolerant vegetation will likely begin to colonise areas when the ground water table remains high for long periods of time.

Drain infilling can often be implemented by utilising laser levelling (Johnston et al., 2003a). Using this technique, a paddock can be levelled with a slight incline that allows surface water runoff to flow across it. Having this angle means that the drainage density can be decreased while still maintaining the same level of drainage. This technique has been effectively implemented across sugar cane farms in NSW (Sunshine Sugar, 2005).

Note, infilling of drains can have an impact on the overall efficiency of a drainage network and its ability to export water from the floodplain. Subsequently, it is important to assess how this type of modification would affect the existing land use.

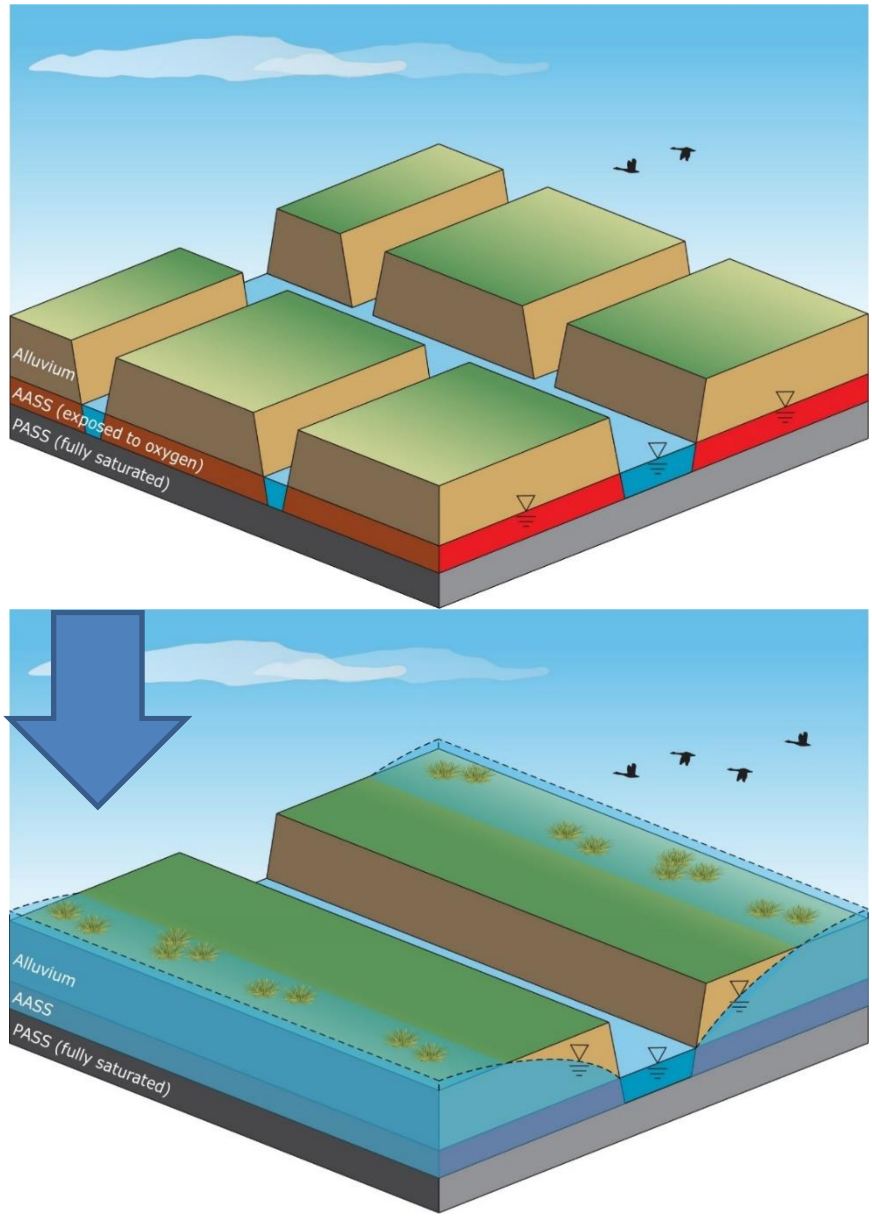


Figure 7-1: Before and after drain infilling and reducing drainage density

7.2.2 Drain reshaping

Shallowing and widening (or 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., 2003a) and can result in a change in vegetation towards water tolerant species (albeit somewhat limited) as the groundwater drawdown is reduced (Southern Cross GeoScience, 2019).

Raising drain invert levels, while maintaining the effective drain cross-sectional area, acts to reduce acid seepage and maintains drainage capacity of the existing system. These drains are commonly referred to as 'swale drains' as illustrated in Figure 7-2. Narrow, deep drains are ideal candidates for drain reshaping, as the drain cross-sectional area required to provide efficient drainage can be maintained by 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 option is applicable where the acid soil layer is sufficiently deep enough to enable an efficient drainage slope from the backswamp to the estuary without the drain invert disturbing the acid layer. It can often be implemented without any changes to existing land uses.

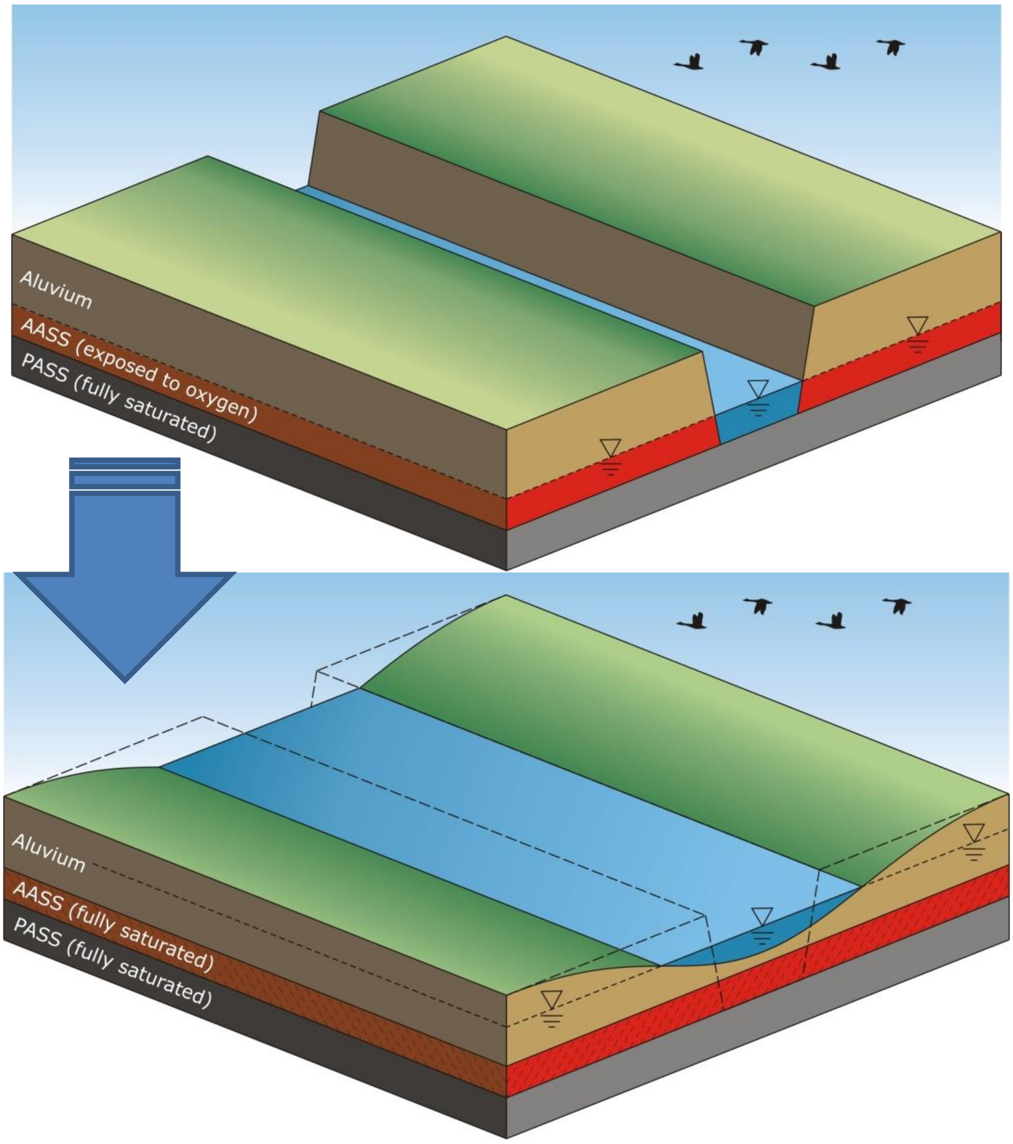


Figure 7-2: Before and after swale drain construction

7.2.3 Groundwater manipulation

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 higher drain water levels and groundwater elevations that reduce groundwater drawdown, thereby minimising the hydraulic gradient between groundwater and surface waters in drainage channels. Higher groundwater tables can also promote growth of water tolerant vegetation, which can further reduce blackwater risk, although this is likely to be limited unless regular surface inundation occurs as a result of the weir installation (Southern Cross GeoScience, 2019). Weirs are generally applicable in higher elevation areas, 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 a successful strategy for minimising acid export in the upper Broughton Creek floodplain, within the Shoalhaven River estuary.

The optimal weir crest elevation for reducing the generation and export of acid is dependent on the elevation of the acidic soil layer. Ideally, the weir crest elevation is situated at, or above the elevation of the AASS layer. This minimises the potential for lateral flow of acidic water from the ground into the drain.

The optimal weir crest elevation for reducing blackwater production is dependent upon the elevation of the surrounding land. By raising the water table so it is just below the ground-surface but remains in-drain, water tolerant vegetation can be encouraged to grow to a limited degree. By constructing the weir so that low-lying land adjacent to the drain and upstream of the weir is inundated, water tolerant vegetation can be encouraged at a larger scale reducing the risk of blackwater generation and export. Note, this is a technique that can also be used to facilitate wet pasture (Section 7.2.11).

Weirs are often designed to reduce acid and blackwater export whilst maintaining effective drainage during wet periods. Adjustable weirs (i.e. drop boards) are desirable and they can be lowered to enhance drainage following flood periods which helps maintain agricultural productivity, while raising the weir crest during dry periods reduces the groundwater hydraulic gradient, minimises acid export and promotes the growth of water tolerant vegetation. Figure 7-3 depicts how a weir effectively increases the groundwater table for management of ASS and blackwater.

Tulau (2007) listed a number of 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 requirements;
- Vandal resistant;
- Cost effective;
- Landholder willingness and approval; and
- Complies with current legislation.

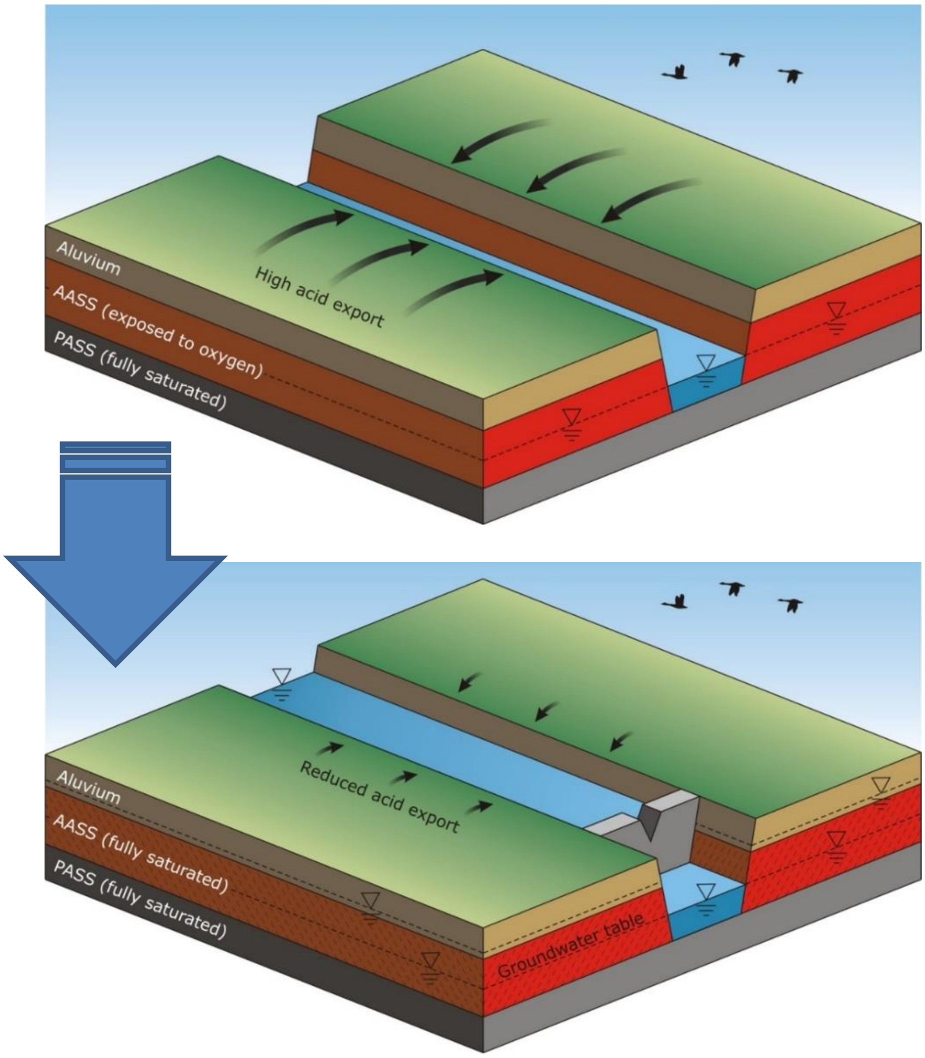


Figure 7-3: Weir implementation before (top) and after (bottom)

7.2.4 Liming for acid neutralisation

When applied to ASS, lime reacts with the soil to neutralise its acidity. Lime is often applied directly to disturbed or exposed ASS as a dry powder. The liming approach is commonly undertaken when soil acidity levels are low, or when ASS are excavated and small-scale neutralisation is required. Lime is rarely applied directly to ASS as a broad-acre solution due to the large quantities required for neutralisation and the difficulty in mixing the lime with clayey soils.

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 often a cost-effective management option in ASS affected areas of coastal NSW due to the high acid content in the soil. Liming is often used in conjunction with other remediation strategies which require small scale earthworks such as, levee removal, laser leveling and drain reshaping. Liming is not effective for management of blackwater.

7.2.5 Land raising

Raising land elevation by addition of fill (or reshaping) enables remediation strategies to be implemented in high priority management areas without impacting agricultural practices. Depending on the site, land raising may require significant volumes of soil to be added to the floodplain to isolate specific areas or only need a small volume of soil for example to create a mound to plant a crop. Design should also consider the impacts that modifying the floodplain has on flooding by modifying flow paths and flood storage. Land raising (or reshaping) could be implemented where saline tidal inundation or wet pasture management is likely to be detrimental to the upper soil profile and existing agricultural practices (Figure 7-4).

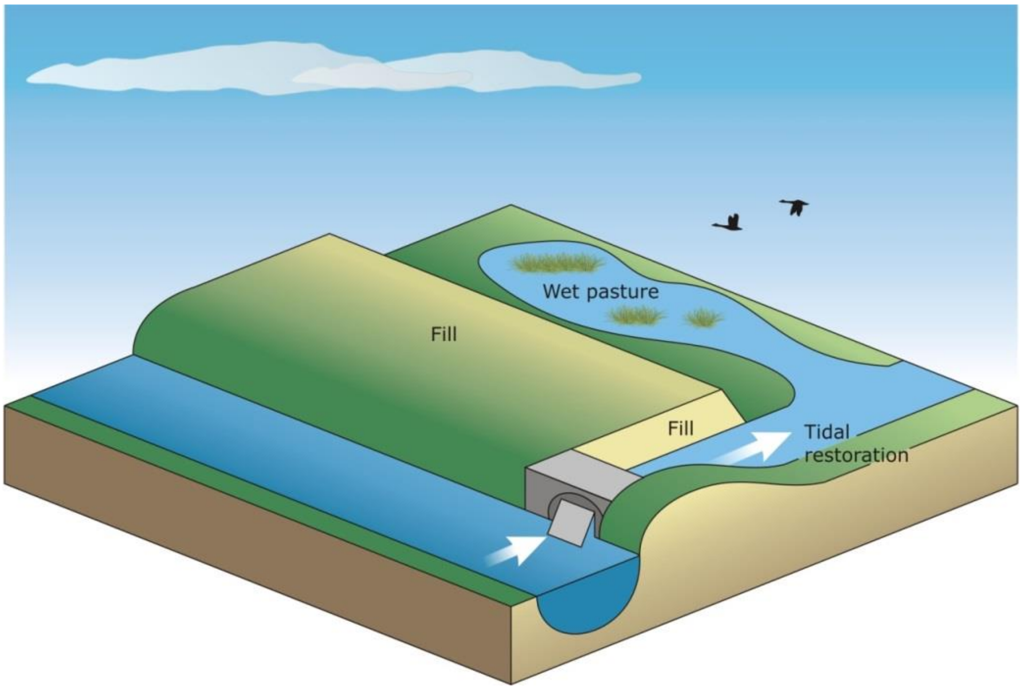


Figure 7-4: Schematic of partial land raising

7.2.6 Management of cuttings

Managing and reducing blackwater generation in the short term is difficult without significant changes to land use. However, land management practises may provide some improvements in blackwater management in coastal floodplains. Both Moore (2007) and Eyre et al. (2006) suggested that reducing pasture cuttings or trash management from cropping (e.g. sugar cane trash or leaf trash from tea trees) would limit the amount of readily available organic material for decomposition.

Eyre et al. (2006) suggested the following measures be encouraged on floodplains to remove carbon content from the area:

- Bale and sell off pasture cuttings after slashing as hay;
- Collection and storage (on higher land) of slashed pasture to use as stock feed during periods of drought or low feed;
- Using grazing animals such as sheep in tea tree plantations to manage weeds and grass between trees;
- Collection of sugar cane trash for burning and production of electricity; and
- Processing of tea tree leaf trash to be sold for mulch.

Some of these measures may already be occurring on the floodplains, however there are often economic disincentives that prevent these practises being implemented (e.g. the cost of baling and transport of hay outweighs the sale price (Eyre et al., 2006)).

7.2.7 Partial retention of floodwaters and controlled release

While blackwater is generated on floodplains, the majority of impacts exemplified by fish kills, occur in the main river channel receiving waters. These impacts occur as the deoxygenated water discharging from the backswamp areas overwhelms the downstream water body which does not have the capacity to assimilate the discharge (Moore, 1996).

At present, floodgates and drainage systems are typically designed to remove floodwaters as quickly as possible. Wong et al. (2011b) suggests that the existing infrastructure could be modified to partially retain floodwaters after the peak of the flood event. This water can then be strategically released at a rate that does not overwhelm the downstream receiving waters, as shown in Figure 7-5. If floodwaters are retained for a sufficient period of time (i.e. greater than 14 days) oxygen consumption rates will start to decrease (i.e. the dissolved oxygenation potential (DOP) will also decrease), which will also reduce the impacts on downstream water bodies (Wong et al., 2011b; Wong et al., 2011a) (the assimilation capacity of receiving waters is discussed further in Section 5.5.3). This option needs to consider how land which is inundated during a flood event would be impacted if this inundation occurred for a longer period.

Retention of floodwaters on the floodplain would temporarily reduce acid runoff. This is due to the water being held on the floodplain and limiting the production of new acid. Once the water table recedes there is potential for export of acid to be exacerbated if the water table drops below the actual acid sulfate soil layer. Design modifications to infrastructure to allow partial retention of floodwaters would need to take this into consideration. Any retention of floodwaters would require careful design and consideration of the social, cultural and economic impacts to local landholders.

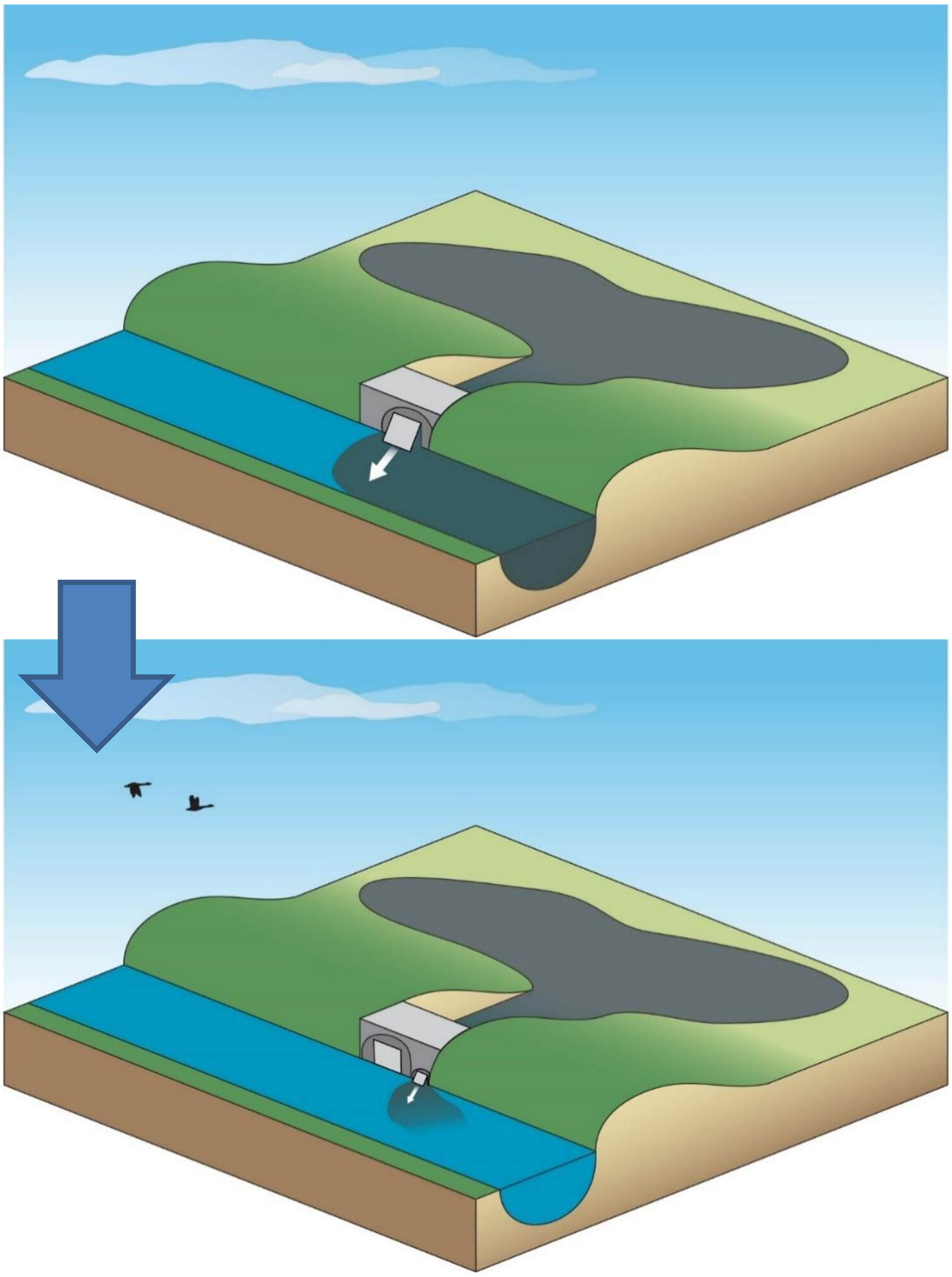


Figure 7-5: Retaining floodwaters and controlling discharges

7.2.8 Permeable Reactive Barriers (PRB)

Permeable Reactive Barriers (PRB) are vertical barriers that treat contaminated groundwater as it passes through the barrier. PRBs have been applied at various groundwater contamination sites due to their overall lower cost when compared to the cost of treating shallow aquifers (Regmi et al., 2009). PRBs can remove contaminants by (i) absorption and precipitation; (ii) chemical reaction; and (iii) biological processes (Tratnyek et al., 2003). The application of PRBs to groundwater contamination is usually applied to a point source contamination to remove the contamination in-situ or installed to protect important infrastructure from damage (e.g. building foundations).

PRBs can be applied to ASS-affected groundwater sites by installation beneath drain levee banks. Acidic groundwater flowing towards the drain passes through the PRB and is neutralised prior to being discharged into the drainage channel (Figure 7-6). The application of PRBs to buffer acidic groundwater was tested on the Broughton Creek floodplain in 2006 (Indraratna et al., 2006). Results from the field testing indicated that acid buffering by the PRB was effective. However, application of PRBs is typically not considered to be a cost-effective management option in the ASS affected areas of coastal NSW due to the widespread distribution of ASS. PRBs are more suited to smaller scale in-situ treatment of acidic groundwater or other sub-surface contamination.

PRBs are ineffective in managing blackwater generation and runoff.

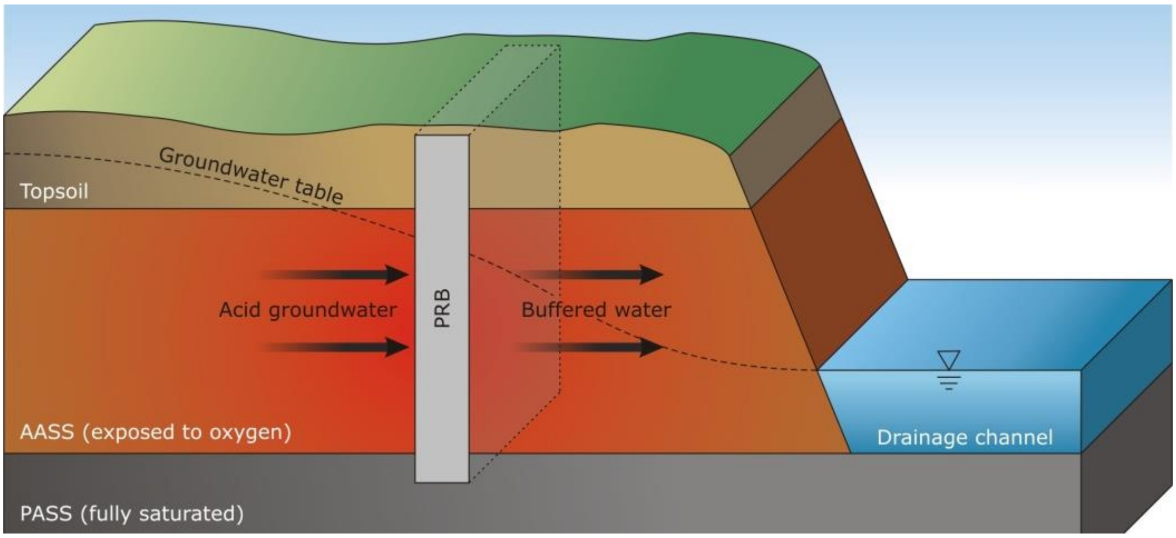


Figure 7-6: Permeable Reactive Barrier (PRB) application to neutralise acidic groundwater

7.2.9 Relocating floodgates further upstream

Replacement of large headworks with a number of smaller structures at strategic locations upstream can open up large stretches of creek and drain channels to tidal flushing (Figure 7-7). The extent to which this decentralisation of floodgates can be implemented is dependent on a range of factors including floodplain topography, levee bank elevations and land tenure. Where there is a low-lying floodplain with levees located below the high tide water mark, this option may not be feasible unless additional works are completed to raise levee banks. Environmental benefits for stretches of creek and drain channels located downstream of floodgates that have been moved upstream include:

- Reduced drainage of acidic groundwater;
- Improved water quality;
- Buffering of acid; and
- Increased aquatic habitat.

Floodgates also act to prevent passage along drainage and creek channels for aquatic life. By decentralising floodgates to strategic locations upstream, large extents of aquatic habitat can be created or re-established. Additionally, drainage of acidic groundwater is limited to low-tide periods and can be buffered by the natural bicarbonate found in saline tidal water. The increased flushing associated with moving the floodgates upstream will also increase dissolved oxygen levels in the main drainage channel (Glamore, 2003). This option is unlikely to have a large impact on blackwater generation, except if the new tidal area includes substantial areas of land which were previously not inundated.

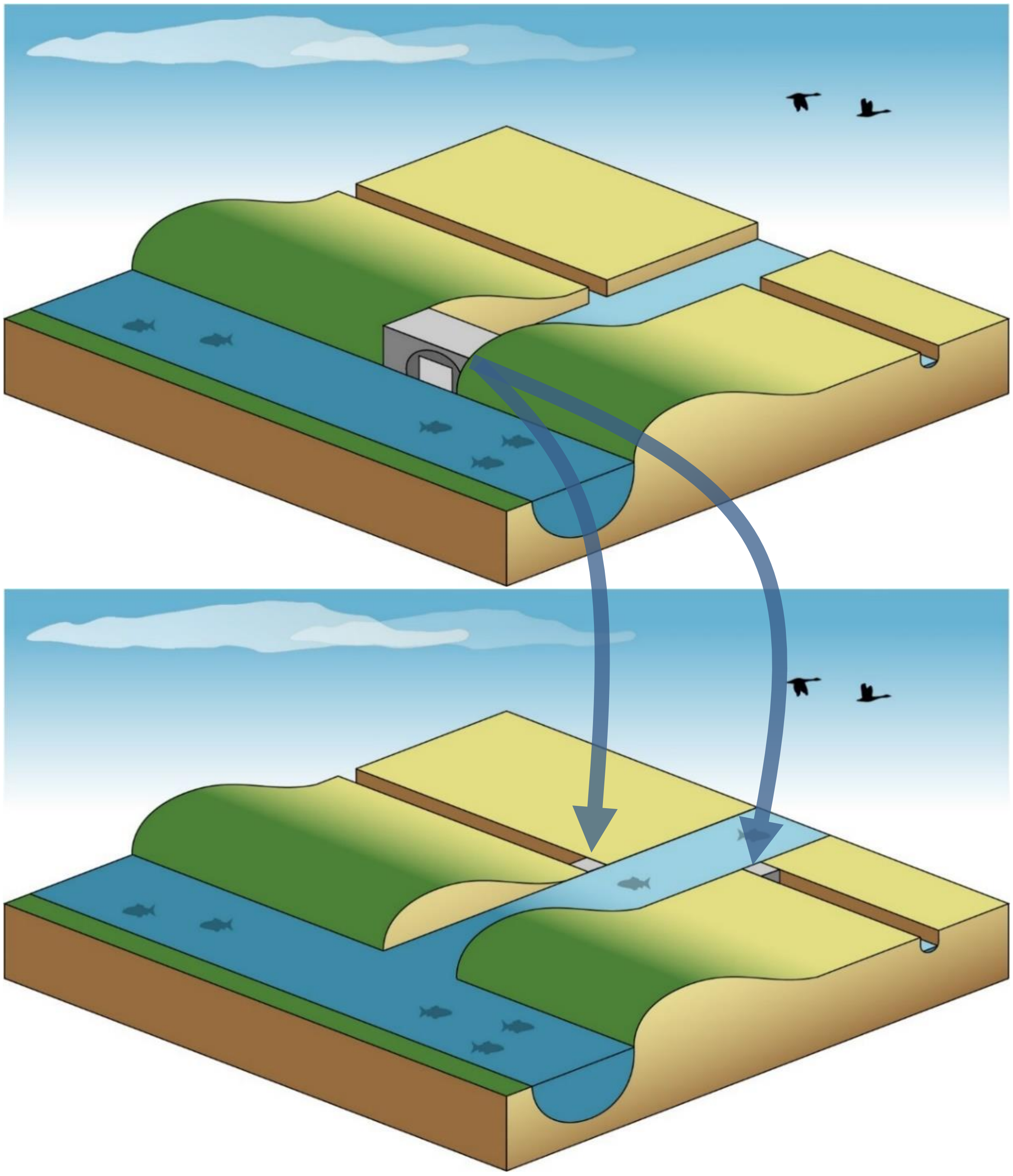


Figure 7-7: Diagram showing increased tidal flushing through relocation of floodgates upstream

7.2.10 Tidal/Saline manipulation

One-way floodgates prohibit tidal inundation, maximise drainage, and maintain drain water levels at low tide elevations. When ASS are present, tidal floodgates increase soil oxidation and acid discharge, and restrict in-drain buffering by tidal waters. Eyre et al. (2006) suggests the lowering of groundwater tables by one-way floodgates has resulted in a change in ground vegetation cover away from species that tolerate flooding towards dryland species used for grazing and agriculture, exacerbating issues associated with blackwater.

Floodgate management and/or modification to improve water quality outcomes and enable aquatic connectivity is widely practiced in NSW. In the Shoalhaven River estuary, Glamore (2003) showed that modified floodgates that permit two-way tidal flows significantly improved water quality within the drainage system, and generally reduced the downstream impacts of ASS discharges. Glamore (2003) also states that dissolved oxygen levels increase through regular flushing and may limit the formation of mono-sulfidic black ooze (MBOs). However, unless the additional tidal flushing is associated with inundation of upstream floodplain areas and a subsequent change in vegetation, modification of floodgates to allow tidal flushing is unlikely to have a significant impact on blackwater generation in the short term.

Benefits of floodgate modification also include:

- Improved drain water quality through flushing and acid buffering;
- Reduced exotic vegetation within the channel (reducing maintenance costs);
- Increased groundwater table reducing the production of acid; and
- Increased fish passage (NSW DPI, 2007).

Modification of floodgates to allow tidal flushing is typically undertaken to allow controlled upstream flows by limiting the tidal amplitude. This is to limit impacts on upstream land use. Uninhibited tidal flow (i.e. floodgates fully open) is rarely adopted, except when tidal amplitude is low, or where there is a change in land use (i.e. agricultural land use practices are abandoned), or where private land is publicly acquired, or where land elevations are above high tide elevations. The extent of tidal restoration at a site is often dependent on the site topography, tidal elevations, available bicarbonate/carbonate from tidal water, and current land use practices. Typically, landholders use controlled in-drain tidal flushing to control weed vegetation, while not impacting adjacent floodplain areas of agricultural production. The installation of auto-tidal gates permits tidal flushing up to a predetermined elevation based on design. Maximum inundation elevations are usually dependent on the topography of the backswamp. Figure 7-8 depicts how a modified floodgate can restore tidal flushing to a drainage channel.

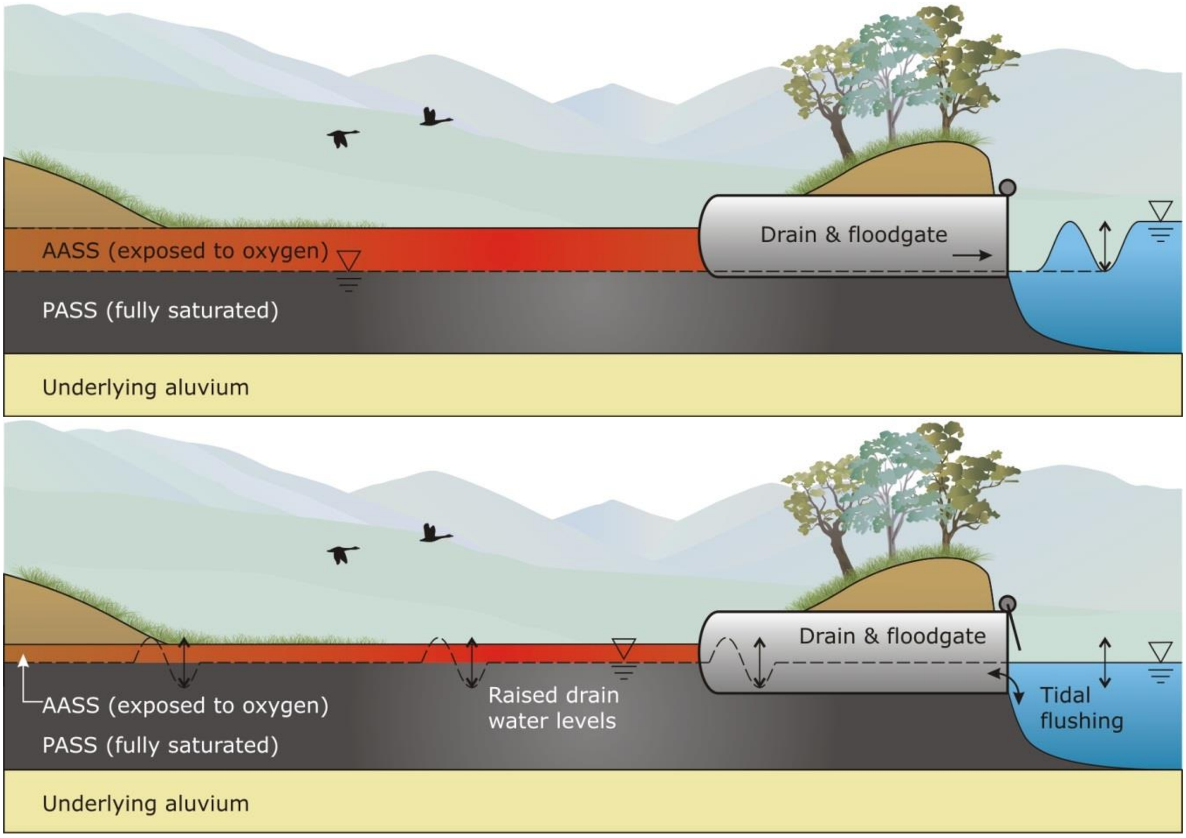


Figure 7-8: Before and after floodgate modification

7.2.11 Wet pasture

Wet pasture is an effective management option for reducing both acid and blackwater discharges from the floodplain to the estuary and is achieved by retaining fresh surface water on the floodplain during dry periods by limiting drainage. This outcome can be engineered by the installation of structures in the drainage channel such as a weir (Figure 7-9), and/or modification of pasture drainage pathways by drain infilling, drain reshaping or restoring natural flow paths. By retaining water on the floodplain, the groundwater table is increased promoting the growth of water tolerant vegetation which is less likely to cause a blackwater event and prevents acid scalding (Johnston et al., 2003a). Furthermore, by retaining water on the floodplain the overall export of poor quality water (either acidic water or blackwater) is reduced.

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

Wet pastures also encourage a change in the vegetation types towards water tolerant species which reduce the risk of blackwater generation (Southern Cross GeoScience, 2019). Water tolerant vegetation is less likely to die off during a flood event and contribute to the biological breakdown of organic matter that is the primary cause of blackwater events. Holding water on the floodplain, as occurs with wet pasture management, also allows the completion carbon cycle to occur on the floodplain, physically preventing deoxygenated water from flowing to the estuary.

Wet pasture management can be an effective strategy utilised by landholders to reduce their exposure during drought conditions. During drought periods, land utilised as wet pasture will be more resilient as a higher groundwater table means there is generally more water available for pasture. This may however mean that land in these areas is not as productive during non-drought periods. Wet pasture management strategies were implemented near Bungawalbin Creek on the Richmond River, and were found to not be successful at maintaining agricultural productivity due to the proliferation of native wetland grasses that were not palatable for cattle (p. comms. C. Clay, 02/06/2021). Wet pasture management should only be implemented with consultation of local landholders and consideration of the types of vegetation that may flourish. The type of vegetation promoted for wet pasture should be selected based on local conditions. Furthermore, consideration should be given for sea level rise which may restrict sections of the floodplain that can be managed as freshwater pasture.

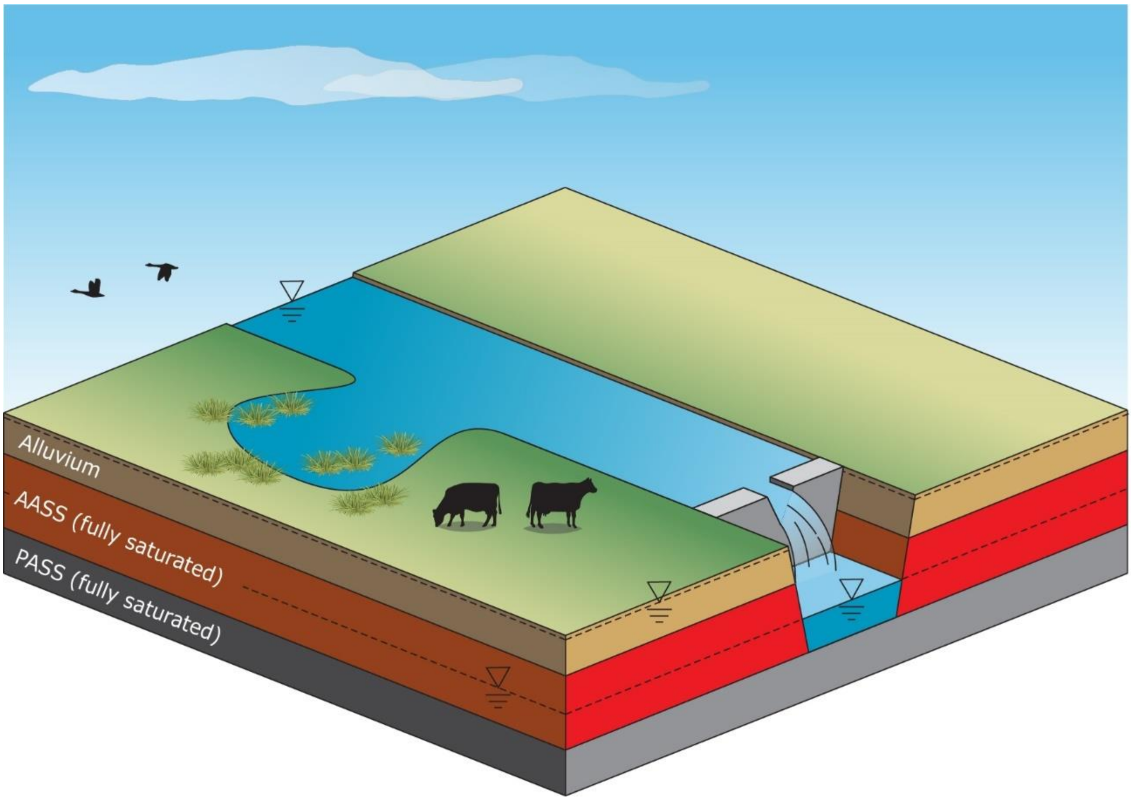


Figure 7-9: Wet pasture management

7.2.12 Wetland remediation

The coastal floodplains of NSW once included extensive areas of freshwater and brackish backswamps. The wettest sites were formerly dominated by grasslands, sedgelands, reedlands, or open water. Full restoration of former backswamp areas to a resemblance of their former condition could effectively reduce acid export, encourage water tolerant vegetation, reduce blackwater dsicharge and provide habitat for primary production.

Wetland remediation may encourage freshwater wetland, estuarine wetland or a combination of both. In a similar manner to land raising and wet pasture management options, remediation of a site to create tidal or freshwater wetlands could be undertaken over an entire subcatchment, or on a portion of the floodplain. This option has been effectively applied at acid affected sites in NSW, such as Tomago wetlands near Newcastle on the Hunter River and Big Swamp on the Manning River (Glamore et al., 2014) and is commonly recommended as the most effective way to manage blackwater (e.g. Eyre et al. (2006), Southern Cross GeoScience (2019) and Moore (2007)).

The creation of both freshwater and estuarine wetlands may require floodgates to be removed or relocated, as well as secondary drains to be infilled or reshaped as illustrated in Figure 7-10. Freshwater wetlands can be created by reducing the connection of the floodplain to the main river through infilling of major artificial drains and the re-instatement of natural levee banks. These changes will hold freshwater on the floodplain after rainfall, promoting water tolerant vegetation. Reducing the number of drainage points to the main river by infilling artificial drainage channels will also retain water on the floodplain for longer after flood events, which would allow carbon cycling to complete after decomposition. This would reduce blackwater discharge to the estuary.

Estuarine wetlands may require drainage networks to be redesigned to allow tidal inundation through shallower and wider drainage waterways. Regular tidal inundation would provide immediate natural buffering of ASS-affected areas, maintain higher groundwater levels and encourage water and salt tolerant vegetation, such as saltmarsh and mangroves. Less efficient drainage will also control discharges in a similar manner to that described in Section 7.2.7, reducing the impact of blackwater on downstream water bodies.

Wetland remediation has the greatest immediate environmental benefit by increasing water quality, eliminating acid discharge, reducing blackwater generation and drainage and providing aquatic habitat and fish passage. This option requires the largest change to existing land management practices. Note that any changes in hydrology will require studies into the impacts to flooding and land uses, and should only be implemented with extensive consultation of local landholders and consideration of the social and economic impacts of such changes.

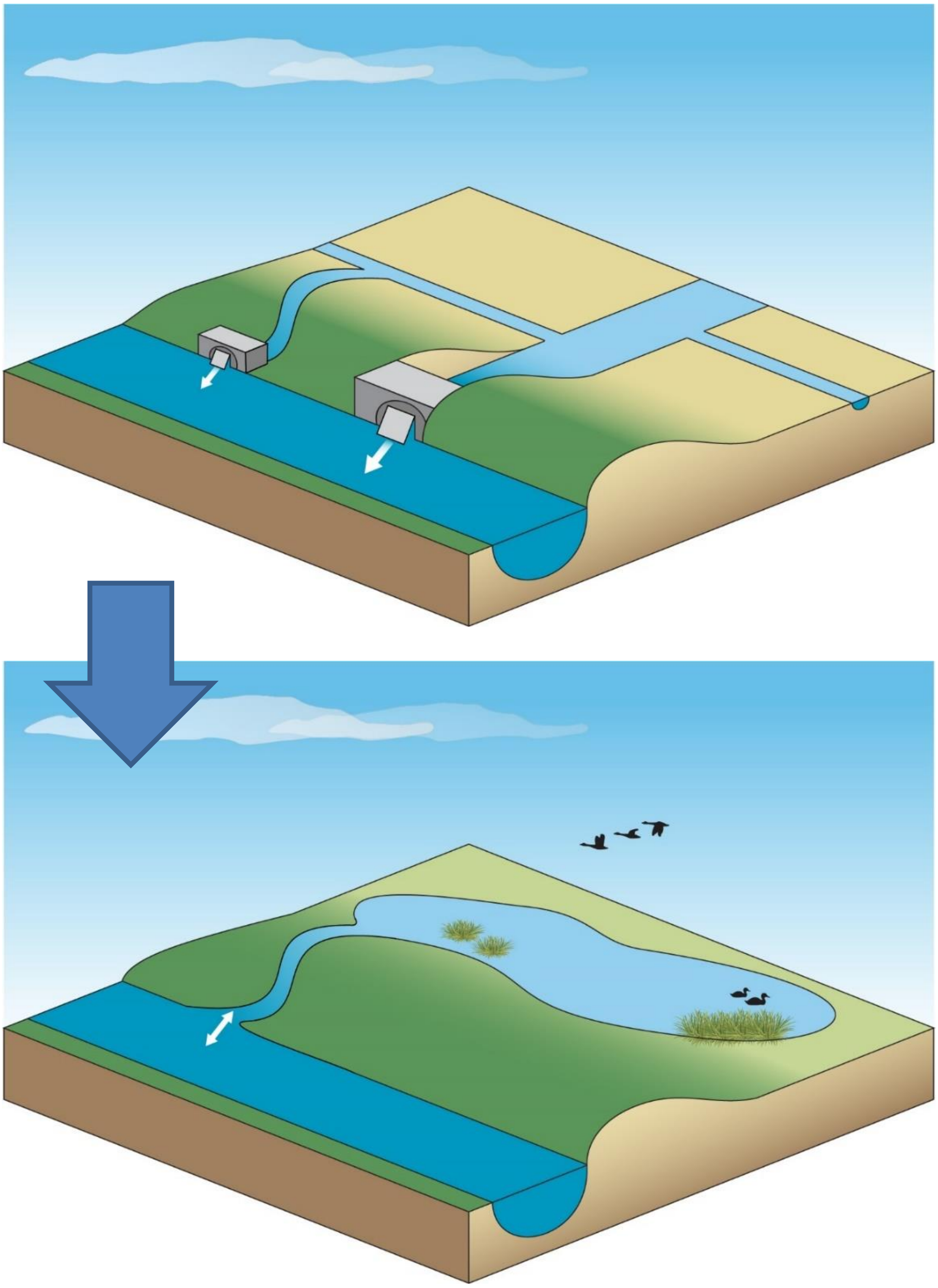


Figure 7-10: Full restoration to natural, unrestricted wetland

8 Development of management options

8.1 Preamble

Subcatchments considered in this study are prioritised based on their relative contribution to acid and blackwater generation within a floodplain, based on the methodology outlined in Chapter 4 and Chapter 6. Chapter 7 provides a summary of the generalised strategies that can be implemented to address the issues associated with acid sulfate soils and blackwater.

However, several additional indirect factors that influence the recommended onsite management strategies, but do not contribute to the prioritisation rating, were also considered in the development of management options. These factors address issues associated with the design and implementation of potential short and long-term management options for the study area. The factors described in this section include:

- Sensitive receivers;
- Asset condition;
- Current and future (where known) land uses;
- Costs and benefits of changes in land management or remediation;
- Sea level rise and associated floodplain and infrastructure vulnerability; and
- Type of waterways in the catchment.

8.2 Sensitive receivers

The proximity of each subcatchment to sensitive environmental receivers is an important factor to consider when assessing the benefits of remediation. NSW estuaries have significant environmental and economic values that are impacted by poor water quality discharging from the floodplains. Some sensitive receivers, such as commercial oyster leases and seagrasses, are located adjacent to the discharge point of high-risk ASS and/or blackwater subcatchments and are subsequently highly susceptible to impacts from poor water quality.

Common stationary sensitive receivers may include:

- Oyster leases;
- Macrophytes;
- Key fish habitat pertaining to the Fisheries Management Act 1994; and
- Endangered Ecological Communities (EEC) such as coastal wetlands defined by the State Environmental Planning Policy (SEPP) (Coastal Management) 2018

Potential aquatic habitat contained within, or downstream of, each subcatchment should also be considered as part of proposed remediation strategies of high-risk drains. Winberg and Heath (2010) identified that floodgates eliminate natural fish and invertebrate life from tributary habitats and reduce overall primary production in the lower estuary. Tributaries function as key fishery nursery habitat and contribute to the overall population of fisheries in estuaries (Winberg and Heath, 2010; NSW DPI, 2007). Mapping of sensitive receivers is provided for each estuary, as well as a summary of proximity (presented as distance along river channel) to each subcatchment. Proximity of end-of-system infrastructure to Coastal Management SEPP coastal wetlands and littoral rainforest sensitive receivers has also been assessed using GIS techniques and inspection of aerial imagery.

8.3 Asset condition

When assessing floodgate structures, condition reporting is undertaken on the ability of the floodgate to restrict tidal intrusion and to maintain efficient drainage. That is, a new floodgate that effectively restricts tidal intrusion into a flood mitigation drain would be reported in 'good' condition. Asset condition can be summarised under the following categories:

- Good;
- Fair;
- Poor; or
- Very Poor/Missing.

Asset condition for all structures surveyed for this study are provided in each floodplain report.

8.4 Current and future land uses and tenure

Current land uses and land-owners are an important aspect of developing the management options. Where present-day land uses may be impacted by changes in drainage management or sea level rise, the potential economic loss in land and productivity value should be acknowledged in the management options.

Chapter 9 provides an overview of the information used to assess current land use. A discussion of future land use mapping (at a local government area scale) is also provided. Consideration of areas marked for urban growth have been acknowledged where relevant, in the subcatchment management options.

8.5 Costs and benefits of land management options

There are a number of costs that need to be considered when developing management plans for coastal floodplains. The magnitude of the costs involved is often a key determinant to whether an action can be implemented in the short term. A rough estimate of costs related to the following aspects is provided in the management options:

- Upfront engineering cost (e.g. design and on-ground costs, summarised in Section 10.2.1);
- Land acquisition (based on NSW Valuer General data, more information on data is provided in Section 10.2.2);
- Lost productivity (based on potential changed land uses resulting from remediation. Information on productivity estimates is provided in Section 10.2.3); and

- Long-term management costs, including maintenance and monitoring (summarised in Section 10.2.4).

The costs estimated in this study do not include additional investigations or studies that may be required (e.g. a Review of Environmental Factors, hydrological assessment, consultation, or Council approvals).

On the other hand, there are a range of environmental, social, cultural and economic benefits of improving land management on coastal floodplains. The effectiveness of the management actions at improving aquatic habitat, the effects of ASS and the effects of blackwater are assessed using a qualitative score (e.g. negligible, low, moderate, high). This is based on the type of remediation, experience, and engineering judgement. While the benefits of remediation are not specifically addressed in the management options, a brief overview of the social, cultural and economic benefits of remediating the environment is provided in Section 10.3.

8.6 Sea level rise and floodplain vulnerability

Sea level rise in coastal estuaries is likely to affect land use and flood mitigation management into the future (Glamore et al., 2016b). As long-term tidal levels increase, individual subcatchments become connected at higher elevations. Although increased high tide elevations are likely to impact the floodplain in the long-term, the major short-term impact will be reduced drainage from higher, low tide water levels. This is particularly relevant to low-lying areas where prolonged periods of inundation following wet weather events are expected by 2050.

Detailed hydrodynamic modelling of each estuary has been completed using the RMA suite of modelling software (King, 2015). Modelling simulated present-day water levels, as well as predicted sea level rise in the near (~2050) and far (~2100) future of +0.16 m and +0.67 m respectively (Glamore et al., 2016b). More information on the modelling and adopted sea level rise can be found in Section 11.3.

The modelling has been used to predict future water levels within the studied estuaries to assess the vulnerability of floodplain subcatchment areas and floodplain infrastructure to sea level rise. A discussion of the methods used to assess vulnerability is provided in Section 11.4. Floodplain infrastructure that is identified as highly vulnerable, and floodplain areas that are expected to be most impacted by reduced drainage are more likely to be highlighted for remediation as a priority. It is likely that the present-day land uses in such areas will be impacted by sea level rise in the near-to-far future, providing opportunities to allow changes in land management and floodplain hydrology. This analysis is intended to be a first-pass assessment to identify vulnerable areas and infrastructure. Further investigation may be required to assess the potential impacts of sea level rise and reduced drainage on individual subcatchments.

8.7 Waterway classification

Connected natural creeks and waterways provided important aquatic habitats prior to human intervention. In general, remediation focuses on restoration of natural waterways and flow paths and removal of constructed drainage networks where possible. Waterways below a 5 m AHD elevation have been categorised as part of this project into one of four categories:

- Natural waterbody watercourse – a natural waterway that pre-dates European settlement. Natural waterbody watercourses are typically sinuous and follow geological features;
- Artificial waterbody – a constructed waterway that was purpose-built to enhance drainage of backswamps or redirect water. Artificial waterways are typically straight and deep;
- Watercourse – a waterway that follows a natural drainage system, but has been heavily modified or disconnected from the upstream catchment; and
- Connector watercourse – typically a waterway with either natural or artificial sections that provides a connection between two natural waterbody watercourses. Typically, connector watercourses flow through a drainage network which was once a backswamp connecting the upper catchment to the river.

Details on how waterways have been categorised are provided in Chapter 12. Waterway categorisations of all identified drainage lines in a subcatchment are provided with each set of management options. Where possible, management options focus on improving aquatic habitat in natural waterways (i.e. natural waterbody watercourses, watercourses or connector watercourses) which would have historically been connected. Drain modifications (e.g. infilling or reshaping) are typically only recommended in artificial waterbodies (or connector watercourses, if appropriate).

In addition to its use within the prioritisation methodology, the categorisation of waterways has enabled an evidence-based approach for determining important habitats. This is particularly relevant to the floodplain where historic flow paths connecting the estuary and the upper catchment through drainage and the construction of floodgates have disconnected a previously continuous system. The approach has taken into consideration and combined relevant legislation in the development of a tool which can be used to guide determinations of important conservation areas within floodplains such as Key Fish Habitat and assist in the overall management of the marine estate.

9 Land use

9.1 Preamble

Understanding present day land uses, as well as the associated values, is important to guiding the type and extent of remediation that could be implemented. This section includes:

- Present day land use – which summarises the data used to estimate land uses; and
- Future land use – which summarises future planning outlined in state and local government documents.

9.2 Present day land use

Knowledge of present-day land use assists in the understanding of the impacts of potential remediation options. For example, wet pasture management may be a viable option in areas that are used for grazing, but not in areas used for sugar cane which is intolerant to prolonged inundation. Land use data was sourced from the NSW Department of Planning, Industry and Environment (DPIE, 2020). This spatially comprehensive land use dataset released in June 2020 is based on land use in 2017 and is the most up-to-date for NSW. For this study, land use definitions were based on the Australian Land Use and Management (ALUM) classification, which separates land use into six (6) primary categories, and subsequently into secondary and tertiary classifications. A summary of the primary and secondary classifications is shown in Table 9-1. In general, primary and secondary classifications are sufficient for this study, with the notable exception of sugar cane, which is included in the tertiary classification of cropping (both dryland and irrigated). Land uses summarised in this section are also used in the blackwater prioritisation method, discussed in Section 6.3.1. For each subcatchment, the land use was provided in the categories outlined in Table 9-2 in absolute areas and as a percentage of total area.

Cadastral data has also been obtained from the NSW Spatial Services that identifies the following features:

- Roads and road corridors;
- Railway corridors;
- National Parks and Wildlife Services Reserves;
- Local Aboriginal Land Councils; and
- Crown Lands.

Table 9-1: NSW ALUM primary and secondary classifications (DPIE, 2020)

Primary Classification	Secondary Classifications
Conservation and natural environments	Nature conservation
	Managed resource protection
	Other minimal use
Production from relatively natural environments	Grazing native vegetation
	Production forestry
Production from dryland agriculture and plantations	Plantation forestry
	Grazing modified pastures
	Cropping
	Perennial horticulture
	Seasonal horticulture
	Land in transition
Production from irrigated agriculture and plantations	Irrigated plantation forestry
	Irrigated grazing modified pastures
	Irrigated cropping
	Irrigated perennial horticulture
	Irrigated seasonal horticulture
	Irrigated land in transition
Intensive uses	Intensive horticulture
	Intensive animal husbandry
	Manufacture and industrial
	Residential and farm infrastructure
	Services
	Utilities
	Transport and communications
	Mining
Water	Lake
	Reservoir/dam
	River
	Channel/aqueduct
	Marsh/wetland
	Estuary/coastal waters

Table 9-2: Land classifications used in subcatchments

Land use	ALUM Secondary Classifications
Conservation and minimal use	Nature conservation Managed resource protection Other minimal use
Grazing	Grazing native vegetation Grazing modified pastures Irrigated grazing modified pastures
Forestry	Plantation forestry Production forestry Irrigated plantation forestry
Sugar Cane	Cropping (where tertiary classification is sugar cane) Irrigated cropping (where tertiary classification is sugar cane)
Other Cropping	Cropping (where tertiary classification is not sugar cane) Irrigated cropping (where tertiary classification is not sugar cane)
Horticulture	Intensive horticulture Perennial horticulture Seasonal horticulture Irrigated perennial horticulture Irrigated seasonal horticulture
Urban/Industrial/Services	Intensive animal husbandry Manufacture and industrial Residential and farm infrastructure Services Utilities Transport and communications Mining
Marsh/Wetland	Marsh/Wetland
Other	Lake Reservoir/dam River Channel/aqueduct Estuary/coastal water Land in transition Irrigated land in transition

9.3 Land use planning

Where it is available, information on how the coastal floodplains in NSW are likely to develop into the future has been considered in the management options. The following sections discuss areas identified for growth in the Local Environmental Plans or regional planning in each local government area.

9.3.1 Framework

In 2017, the NSW Department of Planning, Industry and Environment (DPIE) completed strategic land use plans for the future of regional NSW. Regional plans that are relevant for this study include the:

- North Coast (Tweed, Richmond, Clarence, Macleay and Hastings floodplains);
- Hunter (Manning floodplain); and
- Illawarra/Shoalhaven (Shoalhaven floodplain).

According to NSW DPIE (NSW DPIE, 2020):

> *"The Regional Plans set the framework, vision and direction for strategic planning and land use, planning for future needs for housing, jobs, infrastructure, a healthy environment and connected communities."*

Further to the future regional land use plans outlined by NSW DPIE, Local Environment Plans (LEPs) outline development controls and the way land can be used for each council Local Government Area (LGA). LEPs that are relevant for this study include:

- Tweed Local Environment Plan 2014;
- Ballina Local Environmental Plan 2012;
- Richmond Valley Local Environmental Plan 2012;
- Lismore Local Environmental Plan 2012;
- Clarence Valley Local Environmental Plan 2011;
- Kempsey Local Environmental Plan 2013;
- Port Macquarie-Hastings Local Environmental Plan 2011;
- Greater Taree Local Environmental Plan 2010; and
- Shoalhaven Local Environmental Plan 2014.

The following sections provide brief summaries and future land use maps (where available) for each of the local government planning areas.

9.3.2 North Coast floodplains

Future planning for the North Coast of NSW including the Tweed, Richmond, Clarence, Macleay, and Hastings catchments is focused on developing growth in urban centres while protecting farmland, the coastal strip and important environmental and cultural areas (NSW DPIE, 2017). The future vision for the North Coast region is stated as (NSW DPIE, 2017):

> *"The best region in Australia to live, work and play thanks to its spectacular environment and vibrant communities."*

This will be implemented with the following goals (NSW DPIE, 2017):

- *"The most stunning environment in NSW.*
- *A thriving, interconnected economy.*
- *Vibrant and engaged communities.*
- *Great housing choice and lifestyle options."*

Urban growth maps have been outlined in the North Coast Regional Plan for each of the respective LGAs as relevant for this study. The key for each map is shown in Figure 9-1. Individual maps are shown from Figure 9-2 to Figure 9-8.

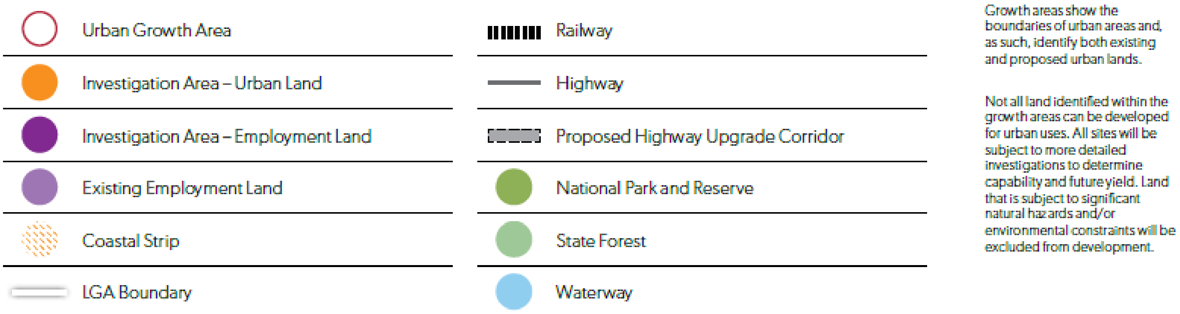


Figure 9-1: Key for North Coast LGA urban growth maps (NSW DPIE, 2017)

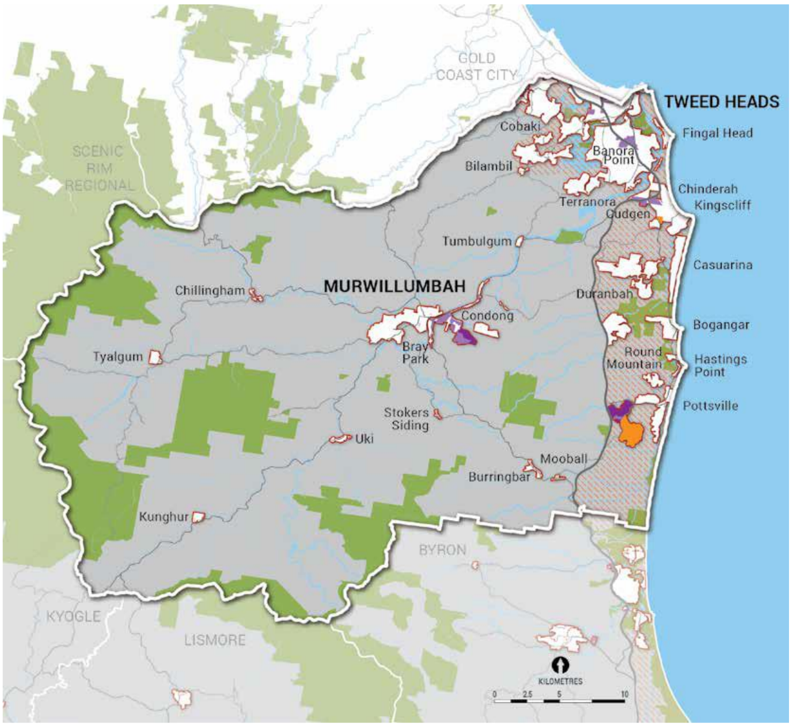


Figure 9-2: Tweed LGA urban growth map (NSW DPIE, 2017)

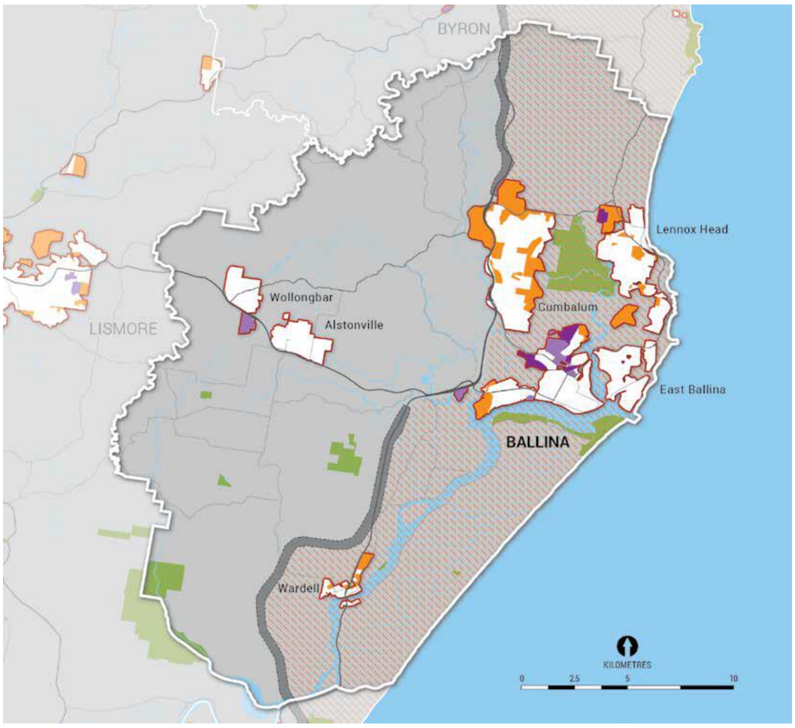


Figure 9-3: Ballina LGA urban growth map (NSW DPIE, 2017)

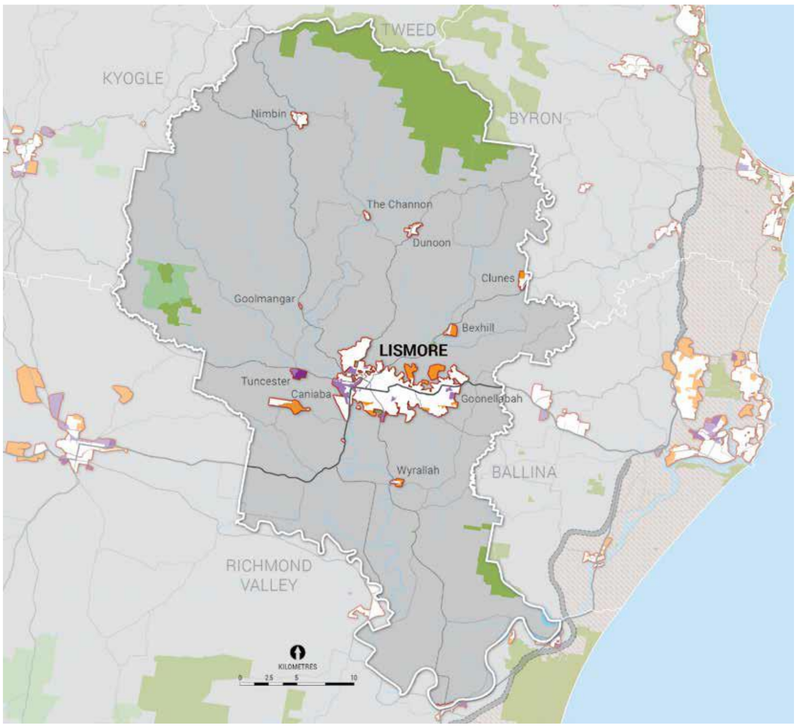


Figure 9-4: Lismore LGA urban growth map (NSW DPIE, 2017)

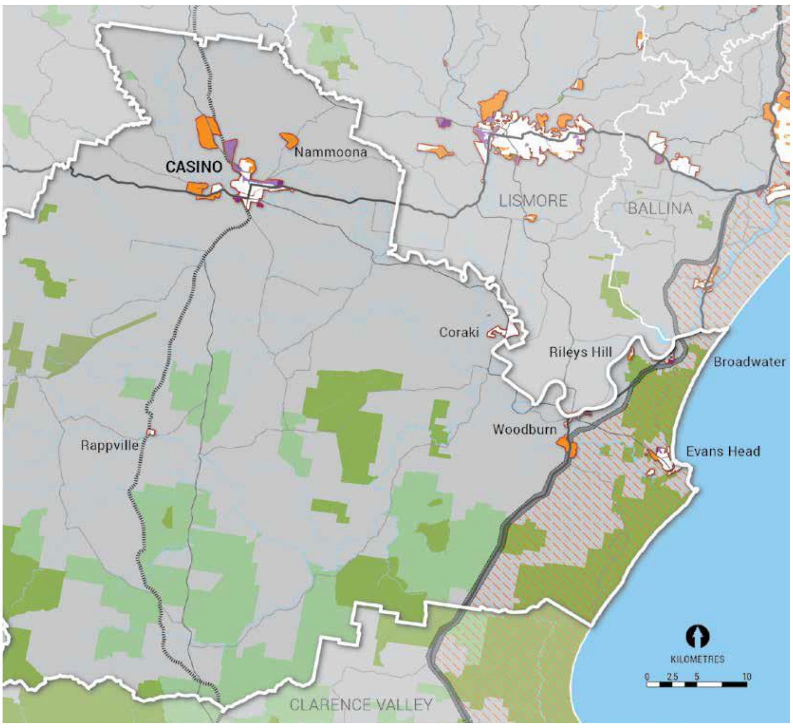


Figure 9-5: Richmond Valley LGA urban growth map (NSW DPIE, 2017)

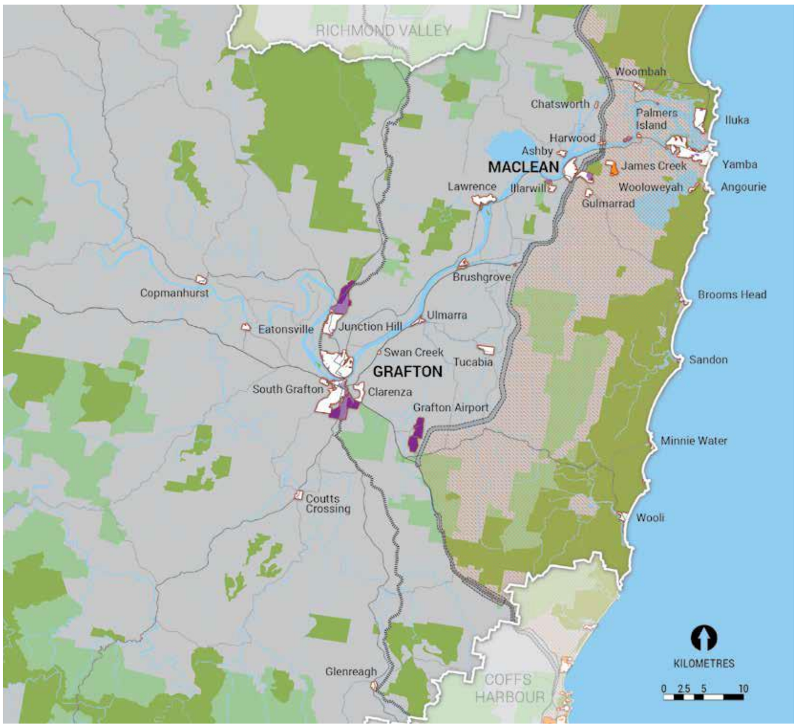


Figure 9-6: Clarence Valley LGA urban growth map (NSW DPIE, 2017)

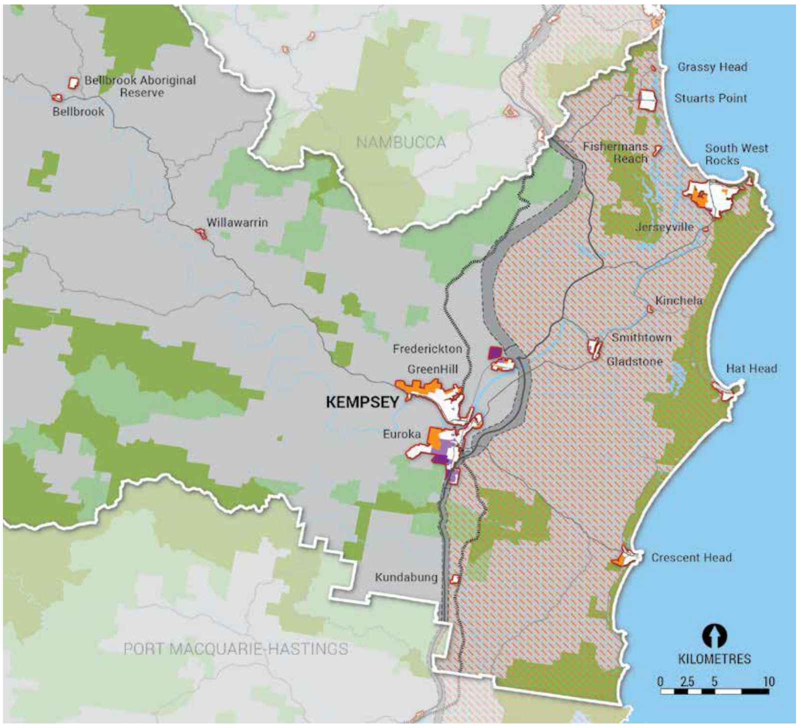


Figure 9-7: Kempsey LGA urban growth map (NSW DPIE, 2017)

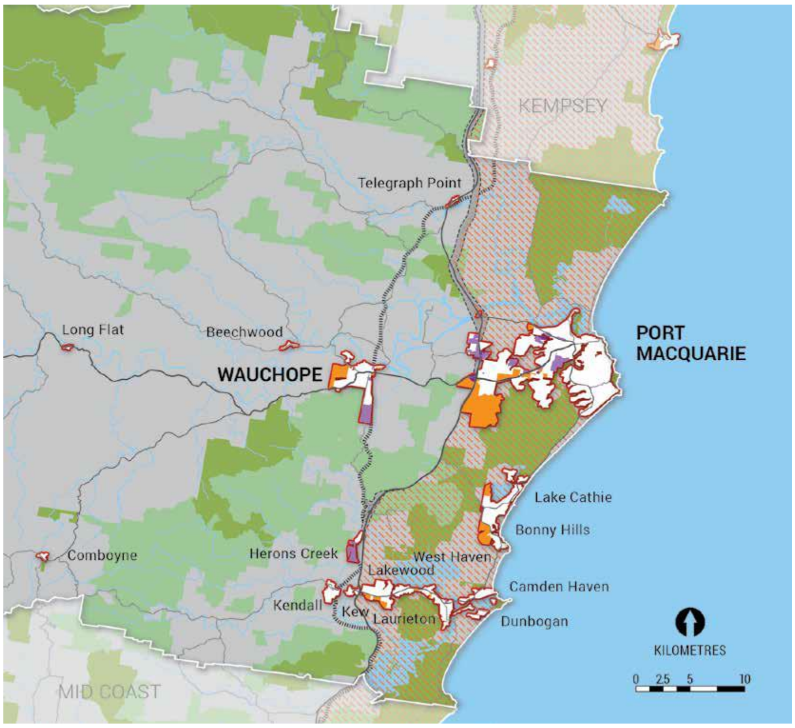


Figure 9-8: Port Macquarie-Hastings LGA urban growth map (NSW DPIE, 2017)

9.3.3 Midcoast (Manning floodplain)

Future planning for the Midcoast, including the Manning floodplain, has forecast a population growth of 5000 and identified food production, tourism, manufacturing and services as key economic drivers (NSW DPIE, 2016). The regional priorities for the area include (NSW DPIE, 2016):

- *"Support the visitor economy by leveraging the natural beauty of the area and enhancing nature-based tourism infrastructure.*
- *Protect productive landscapes that sustain the poultry, dairy and beef industries.*
- *Manage development within sensitive water catchments and protect environments that sustain the oyster industry.*
- *Provide capacity for long-term employment through education and training, and by capitalising on intra- and inter-regional connections.*
- *Provide housing, services and facilities, as well as accessible public spaces for an ageing population."*

9.3.4 Illawarra-Shoalhaven (Shoalhaven floodplain)

Future planning for the Illawarra-Shoalhaven region has laid out the following vision statement (NSW DPIE, 2015):

> "*A sustainable future and a resilient community, capable of adapting to changing economic, social and environmental circumstances".*

The specific measures needed to achieve the following goals have been detailed within the regional plan (NSW DPIE, 2015):

- *"a prosperous Illawarra-Shoalhaven;*
- *a region with a variety of housing choices, with homes that meet needs and lifestyles;*
- *a region with communities that are strong, healthy and well-connected;*
- *a region that makes appropriate use of agricultural and resource lands; and*
- *a region that protects and enhances the natural environment."*

Details of the future planning for the Illawarra-Shoalhaven are also displayed in Figure 9-9.

Figure 9-9: Illawarra-Shoalhaven regional plan strategy map (NSW DPIE, 2015)

10 Costs and benefits

10.1 Preamble

Improving land management on coastal floodplains can have substantial environmental, social, cultural and economic benefits, however there are also costs that need to be managed. The cost of on-ground works and how to acquire funding are often key factors to whether changes in land management that improve environmental outcomes are pursued. The following sections describe the type of costs and benefits that have been considered in the management options developed through this study.

10.2 Costs

10.2.1 Engineering costs

Engineering costs include design, construction and annual maintenance associated with different forms of floodplain management options. Table 10-1 provides a summary of the indicative costs (based on standard commercial rates) for the engineering costs of various management options proposed. Note that these costs do not include any environmental or flood assessments that may be required in some locations.

Table 10-1: Indicative costs for various management options

Management Option	Design cost*	Implementation	Maintenance (per annum)
Weir	\$10,000 to \$30,000	\$10,000 to \$200,000	\$5,000 to \$15,000
Floodgate modification	\$5,000 to \$25,000	\$10,000 to \$30,000 per gate	\$1,000 to \$15,000
Liming	\$5,000 to \$10,000	\$30/m^3 acid soil per application (dependent on acid content)	Dependent on required repetition of liming
Culvert relocation	\$5,000 to \$25,000	\$70,000 to \$120,000 per culvert	\$1,000 to \$10,000
Drain infilling	\$10,000 to \$20,000	Equipment establishment (\$10,000) + unit rate (\$14,000/500 m)	None
Drain reshaping	\$10,000 to \$20,000	Equipment establishment (\$10,000) + unit rate (\$25,000/500 m)	Ongoing drain maintenance
Permeable Reactive Barrier (PRB)	\$20,000 to \$80,000	\$15,000 to \$200,000 per 100 m	\$25,000
Wet pasture	\$10,000 to \$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 remediation	\$40,000 to \$200,000	Land acquisition (per ha) + Drain infilling + Drain reshaping + Infrastructure removal + Infrastructure relocation	Land management (fire control, pests, fencing etc)

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

10.2.2 Land acquisition

Some management options may require the acquisition of privately owned land if there is likely to be a significant change to the way the land might be used and managed (e.g. restoration to a tidal wetland would require cessation of agricultural uses in most locations). In some situations, existing land parcels that contain low-lying area that is ideal for remediation could be subdivided so that higher, more productive land can be maintained for agriculture.

The cost of land acquisition can vary significantly between locations and properties. In this study, land value has been evaluated as average value per hectare. The Rural Bank (2020) released a report on the median value of farmland (with a minimum size of 30 ha) throughout the state annually. Table 10-2 summarises the median rural land value in the local government areas relevant to this study, based on sales in 2019.

Table 10-2: Median farmland property price, based on properties 30 ha or larger (Rural Bank, 2020)

Local Government Area	Median Rural Property Price ($/ha)
Tweed Shire Council	$14,087
Ballina Shire Council*	-
Richmond Valley Council	$8,440
Lismore City Council	$12,299
Clarence Valley Council	$5,577
Kempsey Shire Council	$7,119
Port Macquarie-Hastings Council	$7,487
MidCoast Council	$9,652
Shoalhaven City Council	$11,683

*No rural property price data was available for the Ballina LGA from The Rural Bank (2020)

The NSW Valuer General releases land values across the state for more specific land values. The most recent available data was downloaded on the 30 April 2020. The land values in this database represent an approximation of the market value of a parcel of land if it was sold on 1st July on the year of valuation.

Spatial data from the NSW Valuer General calculates land values for parcels of land throughout NSW. The valuation is assessed using a ‘mass valuation approach’, meaning that properties are valued in aggregate with other properties with similar characteristics. The valuation includes consideration of factors including (NSW Valuer General, 2017):

- Land zoning/classification;
- Productivity;

- Location;
- Access;
- Land size;
- Clearing;
- Drainage;
- Heritage restrictions; and
- Nearby development and infrastructure.

Land valuation does not include the value of most land improvements, including buildings and structures, crops or stock or plant and equipment. NSW Spatial Services provided July 2019 NSW Land Value data throughout the floodplains considered in this study. Data is available for most privately owned land but is not provided for government owned land (such as NPWS land). Land valuations have been provided for three broad types of properties:

- Urban – these properties tend to be small (typically less than 1,500 m^2) and located within the vicinity of regional centres;
- Semi-rural – these properties are generally less than 10 ha in size and often located on the outskirts of towns and regional centres; and
- Rural – these properties vary significantly in size, but are typically larger than 10 ha, and are most commonly used for primary production.

Average land values have been investigated across each coastal floodplain in two forms - the overall average value ($/ha) for every property in the area, and also the value for rural properties and compared to non-rural (urban and semi-rural). The value of rural properties is more comparable with values in Table 10-2, although the local government areas typically extend well beyond the floodplain areas considered in this study. The results of this analysis across the seven (7) floodplains considered in this study are shown in Table 10-3, highlighting the significant difference in per hectare value depending on the property type. Note that these values are averages only, and do not represent the actual price of an individual parcel of land and should only be used to provide a first pass estimate of land value.

Remediation of estuarine environments often focusses on the lowest elevation land on the floodplain. These areas have typically had extensive artificial drainage networks constructed to substantially alter the hydrology to allow for agricultural development. These are often the areas that would have naturally been permanent (or near permanent) freshwater or brackish wetlands. While the drainage systems allow for grazing or cropping to be viable, this land remains susceptible to prolonged flooding and, in some cases, impacts from saltwater infiltration. In rural properties, it is expected that the elevation of the land will have an impact on the value of the property (per unit area).

To assess the impact of elevation on land value, the relevant floodplains have been analysed for properties that are largely above (over 50%) or below a nominated elevation threshold. The critical elevation threshold varies across each estuary, generally increasing for floodplains further upstream. The elevation chosen in each subcatchment was the median elevation used in the blackwater generation analysis (see Section 6.4), which is, at a minimum, mean high water. The results, including the critical elevation threshold, are provided in individual subcatchment management options.

Table 10-3: Average land value ($/ha) on each floodplain, separated by property type

Floodplain	Average Land Value ($/ha)	Total No. Properties	Average Land Value ($/ha) Non-rural	Total No. Properties Area Non-rural	Average Land Value ($/ha) Rural	Total No. Properties Rural
Tweed	$71,777	2,211	$269,167	1,972	$26,615	239
Richmond	$19,942	3,118	$199,820	2,137	$10,910	981
Clarence	$16,087	8,612	$238,410	7,469	$4,677	1,143
Macleay	$9,464	2,062	$65,657	1,415	$5,161	647
Hastings	$14,843	1,073	$157,014	747	$7,489	326
Manning	$14,293	1,552	$61,166	1,057	$8,680	495
Shoalhaven	$61,107	2,108	$503,561	1,777	$27,900	331

10.2.3 Loss in agricultural productivity

Significant agricultural value is produced from coastal floodplains in NSW. Where land uses are significantly impacted by potential changes in land management, it is important to understand and acknowledge that there may be a loss in agricultural productivity. The Australian Bureau of Statistics releases annual data relating to the Value of Agricultural Commodities Produced (VACP). The data is released over a variety of spatial areas, referred to as "Statistical Areas". The two (2) relevant statistical areas for this project are:

1. Statistical Area Level 2 (SA2): SA2 areas generally cover 3,000 – 10,000 people. ABS states that SA2 represents "function areas that represent a community that interacts socially and economically".
2. Statistical Area Level 4 (SA4): SA4 areas generally cover 100,000 – 300,000 people in regional areas, and 300,000 – 500,000 people in metropolitan areas. SA4 areas are specifically designed to reflect labour markets, relating to the availability of employment and labour. SA4 areas typically span more than one LGA.

The ABS releases VACP data annually aggregated over the larger SA4 areas, and every five (5) years for the smaller SA2 areas (most recently in the 2015 – 2016 reporting year). This data provides an estimate of the value of commodities produced in a region based on sample survey or census data, and median commodity prices. The values are broken into classes of agricultural products, including broadacre crops and livestock (products and slaughtered).

VACP data has been downloaded from ABS website for the three (3) most recent years:

- 2015 – 2016 – SA2 and SA4;
- 2016 – 2017 – SA4; and
- 2017 – 2018 – SA4.

All data has been converted to 2019 dollars using the Reserve Bank of Australia inflation calculator.

The land use data discussed in Section 9.2, used in conjunction with the VACP, allows for estimates of production value per unit area ($/ha) to be made. Ideally, the land use categories would be identical to those in the ABS VACP data. However, this is not the case. Table 10-4 summarises how the two (2) datasets have been matched to accommodate the analysis.

To ascertain a production value (in $/ha) relevant to this study, the SA4 and SA2 regions that cover the seven (7) study coastal floodplain catchments have been identified. Table 10-5 summarises the statistical areas considered. Only areas that cover some portion of the floodplain (<5 m AHD) have been included. The SA4 regions are large and typically encompass the catchment of a number of coastal river systems. Note the values of production provided in this section do not consider the cost of production.

Table 10-4: Land use categories and corresponding ABS VACP categories

Category	Land use Categories (Tertiary Codes)	ABS VACP Categories
Grazing	• Grazing native vegetation (210) • Grazing modified pastures (320-321-322-323-324-325) • Grazing irrigated modified pastures (420-421-422-423-424-425)	• Livestock products – Total • Livestock slaughtered and other disposals - Total
Sugar cane	• Sugar (335) • Irrigated Sugar (435)	• Broadacre crops - Non-cereal crops - Sugar cane - Cut for crushing
Other Broadacre Crops	• Cropping, excluding sugar (330-331-332-333-334-336-337-338) • Irrigated cropping, excluding irrigated sugar (430-431-432-433-434-436-437-438-439)	• Broadacre crops – Total (excluding Broadacre crops - Non-cereal crops - Sugar cane - Cut for crushing) • Hay - Total
Horticulture	• Perennial horticulture (340-341-342-343-344-346-347-348) • Seasonal horticulture (350-351-352-353-354) • Irrigated perennial horticulture (440-441-442-443-444-446-447-448-449) • Irrigated seasonal horticulture (450-451-452-453-454-455)	• Vegetables for human consumption – Total • Fruit and nuts (excluding grapes) – Total • Nurseries, cut flowers or cultivated turf - Total

Table 10-5: SA2 and SA4 regions considered

River/Estuary	SA4 Regions	SA2 Regions
Tweed	Richmond – Tweed	Murwillumbah Murwillumbah Region Tweed Heads Terranora – North Tumbulgum Kingscliff – Fingal Head
Richmond	Richmond – Tweed	Evans Head Lennox Head – Skennars Head Casino Casino Region Lismore Region
Clarence	Coffs Harbour – Grafton	Grafton Grafton Region Maclean – Yamba – Iluka
Macleay	Mid North Coast	Kempsey Kempsey Region South West Rocks
Hastings	Mid North Coast	Port Macquarie – West Port Macquarie Region Wauchope
Manning	Mid North Coast	Old Bar – Manning Point – Red Head Taree Taree Region
Shoalhaven	Southern Highlands and Shoalhaven	North Nowra – Bomaderry Nowra Berry – Kangaroo Valley Callala Bay – Currarong Culburra Beach

The spatial area (ha) of a given land use was estimated using the 2017 land use data to calculate the average production value ($/ha) in a particular region. The total value of commodities produced in each year is divided by this area. Only regions with more than 10 ha of the specified land use is used in the analysis.

Basic statistics and boxplots have been produced to show the variation of production values in each catchment (including a category called 'All', which includes all the regions in Table 10-5). Figure 10-1 has been provided to assist in the interpretation of the boxplot data. A summary of the statistics has been provided in Table 10-6, while boxplots have been provided in Figure 10-2 to Figure 10-5. Median values of production have been adopted for this project when estimating the value of primary production. Productivity estimates are only included for rural areas.

Table 10-6: Statistics of production values throughout the seven (7) river catchments

Land use	River	Min	25th Percentile	Median	75th Percentile	Max
Grazing	All	$23	$254	$446	$664	$6,862
	Tweed	$23	$216	$367	$469	$531
	Richmond	$209	$377	$521	$627	$758
	Clarence	$130	$167	$229	$271	$768
	Macleay	$217	$360	$420	$435	$489
	Hastings	$76	$375	$427	$475	$538
	Manning	$420	$440	$473	$829	$945
	Shoalhaven	$563	$732	$979	$3,450	$6,862
Sugar cane	All	$623	$1,267	$1,973	$2,592	$4,349
	Tweed	$623	$1,094	$1,420	$1,877	$2,189
	Richmond	$769	$1,267	$1,721	$1,982	$2,189
	Clarence	$2,491	$2,625	$2,929	$3,768	$4,349
	Macleay	No Sugar Cane Production				
	Hastings	No Sugar Cane Production				
	Manning	No Sugar Cane Production				
	Shoalhaven	No Sugar Cane Production				
Other Broadacre Crops	All	$333	$702	$1,389	$3,170	$56,422
	Tweed	$678	$791	$895	$1,092	$1,483
	Richmond	$333	$690	$828	$1,022	$11,702
	Clarence	$354	$744	$1,161	$1,671	$15,648
	Macleay	$2,831	$3,170	$3,960	$41,958	$56,422
	Hastings	$2,831	$3,085	$3,565	$14,072	$44,408
	Manning	$1,389	$1,502	$2,831	$3,170	$3,960
	Shoalhaven	$539	$611	$684	$796	$908
Horticulture	All	$90	$7,769	$14,340	$23,749	$73,587
	Tweed	$3,425	$6,703	$9,356	$11,199	$14,241
	Richmond	$1,105	$6,634	$8,572	$10,846	$20,720
	Clarence	$3,790	$22,391	$51,259	$56,888	$73,587
	Macleay	$14,340	$15,481	$23,720	$23,777	$47,685
	Hastings	$90	$13,365	$14,340	$23,720	$23,777
	Manning	$14,340	$21,375	$23,749	$25,763	$31,720
	Shoalhaven	$13,974	$16,137	$18,059	$22,558	$32,453

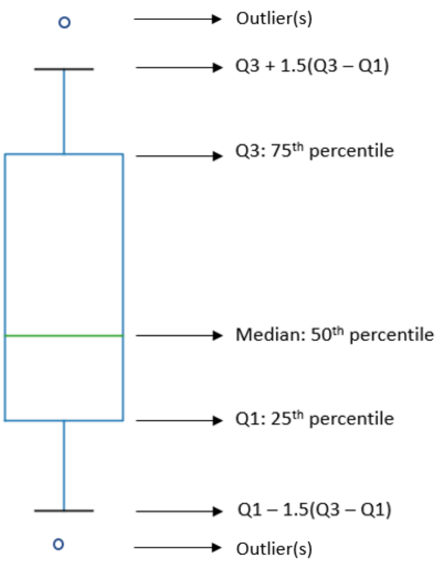


Figure 10-1: Interpreting boxplots

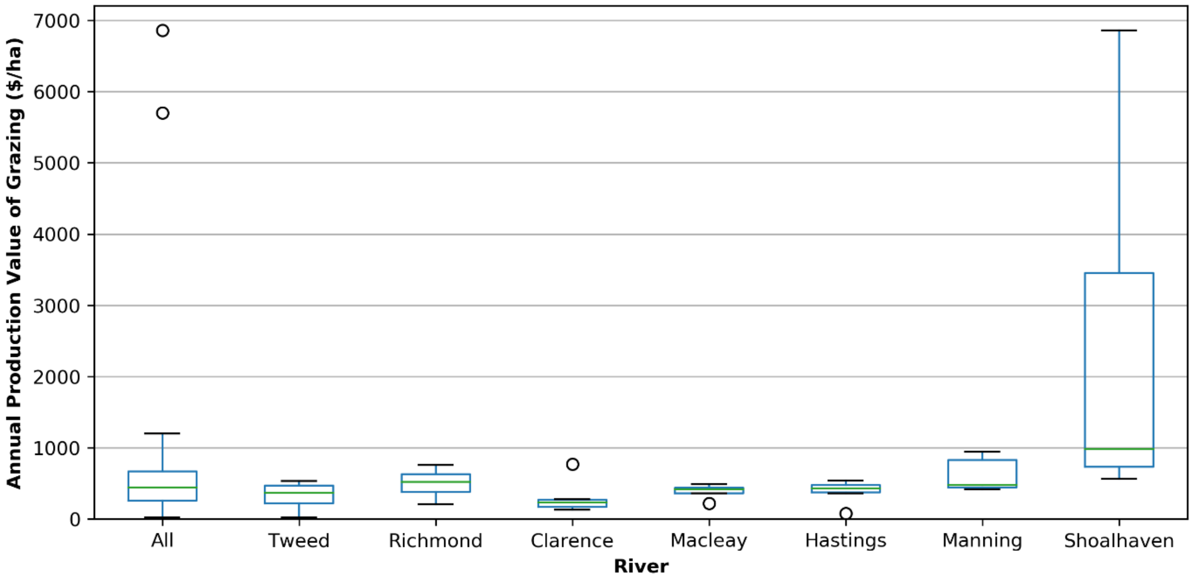


Figure 10-2: Boxplots of annual production value of grazing in each catchment

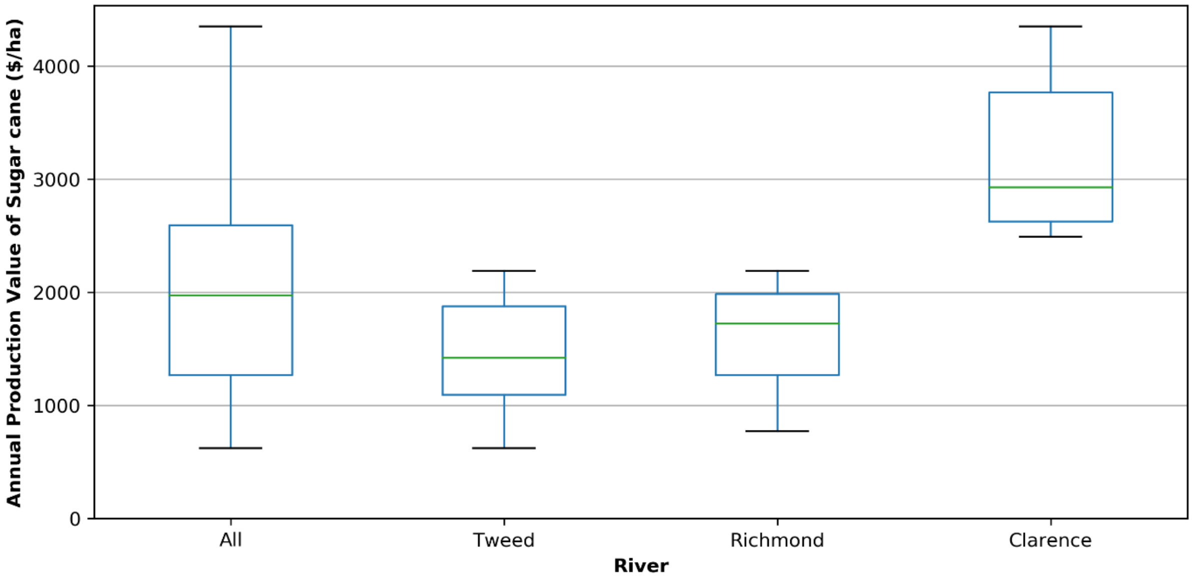


Figure 10-3: Boxplots of annual production value of sugar cane in each catchment (where applicable)

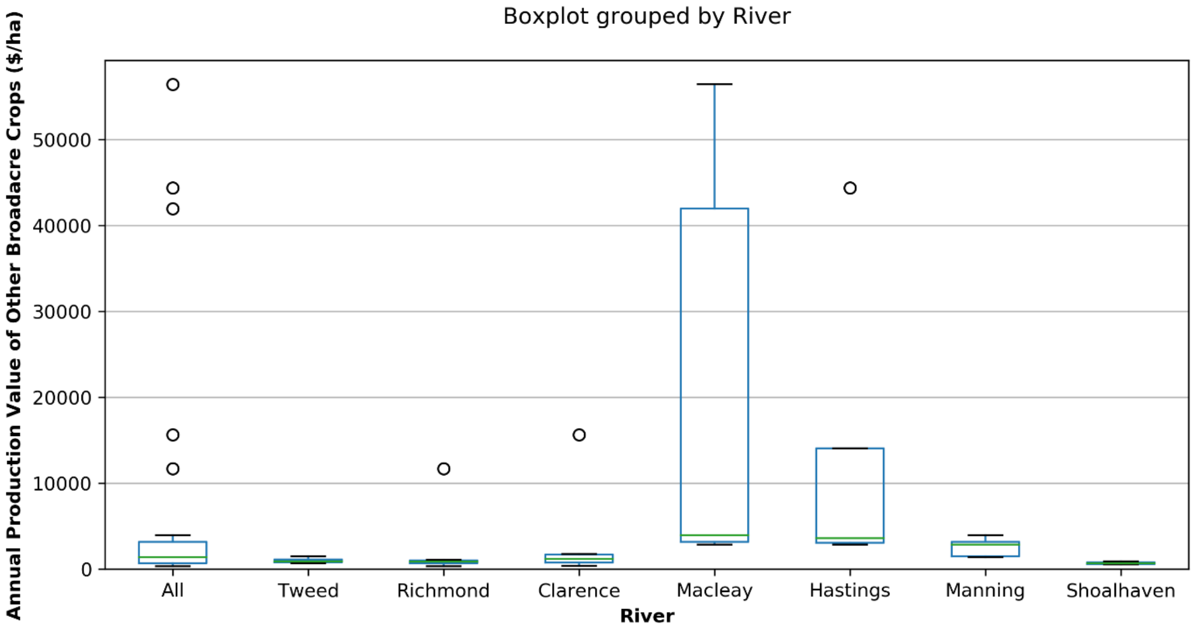


Figure 10-4: Boxplots of annual production value of broadacre crops, excluding sugar cane in each catchment

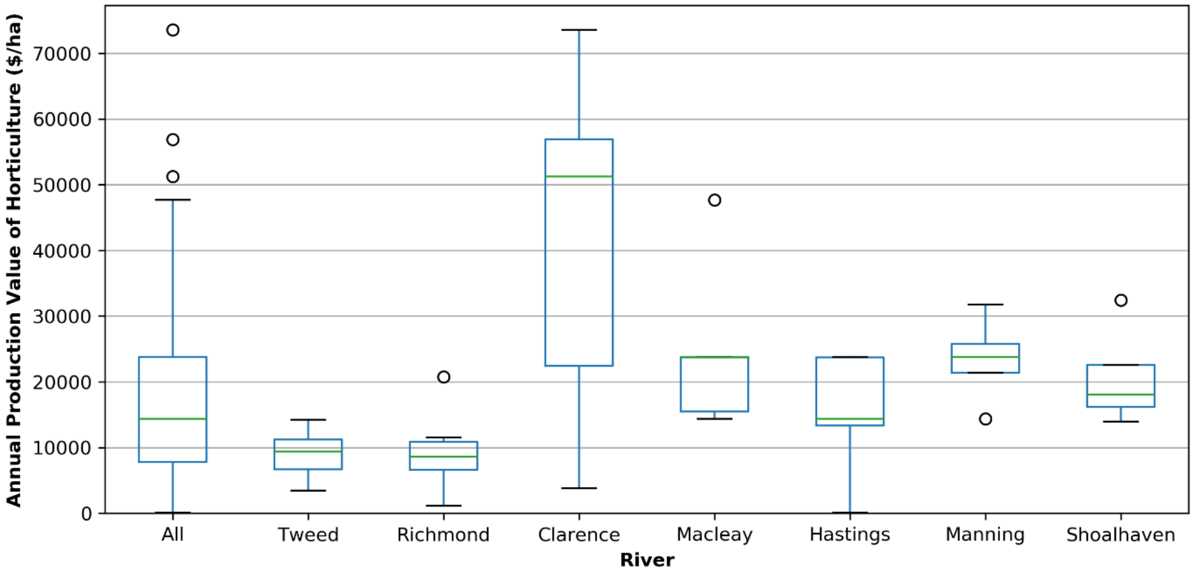


Figure 10-5: Boxplots of annual production value of horticulture in each catchment

10.2.4 Management costs

Where the management strategy requires the acquisition of land into public ownership (either by NPWS, local councils or state government), the long-term management costs should be considered (beyond the engineering maintenance of structures). Management costs include:

- Decommissioning existing onsite infrastructure;
- Developing and maintaining access;
- Monitoring (including water quality and environmental monitoring);
- Land management (including fire and weed management and management of feral animals and pests).

Long-term management costs at Big Swamp on the Manning River have been estimated to be approximately $40,000 p.a. for monitoring and maintenance (Harrison et al., 2019) for an existing restored wetland of approximately 900 ha. Based on this, long-term management costs for restored sites are assumed to be approximately $4,500 p.a./100 ha site.

10.3 Benefits

The benefits of improving land management on coastal floodplains in NSW are typically more difficult to monetise than the costs. Many of the benefits generally relate to improved environmental outcomes such as improved water quality, improved habitat and fish passage but can also include improvements in agricultural productivity. In this project, benefits relating to aquatic habitat, reductions in ASS drainage and reductions in blackwater discharge are only qualitatively scored (e.g. limited, low, medium or high). A brief discussion of the environmental, social, cultural and economic benefits of changes in land management is provided in the sections below.

10.3.1 Ecosystem services

Ecosystem services is the term used to refer to the "benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005), including both the direct and indirect contributions of ecosystems to human welfare (Costanza et al., 1997). These services are typically categorised into one (1) of three (3) types of services, as summarised in Table 10-7.

Table 10-7: Types of ecosystem services
(adapted from Haines-Young and Potschin-Young (2018))

Service Type	Definition	Example of Services
Provisioning	Products derived from ecosystems	Food, freshwater, fuel
Regulation and Maintenance	Benefits derived from the regulating capacity of ecosystem processes	Flood mitigation, climate regulation, disease control, erosion control, carbon sequestration
Cultural	Non-material benefits from ecosystems	Recreational use, spiritual or cultural value

Environmental resources and natural capital have historically not been consistently included in estimates of monetary benefits because they cannot be bought and sold in traditional markets (Costanza et al., 1997). However, there is an increasing awareness that natural capital interacts with human environments and provides a positive contribution to human welfare (Costanza et al., 2017).

In projects where the primary outcome is the remediation of environmental systems, it is important to recognise that there is a real benefit. This can help to justify the costs of environmental projects (De Groot et al., 2012).

Table 10-8: Valuation techniques

Valuation Technique	Description
Market Based	Some environmental goods/services may be sold in a commercial market, and the value can be directly inferred
Avoided Cost/Replacement Cost	Estimates the value by assessing the cost of damages resulting from lost ecosystems (e.g. increase flood damage), or by pricing an alternative replacement to serve the same function (e.g. a waste treatment plant to replace the waste treatment function of a wetland)
Travel Cost	Infers the value of an ecosystem by assessing how much people are willing to pay to travel to visit
Hedonic Pricing	Infers value through changes in prices of market goods due to benefits from an ecosystem (e.g. proximity of a house to the beach)
Contingent Valuation	Estimates value based on surveys of people asking how much they are willing to pay for an ecosystem service
Choice Modelling	Similar to contingent valuation, choice modelling involves stated preferences in regard to ranking a series of pre-defined options
Benefit Transfer	Estimates economic value based on existing valuation studies for other sites or issues which are similar to those in question

De Groot et al. (2012) provided a summary of over 1,350 value estimates from over 320 publications around the world, which they published in a database referred to as the “Ecosystem Service Value Database” (ESVD) (Van der Ploeg and de Groot (2010). The ESVD includes information on 10 different types of ecosystems and values for 22 different types of ecosystem services, which were aggregated, and the mean and median values are provided in Table 10-9.

Table 10-9: Total mean and median values for different types of ecosystems (in 2019 AUD/ha/yr, adapted from De Groot et al. (2012))

Ecosystem	No. of estimates	Total of mean values ($AUD/ha/yr)	Total of median values ($AUD/ha/yr)
Open oceans	14	$903	$248
Coral reefs	94	$649,153	$364,018
Coastal systems	28	$53,190	$49,222
Coastal wetlands	139	$356,559	$22,373
Inland wetlands	168	$47,240	$30,413
Rivers and lakes	15	$7,849	$7,244
Tropical forest	96	$9,683	$4,332
Temperate forest	58	$5,542	$2,073
Woodlands	21	$2,921	$2,800
Grasslands	32	$5,281	$4,963

Of particular importance for this project is the values for coastal wetlands, which include saltmarsh, mangroves and saltwater wetlands and inland wetlands, which can be used as a proxy for freshwater wetlands for the purpose of this study. While ecosystem service values related to remediation are not specifically identified for this project, the values in Table 10-9 show the value of environmental benefits can be significant.

In some cases, site specific investigations of the economic values of remediation may be required to show that the benefits outweigh the cost prior to on-ground works occurring. A number of studies on remediation of ASS affected areas in NSW have shown that that the benefits of remediation outweighed the costs. These include:

- A cost-benefit analysis of a large scale restoration of the Big Swamp floodplain on the Manning River was conservatively estimated to have a benefit to cost ratio of 7 to 1 (Harrison et al., 2019), despite not including the costs of acid discharges in the assessment;
- A cost-benefit analysis of modifications of the Bagotville Barrage to allow tidal flushing and implement works to reduce acid drainage from Tuckean Swamp showed the benefit-cost ratio would be between 1.1 to 1 and 5.7 to 1 (Read Sturgess and Associates, 1996) considering improvements to fishing only. The variations considered a pessimistic scenario of higher than expected costs and lower than expected benefits and an optimistic scenario with lower than expected costs and higher than expected for improved fishing opportunities; and
- A cost-benefit analysis of remediating ASS affected areas on the Maria River floodplain was estimated to have a benefit-cost ratio of 1.1 to 1 to 3 to 1 (Aaso, 2000) (using a pessimistic and optimistic scenario), before considering any non-market ecosystem service benefits from remediation works.

10.3.2 Agricultural benefits

In some instances, changes in floodplain management that reduce the risk of acid and/or blackwater discharges can have tangible benefits for existing agricultural land uses, as well as environmental benefits. Examples of agricultural benefits from a range of management options considered in this study include:

- Introducing saline tidal water upstream of floodgates through controlled tidal flushing is able to reduce maintenance costs associated with managing weeds. Tucker et al. (2020) collated several studies and found that having a salinity level within a drain of 10 parts per thousand would prevent a number of aquatic weeds from growing. Note, this benefit is generally only achievable for locations in estuaries that are closer to the ocean.
- Utilising technology such as laser levelling enables for a reduced drainage density. Instead of having numerous drains, a sloped field facilitates drainage to a singular drain. Having a reduced drainage density has multiple benefits such as having increased area of land available for crop production and reducing costs associated with maintenance (as there are less drains to maintain). Research in Red River Valley, Texas USA, showed that production of some crops (e.g. soybeans, sugarbeets and corn) could be increased by 14 - 19% after the completion of laser levelling (Stone et al., 1998).

- Utilising wet pasture management practices can be a technique employed to improve drought resilience. During drought periods, land utilised as wet pasture will be more resilient as a higher groundwater table means there is generally more water available for pasture.

There are also emerging markets that may allow landholders to pursue environmental remediation on private land in an economically viable way, as the value of biodiversity, conservation and carbon sequestration is realised. Examples of such pathways currently include Biodiversity Stewardship Agreements under the NSW Biodiversity Offset Scheme, or the Australian Government Clean Energy Regulator emissions reduction fund. It is anticipated that such pathways may become increasingly common into the future, which may encourage land use changes on some areas of coastal floodplains.

11 Floodplain vulnerability with sea level rise

11.1 Preamble

Sea level rise is anticipated to impact low-lying coastal areas over the next century. Estuaries are susceptible to future climate change impact and especially to sea level rise, as changes to mean sea level will amplify factors that contribute to flooding and inundation in these coastal regions. Changing inundation patterns may affect present day agricultural land uses, and also influence the type and location of management actions or remediation works.

Glamore et al. (2016b) detail how water levels in estuaries are influenced by oceanic forces and detailed information on how climate change will likely influence estuaries in NSW can be found at: http://estuaries.wrl.unsw.edu.au/index.php/climate-change/ (accessed 23/09/2020). This section summarises the assessment completed in this study to identify floodplain areas and floodplain infrastructure that are vulnerable to sea level rise.

11.2 Estuarine dynamics and sea level rise

NSW coastal catchments can flood as a result of either catchment runoff, coastal inundation or a combination of both factors. Assessment of water levels in estuaries is complex since estuarine water levels can be influenced by a range of factors that are difficult to estimate and forecast. Various factors that can influence local water levels in any particular location include: local bathymetry, catchment rainfall runoff variations (total rainfall intensity and volume) influenced by catchment infiltration and runoff properties, land use distribution, and the conveyance capacity of the catchment drainage systems. Tidal propagations upstream through estuaries can also vary considerably depending on the length, width and depth of the estuary. Estuarine water levels are also particularly sensitive to the state of opening/closure of the estuary entrance, especially where an entrance is prone to closure through sedimentation in the entrance channels closest to the ocean.

Tidal water levels at the entrance of an estuary influence the overall volume of water (tidal prism) moving in and out with each tide. The combination of bed friction, channel geometry and bottom elevation determines whether the tidal range amplifies (increases), remains constant or dampens (decreases) as the tide propagates into the estuary from the entrance (Leuven et al., 2019). Under sea level rise scenarios, tidal elevations at the entrance of an estuary will change but it remains unknown how these changes in mean tide level will affect the tidal flow propagation and equilibrium morphology of different estuaries (Leuven et al., 2019). For example, estuarine sand bars, tidal flats and salt marshes have the potential to grow with sea level rise if there is adequate sediment to adapt to the new boundary conditions (Lentz et al., 2016). Modelling by Khojasteh et al. (2020) has also shown that tidal ranges within estuaries can be amplified by sea level rise depending on entrance restriction conditions. These processes could lead to individual estuaries along the NSW coast (within close proximity to one another) experiencing different impacts from sea level rise. With so many sources of variability it becomes difficult to truly project the future impact of sea level rise. With this in mind, numerical modelling of estuaries has been completed to inform how estuarine dynamics will be influenced by sea level rise.

11.3 Modelling water levels in estuaries

Numerical models of estuaries can be developed to better understand the sensitivity of an individual estuary to sea level rise conditions. However, it is imperative to understand that any numerical representation of a dynamic system, such as an estuary, will come with its own set of limitations.

Different numerical models can be developed to address different climatic problems. For example, a hydrodynamic model of the floodplain which is calibrated to flood events can be used to determine how the wider floodplain inundates during extreme catchment runoff scenarios (i.e. 1 in a 100 year flood event). These types of models might be developed to represent large flow obstructions such as bridges or causeways in greater detail but only run for a short duration of a flood event to assess the impact of floodplain development on peak flood levels. On the other hand, a hydrodynamic tidal model which can adequately represent day-to-day variations to estuarine water levels will likely need more detailed bathymetry in the intertidal range, and will be required to be run over a longer period to capture different tidal conditions. The latter type of model has been developed for each estuary in this study to be used as a tool to guide how these areas might be susceptible to impacts of sea level rise over a longer time period.

The following sections present a brief discussion of the general approach used to model tidal hydrodynamics in this study. Several of the estuaries have been previously investigated using numerical modelling, and where possible these existing models were used with minor modifications (as required). The specific background and model development for each individual estuary can be found in the individual floodplain reports.

11.3.1 Hydrodynamic modelling

A finite element numerical hydrodynamic model (RMA-2) (King, 2015) was used to simulate present day and future sea level rise hydrodynamics in each estuary. The hydrodynamic model solves the shallow water wave equations and is suitable for the simulation of flow in vertically well-mixed water bodies such as estuaries, bays and complex riverine environments. RMA-2 models have been used successfully in applications like this around the world.

The hydrodynamic model for each estuary comprised of three (3) main inputs:

1. Channel bathymetry;
2. Downstream tidal water levels; and
3. Upstream river flow.

The channel bathymetry was defined from existing hydro-survey datasets which had been collected for each estuary. 1-D elements were used to represent well defined channels in which the water levels remain ‘in bank’ and two dimensional 2-D elements were used to represent areas in which flow can occur in both the X and Y planes.

Ocean tidal water levels were based on MHL observations at the entrance of each estuary. Major upstream river flows were applied as inflow boundaries and were based on real-time streamflow observations maintained by WaterNSW. Lower catchment floodplains inflows were not included in the modelling and were likely to have a proportionally minor influence on water level statistics near the areas of interest near the lower parts of the estuary.

11.3.2 Model calibrations and verification

Each of the seven (7) estuary hydrodynamic model developed for this study was calibrated to both water levels and flow (where possible). Water levels were calibrated to match observed water levels recorded by MHL gauging stations within the model domain. Where tidal flow gauging data was available, the model was checked to assess prediction of flood and ebb tidal flow. Tidal flow data was collected at different time periods in each estuary. As such, the hydrodynamic models were set up with corresponding upstream (major river flows) and downstream (tidal water levels) boundary conditions for the period during which the flow data was collected. Calibration and verification periods varied between the seven (7) estuaries based on data availability. Information on the period of calibration and data used for calibration can be found in the appendix of each individual floodplain report.

Once calibrated to historic water levels and flows observations, the hydrodynamic models were used to simulate a representative wet year (i.e. more rain than average across the catchment) and a representative dry year (i.e. less rain than average across the catchment) based on BOM rainfall records for the region. For this project, 2013 and 2019 were selected as the wet and dry years respectively based on analysis of rainfall in coastal NSW. These results were used to verify the water level calibration at the MHL water level gauging stations throughout each estuary. The time series of water levels from these two (2) years were used to summarise the present-day water level statistics in the estuary.

11.3.3 Adopted sea level rise

Understanding the vulnerability of coastal floodplains and infrastructure for a variety of timeframes is important for informing future management. Four (4) time periods have been identified for understanding sea level rise impacts:

1. Historical sea levels when majority of floodplain drainage infrastructure was constructed (circa 1960's);
2. Present day (2020);
3. Near future (2050); and
4. Far future (2100).

Historical sea levels have been included to recognise that sea level rise is, and has been, occurring in NSW since the majority of the floodplain infrastructure was constructed in the 1950's – 1970's. Historical sea level rise in NSW and across Australia is well documented through tidal gauges and data collection programs (Glamore et al., 2016b), including the Australian Baseline Sea Level

Monitoring Program maintained by the Bureau of Meteorology. White et al. (2014) completed an analysis of tidal gauges across Australia and found that the average rate of rise in relative sea levels between 1966 – 2010 in Australia was +1.4 mm/year. However, the study also showed that there was substantial spatial variability in the rate of sea level rise around Australia. The rate of sea level rise observed in Sydney (the most reliable gauge analysed in NSW) over this period was 0.8 mm/year; less than the national average. Therefore, in this study, historical sea levels for NSW have been calculated based on +0.8 mm/year of sea level rise between 1960 and 2020. The adopted change in mean sea level for the historical case is shown in Table 11-1. White et al. (2014) also analysed sea levels across Australia in the period between 1993 – 2010. This analysis showed that the rate of sea level rise is accelerating and had increased to an average of +4.5 mm/year across the country.

Future sea level changes can be predicted through the use of numerical models that simulate changes in the Earth's climate over time due to different scenarios (e.g. the magnitude of greenhouse emissions). The Intergovernmental Panel on Climate Change (IPCC), widely accepted as the peak international scientific body assessing climate change science, has developed a series of four (4) Representative Concentration Pathways (RCPs) which represent different hypothetical scenarios of future human greenhouse gas emissions (note, since this work was completed, the IPCC has released their sixth assessment report (AR6) and replaced RCPs with Shared Socioeconomic Pathways (SSPs)). The RCPs covers a series of scenarios ranging from a scenario in which a substantial reduction in global emissions is urgently and successfully pursued by international governmental bodies, to a scenario in which little action is taken and greenhouse gas emissions continue to climb over time (Glamore et al., 2016b). Sea level rise predicted in NSW (relative to 1996 Mean Sea Level (MSL)) by 2050 ranges between 0.22 – 0.27 m and 0.42 – 0.78 m by 2100 depending on the RCP (including median values only (Glamore et al., 2016b)).

For this project, the median values from the highest emission scenario (referred to as RCP 8.5) have been adopted (note, for purposes considered here RCP-8.5 is equivalent to the new SSP5 – 8.5 in AR6). The values provided by Glamore et al. (2016b), relative to MSL1996, are summarised in Table 11-1. To account for sea level rise that has occurred since 1996, the levels have been adapted by +4.5 mm/year of sea level rise based on the work of White et al. (2014). All levels used in the modelling are relative to present day (2020). The adopted changes in MSL for the near and far future relative to 2020 are presented in Table 11-1.

The variations in sea level rise projections based on different RCPs show there is significant uncertainty in predicting how quickly sea level rise may occur in the future, and therefore the adopted values should be considered one plausible estimate of likely sea levels at 2050 and 2100 in NSW. Although the timing of these changes may still be uncertain, adopting central values from the highest emissions scenario (RCP8.5) provides a useful way to assess and understand how floodplain drainage might be impacted in the future.

Table 11-1: Adopted MSL, relative to present-day (2020)

Time period	Central MSL increase RCP8.5 relative to 1996 (m) Glamore et al. (2016b)	Adopted change in MSL, relative to 2020 (m)
Historical (circa 1960)	NA	-0.05
Present day (circa 2020)	NA	0
Near future (circa 2050)	+0.27	+0.16
Far future (circa 2100)	+0.78	+0.67

11.3.4 Historic and future sea level rise simulations

The changes in tidal levels as a result of sea level rise were modelled by adjusting the present-day entrance tidal level (i.e. downstream tidal boundary condition) to account for historic, near future and far future sea levels. No changes to rainfall and runoff due to climate change or catchment development were considered, and present-day catchment inflows were used for all model scenarios. Day-to-day water levels in the lower parts of the study coastal floodplains were sensitivity tested using the hydrodynamic model and found to be dominated by downstream tidal elevations. As such it is anticipated that this assumption will not significantly impact model predictions of statistical tidal elevations throughout the study estuaries.

It is important to note that the hydrodynamic models are limited in their ability to adequately represent the changes to sediment dynamics/entrance conditions which are also likely to change in the future and may have a considerable impact on water levels of the lower estuary. Accurate representation of the changes to sediment dynamics and entrance conditions are important in predicting future estuarine tidal levels, however the future dynamics of estuarine ocean entrances in NSW is highly uncertain. The model results from this study should be seen as a ‘first-pass’ assessment of sea level rise impacts. Climate change impacts on sediment dynamics at ocean entrances for the considered estuaries should be investigated in detail in future studies.

11.4 Floodplain vulnerability assessment

The primary aim of the numerical modelling analysis was to establish water level statistics for past, present-day, near-future, and far-future planning horizons throughout the study estuaries, considering hydrodynamic processes such as tidal attenuation and amplification. The modelling of the study estuaries also enabled water levels during both wet and dry periods to be considered. Note that tidal plane analysis of estuarine water levels completed by Couriel et al. (2012) removes the influence of catchment runoff from measured water level datasets to establish the tidal components of the water level fluctuations only.

Comparison of floodplain topography and end-of-system infrastructure to past, present-day, near-future, and far-future water levels in the study estuaries was completed to provide a first pass assessment of floodplain and floodgate vulnerability to sea level rise. Rather than assessing which areas may be directly inundated (as per a tidal inundation assessment), this assessment identifies areas which may be subject to reduced drainage due to low gradients between the floodplain and estuary water levels.

11.4.1 Floodgate assessment methodology

The vulnerability of floodgate operations to sea level rise increased estuarine water levels was assessed by determining the reduced drainage potential of the floodgates based on the downstream water levels in relation to floodgate geometry. The assessment was completed by comparing the floodgate invert and obvert elevations to the downstream tidal hydroperiod (level x duration) adjacent to the floodgate. For the floodgate to drain freely and efficiently, the water level upstream needs to be elevated above the downstream water level (i.e. positive hydrostatic head). As such, the floodgate geometry and the tidal level downstream largely control drainage during periods of elevated floodplain water levels. The elevations at which a floodgate is connected to the downstream waterway can influence how efficiently the water can discharge. For example, if the obvert of a structure is positioned higher than all water levels in the downstream waterway, it is reasonable to assume that the water can drain away from the floodplain unimpeded. However, if the obvert of the structure is below the water levels in the downstream waterway most of the time (e.g. more than 50% of the time), there will be periods in which drainage is highly restricted. The future 'drowning out' of drainage infrastructure will also impact how, when and what maintenance is required.

To assess the vulnerability of the floodgates to estuarine water levels, timeseries with a two (2) year duration of modelled water levels were extracted from the historic, present day, near-future and far-future scenarios adjacent to each individual floodgate structure. Next, these time series results were summarised using statistical methods to ascertain the 5th, 50th and 95th percentile exceedance water levels which were then compared to the surveyed floodgate elevation. Table 11-2 summarises the classifications applied to each floodgate. This assessment is also presented graphically in Figure 11-1.

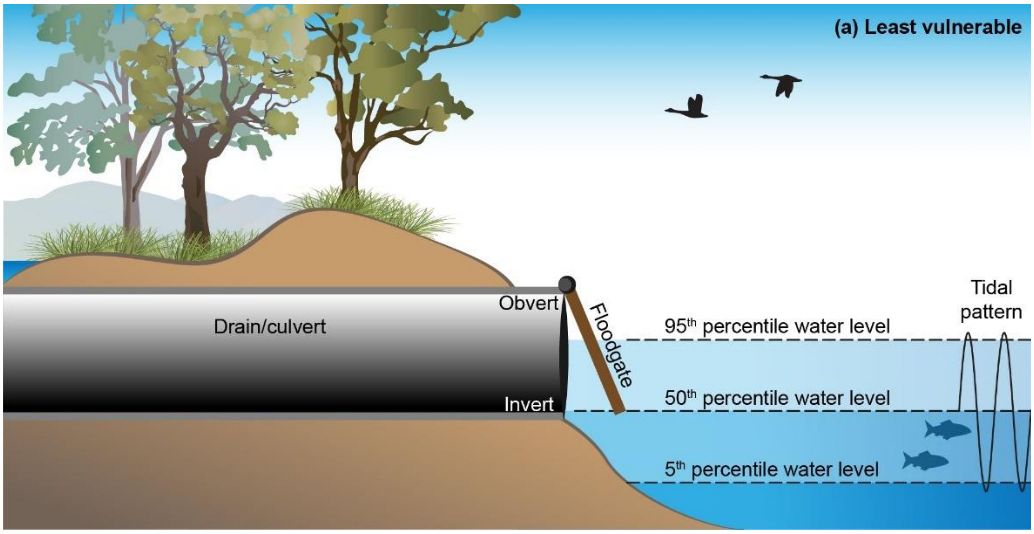
Table 11-2: Rules for floodgate vulnerability classification

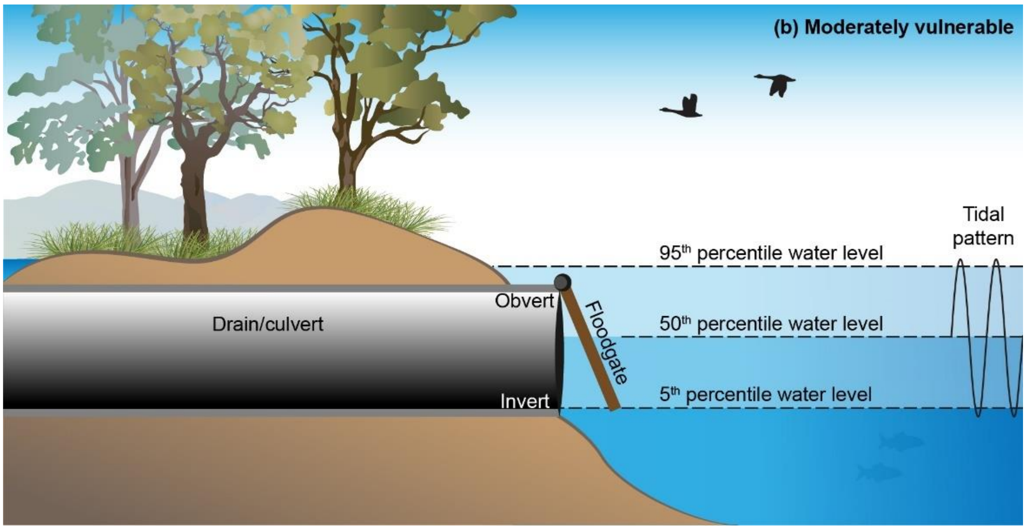
Colour	Classification	Criteria
Green	Least Vulnerable	Obvert > 95th percentile water level
Orange	Moderately Vulnerable	95th percentile WL > Obvert > 50th percentile water level
Red	Most Vulnerable	Obvert < 50th percentile water level

Note: Obvert is the inside top of the floodgate structure

The classification developed identifies floodgates that will not allow efficient drainage of surface water (either now or into the future). Based on this classification, a floodgate is classified as:

- ‘Least Vulnerable’ if the structure can drain effectively for at least 95% of the time (approx. 23 hrs in a day) (Figure 11-1a).
- ‘Moderately Vulnerable’ if the structure can drain effectively between 50% – 95% of the time (i.e. between 12 – 23 hours of the day) (Figure 11-1b).
- ‘Most Vulnerable’ if the structure can drain effectively for less than 50% of the time (i.e. for less than 12 hours of the day) (Figure 11-1c).





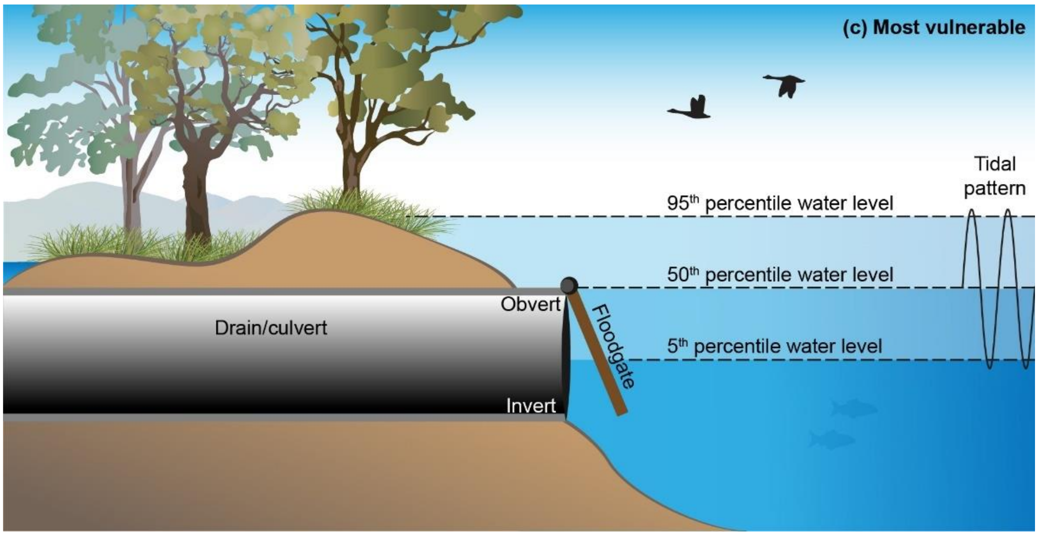


Figure 11-1: Floodgate vulnerability assessment

11.4.2 Floodplain vulnerability assessment methodology

Future sea level rise in estuaries is likely to result in reduced floodplain drainage and prolonged inundation of connected floodplain areas, with potential impacts on land use and productivity. The severity of the impact is dependent on a range of factors, including but not limited to:

- Drainage connectivity;
- Drainage conveyance;
- End-of-system floodgate vulnerability; and
- Existing and future potential land use and floodplain topography.

The results from the hydrodynamic models of each estuary were used for a first pass assessment of the risk sea level rise poses to floodplain drainage based on the floodplain topography. The model results for the present day, near future and far future scenarios for each estuary were used to summarise the 5th, 50th and 95th percentile water levels at the major discharge points of each subcatchment. The modelled water level statistics were transposed to the floodplain using a GIS 'bathtub' approach. This is a simplified approach which does not account for hydraulic and hydrodynamic processes such as floodgate dynamics, hydraulic head losses, or dampening/amplification through floodplain drainage channels. The purpose of this assessment is to show areas likely to be directly impacted by higher estuarine water levels and reduced drainage, rather than areas that may be actively inundated due to sea level rise. Table 11-3 and Figure 11-2 shows the risk classification for different floodplain levels with respect to water level statistics and an example of an increase in risk due to sea level rise is shown in Figure 11-3.

Table 11-3: Rules for floodplain drainage vulnerability

Classification	Criteria	Description
High risk	Land with an elevation below the 5th percentile water level (approximate low tide level)	Water can only drain from this land effectively 5% of the time, or for around 1 hour in a day. These areas are typically permanently inundated and difficult to drain without additional mechanical assistance (i.e. pumping).
Medium risk	Land with an elevation below the 50th percentile water level (median water level)	Water can drain from this land effectively 50% of the time, or for around 12 hours in a day. These areas are generally difficult to drain efficiently.
Low risk	Land with an elevation below the 95th percentile water level (approximate high tide level)	Water can drain from this land effectively 95% of the time, or for around 23 hours in a day. These areas can be impacted by inefficient drainage, particularly after flood events.
Not vulnerable	Land with an elevation above the 95th percentile water level (approximate high tide level)	Water can drain from this land effectively more than 95% of the time, or for more than 23 hours in a day. These areas are generally not impacted by reduced drainage.

Results from this analysis are presented in the individual floodplain reports.

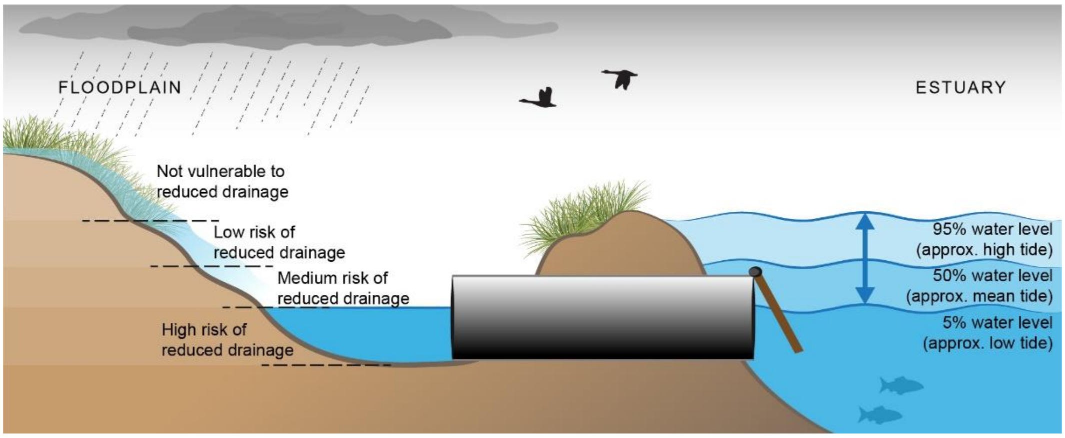
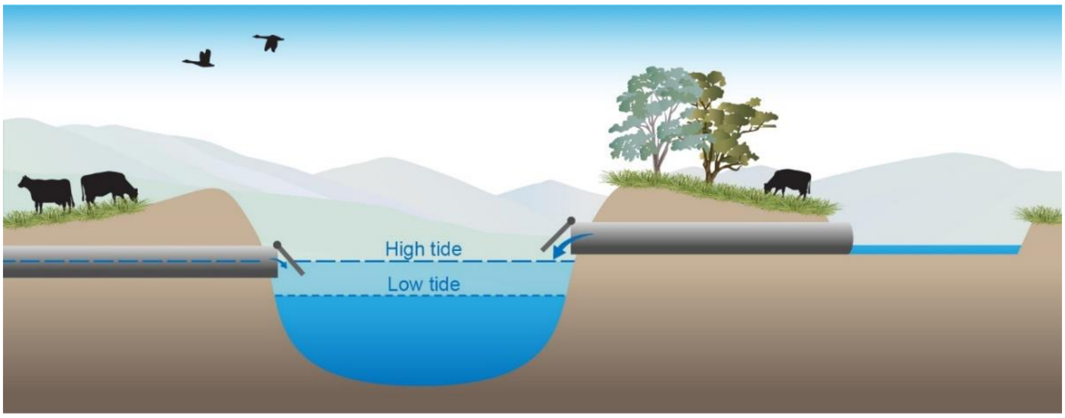
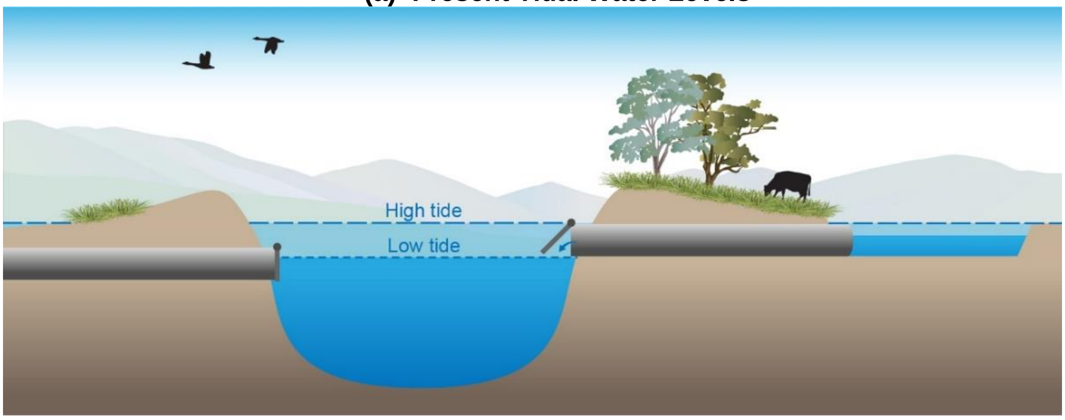


Figure 11-2: Floodplain vulnerability assessment



(a) Present Tidal Water Levels



(b) Future Tidal Water Levels due to sea level rise

Figure 11-3: Floodplain vulnerability due to sea level rise

12 Floodplain waterway classification

12.1 Preamble

This report section outlines the approach taken to develop an updated GIS layer for floodplain waterways and create a multi-criteria assessment for categorising waterways as natural or artificial (i.e. constructed). The resulting detailed waterway GIS layer provides a consistent dataset across each catchment for use in the subcatchment prioritisation. The multi-criteria assessment used a data focused approach utilising quaternary geology, Crown land, waterway name, waterway sinuosity and stream order information to categorise waterways. This categorisation provides information for land managers and government for consideration when implementing recommendations from the subcatchment management options.

Further to its usage as part of the floodplain prioritisation methodology, the multi-criteria assessment of waterways has broader management implications. This particularly focuses on the definition of Key Fish Habitat pertaining to the Fisheries Management Act 1994 and more broadly the management of the marine estate. On developed floodplains, there is a disconnect between the estuary and the upper catchment as drainage and the installation of floodgates have disrupted natural flow paths. The multi-criteria assessment of waterways aims to provide classifications of waterways which enables an evidenced based approach for the reconnection of aquatic habitat within the estuary to the upper catchment and identification of important habitat.

The methodology includes existing terminology outlined by Standard Instrument for preparing Local Environment Plans (LEPs), GIS layers utilised in the Water Management General (2018) Regulation, and definitions of coastal wetlands determined in the State Environment Planning Policy (Coastal Management) 2018 to provide a holistic and concise framework for identification of natural or artificial waterways. This, in turn, can be utilised as a tool to guide determinations of important conservation areas within floodplains, including Key Fish Habitat.

12.2 Waterway delineation

Coastal floodplains often have an intricate network of waterways which transport water from upstream catchments and low-lying floodplain areas to the ocean. These networks consist of both natural and artificial waterways, the latter having been constructed for various reasons such as flood mitigation, agricultural drainage, and swamp drainage (Tulau, 2011). Management of waterways is often complex with ownership divided between Crown land, local councils, drainage unions, private landholders or other stakeholders.

Subsequently, drain alignments can often change to meet the varying requirements of floodplain drainage. For the outcomes of this study, an accurate dataset of waterway classification was required for areas below the 5 m Australian Height Datum (AHD) elevation contour with the following key details being identified as important:

- Accurate and up-to-date waterway alignments;
- Accurate and up-to-date waterway length information;
- Distinction between natural and artificial waterways; and
- A consistent level of detail for drainage density based upon drain sizes across the entire catchment.

Artificial waterways have various shapes and sizes depending upon the reason they were constructed. It is important for this study that within each subcatchment the same level of detail for the drainage network is achieved. Subsequently, the following definitions have been created to describe the different sizes of constructed waterways:

- **Paddock scale**: small drains generally less than 0.5 m deep responsible for draining individual paddocks. They generally transport water to a larger farm scale drain and are managed by individual landholders. Smaller drains that run along the side of roads are also classified in this category.
- **Farm scale**: medium to large drains that remove water from individual farms. They generally transport water to a flood mitigation trunk drain or larger water bodies (e.g. a river) and are managed by either individual landholders or drainage unions.
- **Flood mitigation**: large drains or canals that are important in draining the majority of water from a subcatchment. They are generally managed by a drainage union or local council.

It has been determined that farm sized drains (and larger) are important when considering acid drainage and blackwater runoff. Drains smaller than this (i.e. paddock size) are unlikely to significantly influence overland drainage of a subcatchment and, because of their shallow geometry, are also unlikely to facilitate or control transport of acidic groundwater (i.e. through groundwater drainage).

A detailed waterways layer was created using GIS techniques for floodplain waterways located below the 5 m AHD elevation contour, ensuring the desired level of detail and consistency of waterway density was achieved across the floodplain. This process included a detailed waterway-by-waterway approach and utilised advanced GIS skills consulting the following datasets for each study floodplain to develop the final waterways layer:

- Existing waterway GIS layers (e.g. the NSW Spatial Data hydro lines shapefile);
- One metre digital elevation models (DEMs);
- High resolution aerial imagery; and
- Inspections completed during field investigations.

The updated waterways GIS layer has been used to determine the drainage density factor (see Section 4.3.1) for subcatchment prioritisation. Additionally, the waterways delineated within the GIS layer have been categorised as natural or artificial using the multi-criteria analysis outlined in Section 12.3.

12.3 Multi-criteria assessment

A multi-criteria assessment has been developed to distinguish between natural and artificial waterways on coastal floodplains. Categorisation of natural and artificial waterways has incorporated terminology defined in the Standard Instrument for preparing Local Environment Plans (LEPs) which is outlined further in Section 12.3.3. This categorisation approach was applied to waterways below the 5 m AHD elevation contour. Key criteria used during the assessment include:

- Quaternary geology;
- Crown land status;
- Named status of waterways;
- Waterway sinuosity; and
- Strahler stream order.

Each of these criteria was analysed to determine how they would be used within the assessment, as summarised in the following sections. A description of the multi-criteria assessment method is provided in Section 12.3.7.

12.3.1 Waterway categorisation definitions

The Standard Instrument for preparing LEPs provides a number of definitions for different types of waterways which have been adopted for the multi-criteria assessment. These definitions include artificial waterbodies, natural waterbodies, and watercourses. Additionally, these descriptions prescribe how to define a natural waterway which has been modified. The descriptions for each different type of waterways are outlined in Table 12-1.

Table 12-1: Definitions for types of waterways as per the Standard instrument for preparing LEPs

Name	Definition
Artificial waterbody	An artificial body of water, including any constructed waterway, canal, inlet, bay, channel, dam, pond, lake, or artificial wetland, but does not include a dry detention basin or other stormwater management construction that is only intended to hold water intermittently.
Natural waterbody	A natural body of water, whether perennial or intermittent, fresh, brackish, or saline, the course of which may have been artificially modified or diverted onto a new course, and includes a river, creek, stream, lake, lagoon, natural wetland, estuary, bay, inlet or tidal waters (including the sea).
Watercourse	Any river, creek, stream, or chain of ponds, whether artificially modified or not, in which water usually flows, either continuously or intermittently, in a defined bed or channel, but does not include a waterbody (artificial).

Using these definitions, four categories have been developed for categorising floodplain waterways:

1. Natural waterbody watercourse;
2. Artificial waterbody;
3. Watercourse; and
4. Connector watercourse.

These four categories can be used to describe the complex nature of floodplain waterways. The natural waterbody watercourse and the watercourse categories describe natural waterways. The artificial waterbodies category describes artificial waterways. The connector watercourse category has been added to the list of definitions and describes waterways with either natural or artificial sections that provide a connection between two natural waterbody watercourses (this is particularly important where historic natural waterways have been modified through artificial methods – see below). The relationship of these categories is shown in Figure 12-1. Note, within this study the LEP definitions for a natural waterbody and a natural waterbody watercourse have been considered the same and their depiction in Figure 12-1 highlights how natural waterbodies can also be watercourses in contrast to artificial waterbodies which cannot be watercourses within the LEP definitions.

A connector watercourse category was required to identify natural waterways in the upstream catchment which have, in some instances, become disconnected from the floodplain. An example of this is where historically a stream would have flowed into a backswamp and then to the estuary. On a developed floodplain, the same backswamp would have been drained via an artificial drainage network, however, there is still a natural flow path connection from the upper catchment to the estuary. The connector watercourse category captures how these historic flow paths would have connected the upper catchment to the estuary within the context of a developed floodplain.

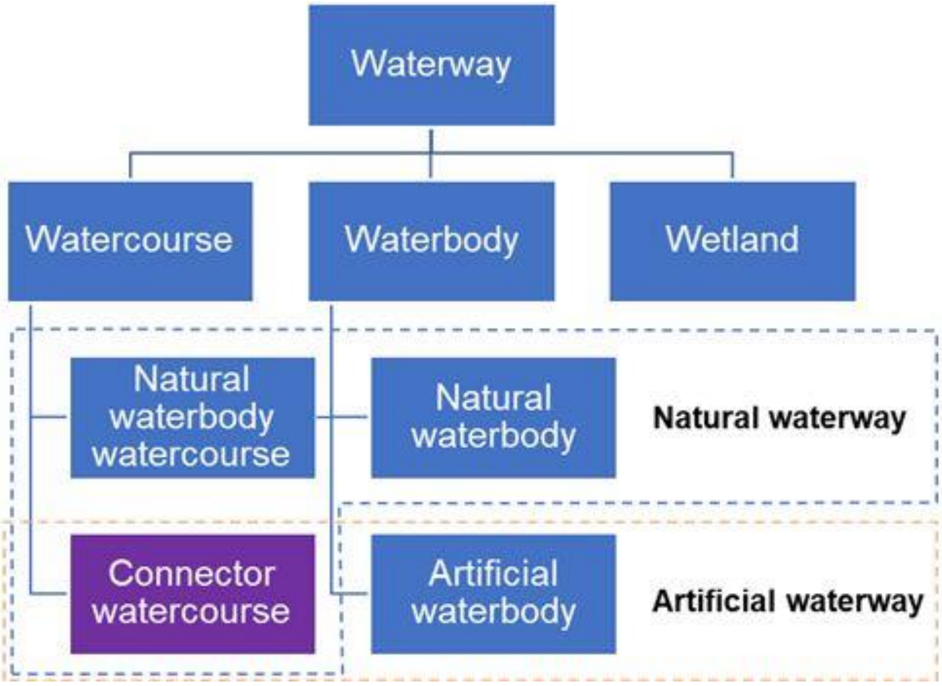


Figure 12-1: Relationship between natural and artificial waterways based upon standard LEP definitions

12.3.2 Crown land status

In NSW, the State Government owns parcels of land known as 'Crown land'. This land includes various natural waterways such as tidal waterways (to the mean high-water mark) and non-tidal rivers/streams. GIS information for the location of Crown land in NSW has been provided by the NSW Department of Primary Industries included the following classifications:

- Crown parcel;
- Crown road; and
- Crown waterway.

During the multi-criteria assessment where a waterway was identified as being a Crown land waterway it was used as an indicator for a natural waterway.

12.3.3 Quaternary geology

Quaternary geology is the term used to describe the formation of geological deposits in the last 1.8 million years of earth's history. It can be divided into Holocene, typically deposits formed in the last 0.01 million years, and Pleistocene, such as quaternary geology deposited prior to the Holocene period (Troedson and Hashimoto, 2008). Geological maps for the quaternary deposits on the NSW coastline were developed as part of the Comprehensive Coastal Assessment (CCA), a program designed to build a robust scientific dataset for coastal regions of NSW (Troedson and Hashimoto, 2008). These maps were developed using detailed datasets including aerial photography, soil profiles and geophysical survey. Three layers were mapped which represent the stratigraphical complexity of the quaternary deposits (Figure 12-2):

- Veneer: shallow modern deposits;
- Unit 1: surface and near surface level deposits; and
- Unit 2: extensive subsurface deposits (greater than 5 m depth).

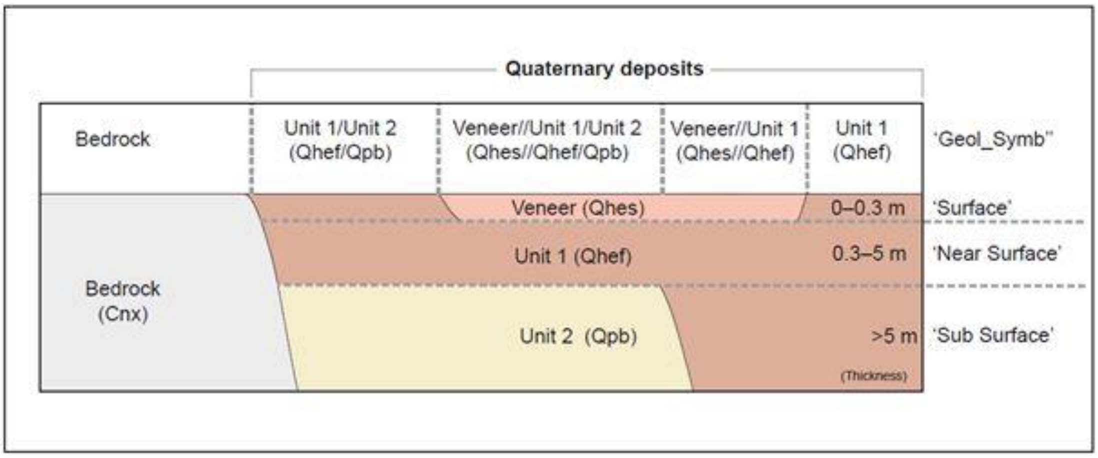


Figure 12-2: Diagram of the different layers of Quaternary deposits (from Troedson and Hashimoto, 2008)

The Unit 1 layer of the quaternary geology was used for the purpose of determining the location of natural waterways which existed prior to European modification of the floodplains. This is consistent with other similar studies (Rogers et al., 2015) and excludes recent modifications to the geology identified in the Veneer layer.

As part of the development of the quaternary geology mapping, a classification scheme was developed for different deposit types (Troedson and Hashimoto, 2008). Table 12-2 summarises this four letter classification scheme. For the multi-criteria analysis it was determined that areas corresponding to classifications of Qhec, Qhea, Qhac, Qhaa, Qhes and Qhab (underlined in Table 12-2) within this scheme would be used to determine if waterways are natural as this would indicate the waterway existed prior to European settlement.

Table 12-2: Summary of classification scheme adopted for Quaternary deposits (from Troedson and Hashimoto, 2008)

Age	Age division	Depositional systems	Subdivisions
Quaternary (Q)	Holocene (h)	Barrier (b)	Beach (b)
			Gravel beach (bg)
		Estuarine (e)	Dune (d)
	Pleistocene (p)		Channel (c)

<table>
<tr><td rowspan="6"></td><td rowspan="2"></td><td rowspan="2"><u>Alluvial (a)</u></td><td>Floodplain (p)</td></tr>
<tr><td>Swamp (s)</td></tr>
<tr><td rowspan="4">Undifferentiated (-)</td><td rowspan="2">Undifferentiated (u)</td><td><u>Abandoned channel (a)</u></td></tr>
<tr><td>Sand flat (f)</td></tr>
<tr><td rowspan="2">Anthropogenic (m)</td><td>Subaqueous (w)</td></tr>
<tr><td>Levee (l)</td></tr>
</table>

A number of additional classifications for quaternary geology were used to supplement the analysis:

- Where waterways passed through large open waterbodies the section within these large open waterbodies was determined to be natural if it had the subaqueous (w) subdivision in the quaternary geology; and
- Classifications of Qhap, Qhal and Qhas were used to help determine flow paths where 3rd order waterways from the upper catchment flowed onto the floodplain (when categorising connector watercourses).

12.3.4 Waterway name

Waterway names can be an indicator of whether a waterway is natural or artificial. To determine if a particular name described a natural or artificial waterway, the definitions for natural and artificial waterbodies as outlined in the Standard Instrument for preparing LEPs were used. To further supplement these definitions the Geographical Names Board of NSW Policy for Place Naming was used (Geographical Names Board, 2019). Note in some instances particular names were not included in either documentation or were described as names for both artificial and natural waterways. Names were only used as a tool to categorise waterways when the name was clearly defined in the literature. Table 12-3 summarises the waterway names used to distinguish between natural and artificial waterways.

Table 12-3: Summary of waterway name categorisations

Natural names	Artificial names	Other names*
Arm	Canal	Anabranch
Brook		Broadwater
Creek		Channel
Gully		Drain
River		Inlet
Rivulet		Passage
Stream		Reach

*Waterway names that were categorised as both natural and artificial or were not defined in the literature.

12.3.5 Waterway sinuosity

Sinuosity is a measure of the degree of meandering of a waterway and can also be an indicator of a waterway's origins. Sinuosity can be expressed mathematically as in Equation 12-1.

$$\textbf{Sinuosity} = \frac{\textbf{Waterway length}}{\textbf{Valley length}} \qquad \textbf{Equation 12-1}$$

As per Equation 12-1, a sinuosity value equal to 1 indicates a straight channel with no meanders. Generally, natural waterways tend to have a larger sinuosity in comparison to straighter artificial channels. Various literature defines the limits for defining a straight channel, with Charlton (2008) describing a sinuosity less than 1.1 as straight and Melbourne Water (2019) suggesting a sinuosity of less than 1.05 as straight.

Distinguishing between natural and artificial waterways by using calculated sinuosity can be misleading. For example, constructed agricultural waterways can have an 'L' shape with two straight sections. The sinuosity of such a drain will be greater than 1.1 suggesting that the waterway is natural when it clearly is not. On the other hand, the two straight sections could be analysed separately, however, determining the sub-sections of a waterway to calculate sinuosity is somewhat arbitrary and ambiguous in many cases. Often, over short sections, natural waterways can be straight, and it is only when the whole waterway is considered that the sinuosity value increases. For the multicriteria assessment, expert engineering judgment was used to assess waterway sinuosity using three categories (sinuous, straight, unclear) to describe a waterway's overall shape, and assist in determining whether it is natural or artificial. Where waterways comprise straight line sections they were categorised as straight and where waterways have a natural meander they were categorised as sinuous. Where this distinction was unclear sinuosity was not used as a means to determine if waterways were natural or artificial.

12.3.6 Strahler stream order

Stream order is a method used to describe the number of upstream contributing streams for any given section of a stream network. Determining stream order can have significant legal and environmental implications. For example, in certain circumstances, streams that are 3rd order or higher are used to define key fish habitat.

The method for determining stream order adopted by the NSW Government is the Strahler system (NSW Department of Industry, 2018). Using this method, the most upstream waterways are 1st order. Where a waterway meets another waterway of the same order, the order is increased by a magnitude of one. An example of the Strahler system being implemented is shown in Figure 12-3.

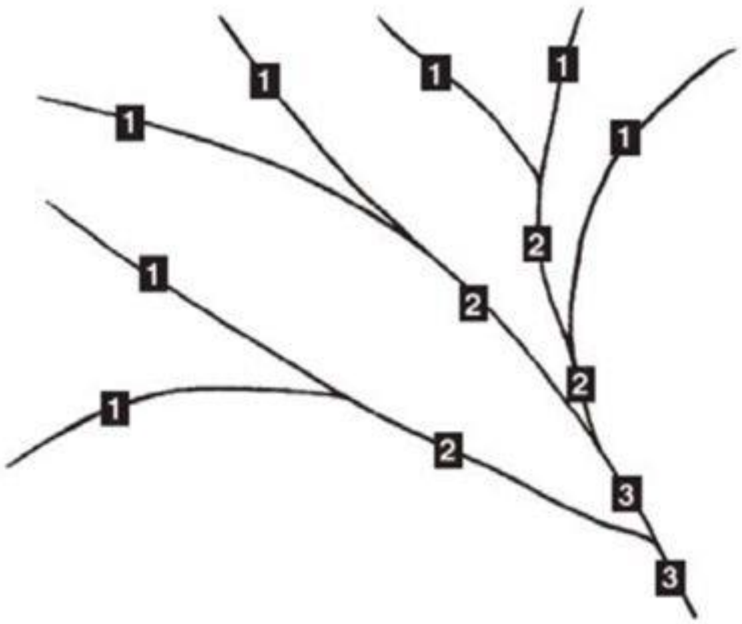


Figure 12-3: Example of Strahler stream order implementation (from NSW Department of Industry, 2018)

Stream order has been used in the multi-criteria assessment to determine input points for natural waterways, specifically for determining the upstream inputs for the connector watercourse category. Stream order was determined for the Spatial Services (Department of Finance, Services & Innovation) NSW Hydro Line dataset using the Strahler system. Note, this dataset was also the basis of the Water Management (General) Regulation 2018 Hydro Lines spatial data. An alternate method for determining stream order is to identify streams using the largest scale topographic map available for a specific area, and is used to perform additional stream order analysis when assessing Key Fish Habitat.

12.3.7 Multi-criteria assessment description

As previously discussed (Section 12.3), a staged approach has been taken to implement the multi-criteria assessment for the categorisation of waterways. This approach has given greater weight to data such as quaternary geology and Crown land for categorising waterways. Other criteria such as waterway names, sinuosity and stream order have been used to supplement the primary datasets. This stepped approach is outlined in Figure 12-4 with three categorisation levels. A flow chart describing this method is also provided in Figure 12-5.

Note that this categorisation process identifies natural waterways where data provides a strong indication that this is appropriate. This method is designed as a high-level categorisation process and is only able to provide a categorisation where data is available on a catchment scale using GIS techniques. For categorisation on a smaller scale, additional investigations may be necessary to validate the high-level approach.

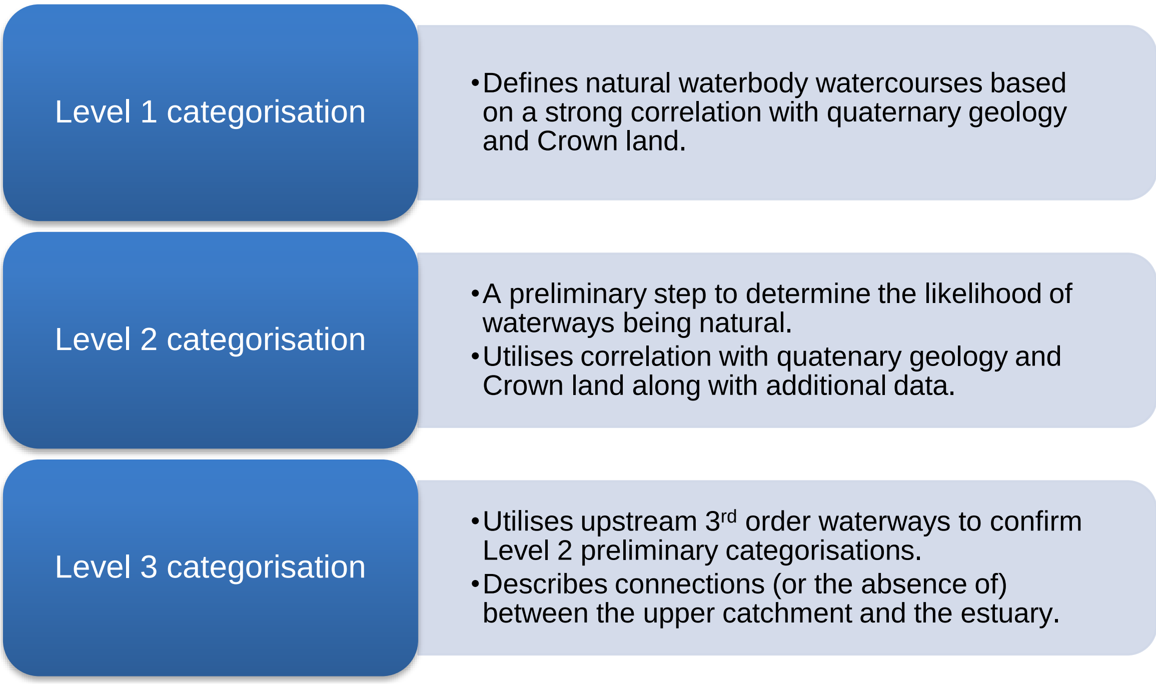


Figure 12-4: Description of the categorisation levels for the multi-criteria assessment

Level 1 categorisation

This initial classification step utilises quaternary geology and Crown land information to determine if a waterway is a natural waterbody watercourse. Waterways that are not categorised in this level require additional information and undergo categorisation in Level 2 and Level 3.

During the Level 1 categorisation GIS techniques have been used to determine the percentage of waterways that overlap with quaternary geology and Crown land data. Waterways are categorised as natural waterbody watercourses if they:

1. Have a 100% overlap with both the quaternary geology and Crown lands data; or
2. Have a 75% overlap with both the quaternary geology and Crown lands data and have either a natural sinuosity or a natural name.

Major natural tributaries are categorised during the Level 1 step. Waterways which are not categorised proceed to the Level 2 step.

Level 2 categorisation

Waterways underwent Level 2 categorisation only once the Level 1 step had been completed. If a waterway underwent Level 2 categorisation, this indicated that the evidence for its categorisation as a natural waterway was not as strong as a waterway categorised in Level 1. Subsequently, during Level 2 categorisation data is collated to determine the likelihood that a waterway is either natural or artificial. Two preliminary categorisations are given to each waterway describing the likelihood that they are a natural waterway:

1. Potential natural connector watercourse; or

2. Unlikely connector watercourse.

There are two consequences of the Level 2 categorisation. Firstly, categorisation of waterways as a potential natural connector watercourse is dependent on their correlation with the quaternary geology and Crown land data, meaning that within the floodplain context there is good evidence to suggest they are a natural waterway. Secondly, potential natural connector watercourses are identified as likely receiving waters for natural upstream catchment inflows. Level 2 categorisation can be considered a prerequisite of Level 3 categorisation.

Waterways are categorised during Level 2 as follows:

- **Potential natural connector watercourse**: Waterways that have a 50% overlap with both the quaternary geology and Crown lands data, waterways that have a 75% overlap with the quaternary geology data and have a natural name, or waterways that have a 75% overlap with either the quaternary geology and Crown lands data and have a natural sinuosity.
- **Unlikely connector watercourse**: Any remaining waterways that do not have a strong correlation with quaternary geology or Crown lands data.

Level 3 categorisation

Waterways underwent Level 3 categorisation only once the Level 1 and Level 2 classification steps had been completed. Where the Level 1 and 2 categorisation focuses on the floodplain characteristics of waterways, the Level 3 categorisation considers the interaction of floodplain waterways with the upper catchment. To this end, Level 3 categorisation determines the flow paths that upper catchment streams of 3rd order or greater take to reach the natural waterbody watercourses categorised during the Level 1 step. Waterways are categorised as follows:

- **Natural waterbody watercourse**: Potential natural connector watercourses which flow into a natural waterbody watercourse (defined in Level 1) and are a 3rd order stream (or greater).
- **Connector watercourse**: Waterways that connect between a 3rd order stream in the upper catchment (above the 5 m AHD contour) and a potential natural connector watercourse (defined in Level 2) or natural waterbody watercourse (defined in Level 1).
- **Watercourse**: Potential natural connector watercourses (defined in Level 2) which do not have a 3rd order waterway upstream, or any waterway that is located within a Coastal Management SEPP coastal wetland (Costal Management Act 2016).
- **Artificial waterbody:** Remaining waterways which do not have a strong correlation with quaternary geology or Crown lands.

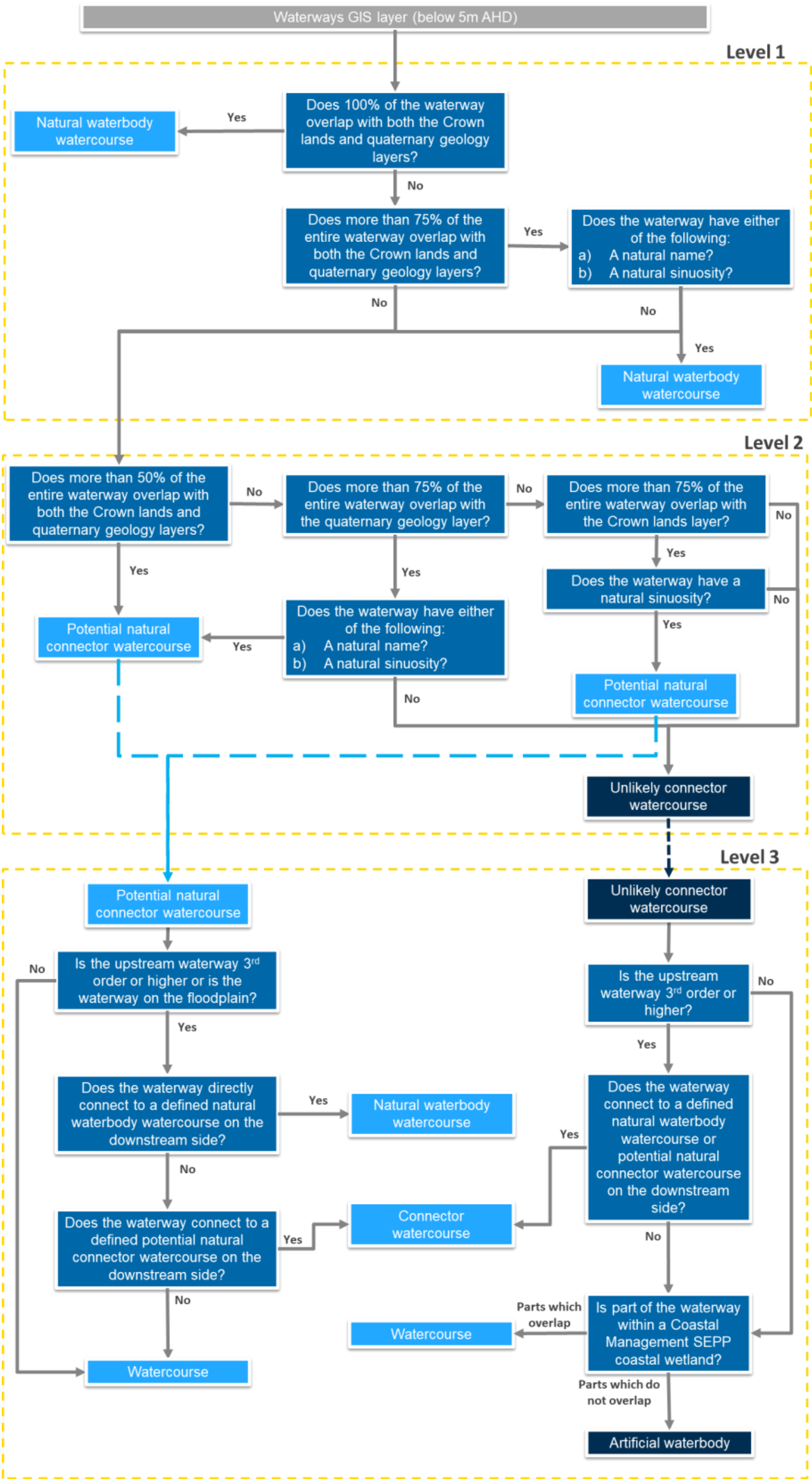


Figure 12-5: Three level multi-criteria assessment flow chart

13 Conclusion

Over the past 25+ years, significant efforts have been made by local councils and landholders to remediate ASS and blackwater drainage, despite practical limitations due to insufficient funding, resources, and social and economic barriers. To overcome this limitation and better target remediation efforts, the Coastal Floodplain Prioritisation Study was initiated by the Marine Estate Management Strategy (MEMS) (Marine Estate Management Authority, 2018). The study utilises the methodology detailed in Glamore and Rayner (2014), to prioritise floodplain subcatchments in seven (7) coastal floodplains in NSW. This approach enables the identification of high priority floodplain subcatchments and provides the basis for a strategic approach to floodplain management, ensuring clearer justification for investment, or non-investment, in changes in land management or remediation.

Two (2) objective methods have been developed to prioritise floodplain subcatchments in relation to (1) acid discharge associated with ASS as well as for (2) blackwater generation associated with floodplain inundation. These methods separately utilise multi-criteria analysis to assess the risk of poor water quality from floodplain subcatchments and rank them relative to their contribution to these key water quality issues. The purpose of this prioritisation is to establish an evidence-based list of high priority subcatchments to be targeted for on-ground remediation.

The study floodplains were delineated into subcatchments based on topography and drainage infrastructure. Key datasets relevant to implementation of the prioritisation methods were collated and, where data gaps were identified, additional data collection was undertaken.

There are a number of potential management strategies that can be employed to address acid and blackwater discharges from coastal floodplains. Some of these strategies can be implemented immediately without significant impacts to existing land uses, while others require substantial changes to land management to create effective improvement in water quality outcomes. A range of site-specific and administrative constraints were identified that do not influence the physical generation of acid and blackwater, but influence implementation of potential management strategies. All physical and administrative factors relating to each floodplain subcatchment were summarised in individual subcatchment management options. To develop on ground management options for each subcatchment, the following factors were considered:

- Priority ranking for acid and blackwater;
- Condition of existing floodplain infrastructure;
- Current and future land uses and land values;
- The relative costs and benefits of remediating the floodplain;
- Predicted vulnerability to sea levels; and
- Types of waterways.

A range of additional analysis and assessments were undertaken to complete the study, including:

- Development and calibration of hydrodynamic numerical models of each study estuary to facilitate detailed assessment of floodplain vulnerability to sea level rise;
- Collection and collation of data relating to constraints that will be applicable to implementation of management options such as proximity to sensitive receivers, heritage items, cross-section data and water quality data.
- Collation of data relating to existing floodplain land use, productivity, and land value; and
- Multi-criteria assessment to determine waterway classification.

This report outlines the methods, data and analyses used to prioritise and create management options for seven (7) coastal catchments in NSW. These methods were implemented on the seven (7) study floodplains, with the results and outcomes for each study floodplain summaries in a separate report. Floodplain and estuary specific datasets are also provided in the individual floodplain reports and represent the first collation of such datasets.

The outcomes from this study aim to provide a prioritised list of floodplain subcatchments that pose the greatest risk of poor water quality within each estuary. Therefore, the greatest potential benefit can be gained by addressing the sources of poor water quality in these subcatchments. The individual floodplain assessments and prioritisations provide potential subcatchment remediation strategies and data summaries to guide land managers and decision makers in implementing on-ground actions on both floodplain and paddock scales.

There are seven (7) associated floodplain prioritisation reports which detail the outcomes of this assessment:

- Tweed River Floodplain Prioritisation Study – WRL TR2020/04;
- Richmond River Floodplain Prioritisation Study – WRL TR2020/05;
- Clarence River Floodplain Prioritisation Study – WRL TR2020/06;
- Macleay River Floodplain Prioritisation Study – WRL TR2020/07;
- Hastings River Floodplain Prioritisation Study – WRL TR2020/08;
- Manning River Floodplain Prioritisation Study – WRL TR2020/09; and
- Shoalhaven River Floodplain Prioritisation Study – WRL TR2020/10.

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Appendix A Data collection methods and techniques

A1 Preamble

Following the collation and review of available datasets, a data collection campaign was implemented to fill identified data gaps and build knowledge in the following areas:

- Floodplain drainage infrastructure;
- Water quality;
- Acid sulfate soils; and
- Soil hydraulic conductivity.

Details of the equipment and techniques used are outlined in the following sections including information on measurement accuracy. The data processing methods are outlined where applicable. Where analysis has been completed by an analytical laboratory, the methods of analysis and quality control procedures followed by the laboratory have also been outlined.

A2 Equipment

A2.1 Geospatial positioning

Elevation and position data have been collected using Trimble survey equipment. Specifically, the Trimble R10 (Figure A.1) and Trimble R2 global navigation satellite system (GNSS) receiver models were used. All position measurements have been collected using the geocentric datum of Australia 1994 (GDA94) and all elevation measurements have been collected using the Australian height Datum (AHD) 1971. Real time kinematic (RTK) positioning was utilised whereby GNSS position measurements captured by the Trimble rovers were compared in real time to GNSS position measurements captured by continuously operating reference stations (CORS), specifically CORSnet-NSW operated by the NSW Spatial Services, to improve accuracy. Absolute accuracy of the Trimble GNSS RTK survey equipment is shown in Table A.1.

Figure A.1: A Trimble R10 GNSS receiver being used to survey culverts

Table A.1: Root mean square error for Trimble GNSS equipment during network RTK surveying

Equipment	Horizontal accuracy (mm)[1]	Vertical Accuracy (mm)[1]
Trimble R10	8	15
Trimble R2	10	20

[1]For every 1 km the GNSS receiver is from the closest CORSnet-NSW base station there is an additional 0.5 mm of uncertainty.

In addition to the base RMS measurement accuracy (Table A.1), factors such as geographic location and atmospheric activity can also increase the root mean square (RMS) error. During survey, the Trimble GNSS equipment records the horizontal and vertical precision of the measurement it is recording. This allows for the true accuracy of measurements, including errors such as those associated with the distance from the base station or atmospheric conditions, to be determined. In total, 3,340 survey measurements were collected during the data collection campaign completed for this study. Of these, 99% of the horizontal measurements and 95% of the vertical measurements had a precision within 0.05 m. Figure A.2 shows the distribution of precisions recorded for the horizontal and vertical measurements. Note that where a large uncertainty was recorded (i.e. greater than 0.1 m), these measurements have been flagged as approximate only.

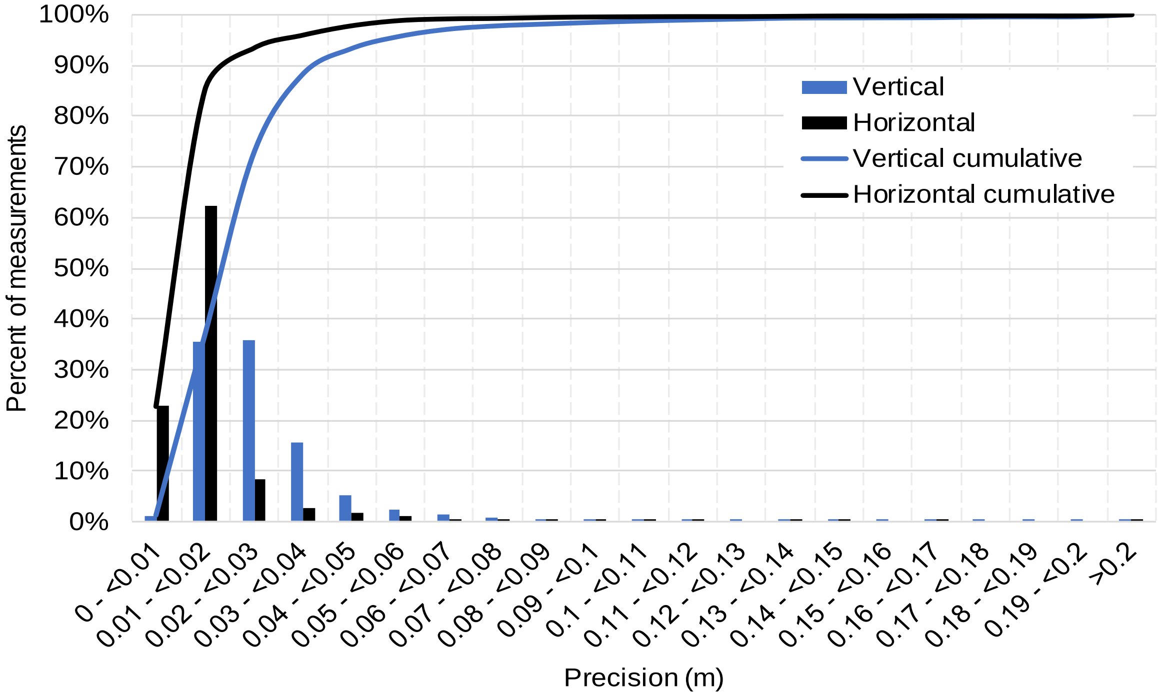

Figure A.2: Distribution of the true precision for all survey measurements

To confirm the accuracy of RTK GPS observations, survey of permanent survey marks (PSM) was completed where practical. Results for elevation measurements of survey marks compared to the reported elevation measurements are shown in Table A.2.

Table A.2: Registered survey mark elevations compared to RTK GPS measured elevations

Survey mark	Survey Mark Class/order	Registered Elevation (m AHD)	Measured Elevation (m AHD)	Difference (m)
SS59233	D/4	2.150	2.148	0.002
PM104829	LB/L2	0.996	0.989	0.007
SS102548	B/2	44.280	44.270	0.010
SS146085	U/U	3.000	2.990	0.010
PM104533	B/2	1.151	1.140	0.011
PM40452	LB/L2	14.859	14.848	0.011
PM58999	B/2	2.088	2.099	0.011
PM24471	LB/L2	3.044	3.029	0.015
PM129060	B/2	2.429	2.409	0.020
PM13857	B/2	11.631	11.611	0.020
SS186213	LC/L3	5.999	6.020	0.021
SS59232	D/4	1.950	1.927	0.023
PM30823	LC/L3	14.085	14.109	0.024
PM69928	LC/L3	9.580	9.607	0.027
SS62109	LB/L2	1.386	1.351	0.035
PM106581	B/2	0.791	0.754	0.037*
PM72519	D/4	1.410	1.448	0.038
PM129057	B/2	1.323	1.280	0.043
PM30834	LC/L3	9.725	9.679	0.046
PM41566	Lb/L2	1.332	1.387	0.055
PM40629	LB/L2	2.757	2.699	0.058
PM78050	B/2	2.050	1.990	0.060
PM24425	LB/ n/a	3.047	3.108	0.061
PM30824	LC/L3	13.833	13.771	0.062
PM78429	LC/L3	2.956	2.892	0.064
PM30823	LC/L3	14.085	14.014	0.071
SS136291	LC/L3	2.658	2.729	0.071
PM24404	LB/ n/a	4.637	4.728	0.091*
SS62109	LB/L2	1.386	1.290	0.096
SS145517	LC/L3	2.207	2.317	0.110
PM78410	LC/L3	3.918	3.793	0.125
PM41640	LB/ n/a	1.924	2.054	0.130*
PM66055	LB/L2	2.078	2.216	0.138*
PM24441	LB/ n/a	4.588	4.727	0.139
PM41635	LC/ n/a	0.815	0.955	0.140
SS6235	LA/ n/a	4.567	4.401	0.166
PM78424	LC/L3	3.488	3.781	0.293

* Duplicate measurements have been completed. See Table A.3.

In some instances, the difference between measured elevations and registered elevations was significant (greater than 0.1 m). In these circumstances, discrepancies could be associated with inaccuracy due to movement of the PSM or poor measurement accuracy. Where this is the case further investigation is required. To further check the reliability of survey accuracy, in some instances, multiple measurements at survey marks were completed. Table A.3 shows the discrepancies between multiple measurements of the same survey mark.

Table A.3: Duplicate measurements of survey mark elevations

Survey Mark	WRL Survey #1 Elevation (m AHD)	WRL Survey #2 Elevation (m AHD)	Difference (m)
PM106581	0.754	0.765	0.011
PM24404	4.728	4.752	0.024
PM41640	2.054	2.059	0.005
PM66055	2.216	2.232	0.016
SS62109	1.351	1.290	0.061

These measurements indicate that survey equipment used can reliably record repeat measurements with all results having a variability of less than 0.1 m. It also provides further evidence to suggest that discrepancies between measured and registered PSM values may require further investigation.

On four (4) occasions, an additional check was completed whereby two (2) measurements of a structure's invert were taken independently. Original measurements were taken at the start of the fieldwork campaign in August/September 2019 and repeat measurements taken at the end of the campaign in February/March 2020. The results from this check are shown in Table A.4. All duplicate measurements for structure inverts showed discrepancies of less than 0.1 m. This indicated that the methodology used for surveying structures was reliable and repeatable.

Table A.4: Repeat measurements for structures taken at the start and end of the fieldwork campaign

Catchment	Structure ID	WRL survey #1 Invert elevation (m AHD)	WRL survey #2 Invert elevation (m AHD)	Difference (m)
Richmond	4520-031-02	-0.653	-0.691	0.038
Richmond	2410-030-01	1.310	1.284	0.026
Macleay	016G1	-1.743	-1.803	0.06
Macleay	025G1	-0.212	-0.302	0.09

A2.2 Water level measurements

A Solinst LevelVent (model 3250) vented water level datalogger (Figure A.3) was used to measure water level recovery rates for hydraulic conductivity measurements. The data logger was connected to a field computer which was able to record instantaneous water levels at a frequency of 1 Hz. Accuracy of the datalogger was ±5 mm, including barometric compensation. Hydraulic conductivity measurement methods are discussed in Section A3.2.

Source: solinst.com

Figure A.3: Solinst LevelVent (model 3250) vented water level logger

A2.3 Water quality measurements

An In-Situ Aqua TROLL 600 multiparameter sonde was used to measure temperature, electrical conductivity (EC), pH, oxidation reduction potential (ORP), rugged dissolved oxygen (RDO) and turbidity in different water bodies during the fieldwork campaign. The pH and EC probes were calibrated on a weekly basis. The accuracy of measurements for each of the parameters is outlined in Table A.5. An example of live readouts from the Aqua TROLL 600 is shown in Figure A.4.

Table A.5: Accuracy for various parameters measured using an Aqua TROLL 600

Parameter	Accuracy
Temperature	±0.1°C
Electrical conductivity	1µS/cm plus 0.5% of the reading
pH	±0.1pH units
Oxidation reduction potential	±5.0 mV at 25°C
Rugged dissolved oxygen	±0.1mg/L from 0 to 20mg/L or ±2% of the reading from 20 to 60mg/L
Turbidity	Either, ±2% of the reading or ±0.5 NTU (or FNU), whichever is greater

Source: in-situ.com

Figure A.4: Example of live readouts (left) being obtained from an Aqua TROLL 600 (right)

A2.4 Soil profile sampling

Soil profiles were completed using the following equipment:

- Christie Engineering trailer mounted soil sampler;
- Christie Engineering post driver soil sampler; and
- Dormer soil auger and gouge.

Christie Engineering trailer mounted soil sampler

The Christie Engineering trailer mounted soil sampler was used to retrieve soil core samples (Figure A.5). A hydraulic arm was used to push a 51 mm hollow flight push tube into the ground (Figure A.6). The push tubes are each 1.6 m in length and can be connected together to reach the desired depth. The maximum sample depth of the equipment is approximately 5 m depending on the soil type. Once a push tube has been inserted into the ground, the hydraulic arm was used to extract the tube along with the soil sample contained within the hollow push tube.

Figure A.5: The trailer mounted soil sampler being prepared for sampling

Figure A.6: The trailer mounted soil sampler being used to push a 51 mm hollow flight push tube into the ground to collect a soil profile

Christie Engineering post hole driver soil sampler

The Christie Engineering post hole driver soil sampler functions similarly to the trailer mounted soil sampler. A post hole driver has been re-configured to hammer push tubes (with the same specification as those used by the trailer mounted soil sampler) into the ground to retrieve soil core samples (Figure A.7). To remove the push tube from the ground a manual foot pedal is used. The benefit of using the post hole driver soil sampler is that it can be easily transported to remote locations that may be difficult to access with a vehicle. Due to its size, the depth from which soil samples can be collected is generally limited to one sample tube (1.6 m depth).

Figure A.7: Post hole driver soil sampler with manual foot pedal tube extractor

Dormer soil and gouge augers

The Dormer soil auger and gouge are manual instruments used to collect soil profiles (Figure A.8). They are lightweight and extremely portable. To collect a sample the soil auger is twisted into the ground to the maximum length of the auger (approximately 0.3 m) and then removed along with a soil sample. This is repeated until the desired depth is reached using 1 m extension.

The soil gouge is a semi-circle shaped auger that collects a soil sample by being pushed directly into the soil surface. Once inserted up to its maximum length (1 m) it is then twisted to gouge a soil sample from the ground before being removed. During the data collection campaign, the gouge auger was used to sample from the bottom of holes.

Figure A.8: A soil auger (left) and gouge auger (right) being used to collect soil samples

A3 Field methods

A3.1 Soil sample analysis

Once soil samples were collected using one of the methods outlined in Section A2.4, the soil profile was laid out and the properties of the different soil layers (horizons) within the profile were analysed and recorded in the field (Figure A.9). Soil properties that were recorded include:

- Depth of layer;
- Layer thickness;
- Soil type (gravel/sand/clay);
- Colour;
- Moisture;
- Plasticity;
- Cohesiveness;
- Acid sulfate soil indicators (e.g. iron mottling, jarosite, macropores);
- Hydrogen peroxide reaction rate; and
- Other observations where applicable (e.g. sea shells).

Figure A.9: Example of a soil profile laid out to have the properties of each layer recorded and analysed

In addition to this information, the elevation and location of the soil profile was recorded using GNSS RTK survey equipment (Section A2.1). If intersected, the groundwater table, the pH and electrical conductivity were recorded (often water quality measurements were compared to nearby surface water observations). Colour was classified using the Munsell colour charts (USDA, 1994). A sample of each soil horizon was sent for analysis to a NATA accredited analytical laboratory (Eurofins Australia) (see Section A4 for further details). Ideally, the tests completed by Eurofins should be undertaken in the field immediately after the soils are extracted (along with logging of the soils in a bore log) as the acidity of these soils can change rapidly if not stored properly. To ensure sample integrity, soils were sealed within zip lock bags (with air first removed from the bag to prevent further oxidation) and stored in a freezer below 6ºC. At the end of each day samples were frozen. These steps were completed to ensure samples were kept as per the recommended preservation guidelines outlined by the laboratory.

For each soil horizon, a hydrogen peroxide reaction rate test was completed in the field as per Sullivan et al. (2018) (Figure A.10). Un-oxidised ASS (referred to as potential acid sulfate soil (PASS)) can commonly have a neutral pH To test for the presence of un-oxidised sulfides, a small amount of soil was covered with concentrated (30%) hydrogen peroxide. The rate of the reaction was visually assessed on 0 – 5 scale, as described in Table A.6. The results of the field peroxide test by themselves are not able to definitively identify the presence of ASS, as the peroxide can also react with organic materials in the sample. However, a strong reaction (4 or 5 on the scale) is often an indicator of the presence of oxidising sulfides.

Figure A.10: Different layers of a soil sample in an ice cube tray reacting after being exposed to hydrogen peroxide

Table A.6: Field peroxide test scale (Sullivan et al., 2018)

Reaction Scale	Rate of Reaction
0	No reaction
1	Low reaction
2	Medium reaction
3	High reaction
4	Extreme reaction
5	Volcanic reaction

A3.2 Soil hydraulic conductivity

Soil hydraulic conductivity is the measure of the potential groundwater flow rate and has significant implications when considering the risk of acidic groundwater discharge. Hydraulic conductivity was measured using three alternate approaches:

- Pit bail method;
- Slug test method; and
- Inverse auger method.

The pit bail method described by Johnston and Slavich (2003) was used to collect hydraulic conductivity data when the groundwater table was within 0.5 m of the surface. When this was not the case, either the slug test method or inverse auger method was used. Further details including a literature review describing each of these methods and others can be found in Appendix B .

Hydraulic conductivity data collection (slug test and inverse auger test)

During the soil sampling component of the field investigations, a hollow flight tube was used to extract soil cores across the coastal floodplains. Whenever this was completed a 51 mm hole in the ground surface was created using a hydraulic soil sampler (see Section A2.4). The depth of this hole generally extended below the water table and whenever this was the case the hole was used to complete a slug test.

To complete the slug test, a Solinst LevelVent datalogger (see Section A2.2) was inserted below the water table within the hole. Once the water table had stabilised, a 38 mm PVC bailer was used to extract approximately 1 litre of water from the hole. The data logger was then able to record the recharge rate of the water table (Figure A.11). Once the water table had fully recovered and reached equilibrium, additional bails of water were taken from the hole wherever practical as duplicate measurements. Inverse auger tests were completed using the same equipment, however, instead of recording the rate at which the water table rises, the rate at which the water level receded when introduced to a dry hole was measured.

Figure A.11: A field computer connected to a water level logger (via the orange cable) to measure the recharge rate following a removal of a slug of water from the temporary borehole

Note that in some circumstances a slug test could not be completed even when the soil sample depth extended below the water table. Reasons for this include:

- The hole penetrated a sand layer which, once sampled, would collapse;
- The depth of water in the hole was less than 0.2 m; the water level logger equipment is approximately 0.2 m long and when in place there is no freeboard above the logger to bail water; or
- The water level took too long to recover and reach equilibrium (in some instances greater than 1 hour).

Hydraulic conductivity data processing

An algorithm was used (Bouwer and Rice, 1976) to convert slug test measurements of the recharge of water collected in the field to hydraulic conductivity. Analysis was undertaken using MATLAB. Initially, the raw water depth measurements were compiled into a template document used as an input to the algorithm. When raw water depth measurements were compiled into the template document, each recovery event was inspected to ensure that no erroneous readings would be used for calculating the hydraulic conductivity value. An example of one of the recharge measurements that was used to calculate hydraulic conductivity is shown in Figure A.12.

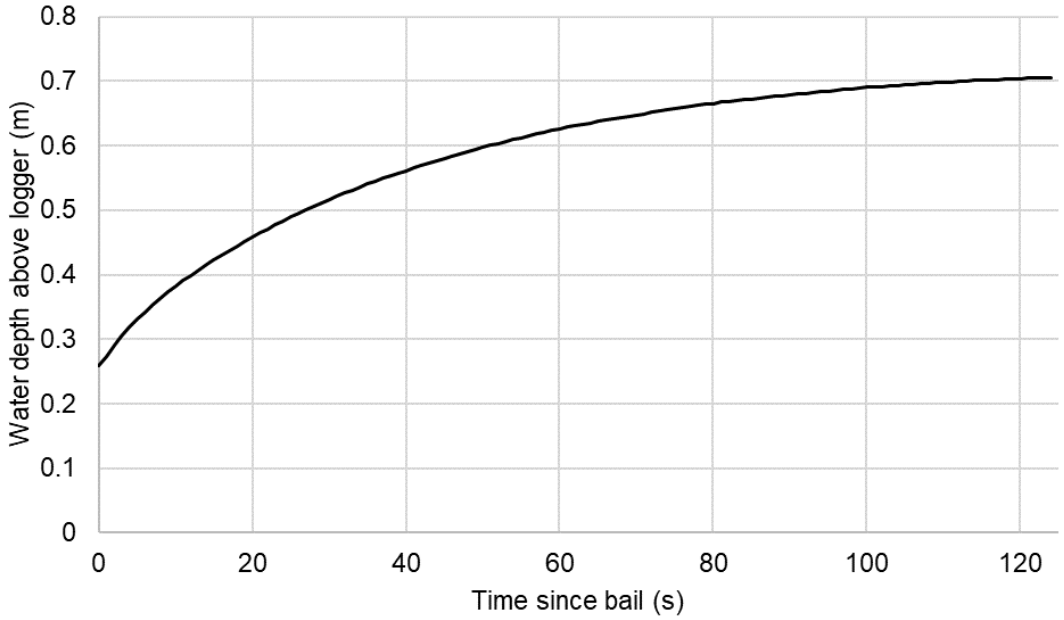

Figure A.12: Measurements of the water level recovering following a slug of water being removed from the sample hole

The processed water depth measurements were then input into the algorithm and the average hydraulic conductivity for all the recovery events measured at each hole was calculated. This used the method outlined by Bouwer and Rice (1976) to determine a discrete value for the hydraulic conductivity. It was assumed that the impermeable layer was located at the base of the sample hole meaning that any water that contributed to recharge was from horizontal flow into the hole. In order to determine the shape factor outlined by Bouwer and Rice (1976), the recharge was plotted against the recovery time for each bail as shown in Figure A.13. A polynomial fit was then used to calculate the actual displacement to be used in the shape factor calculation.

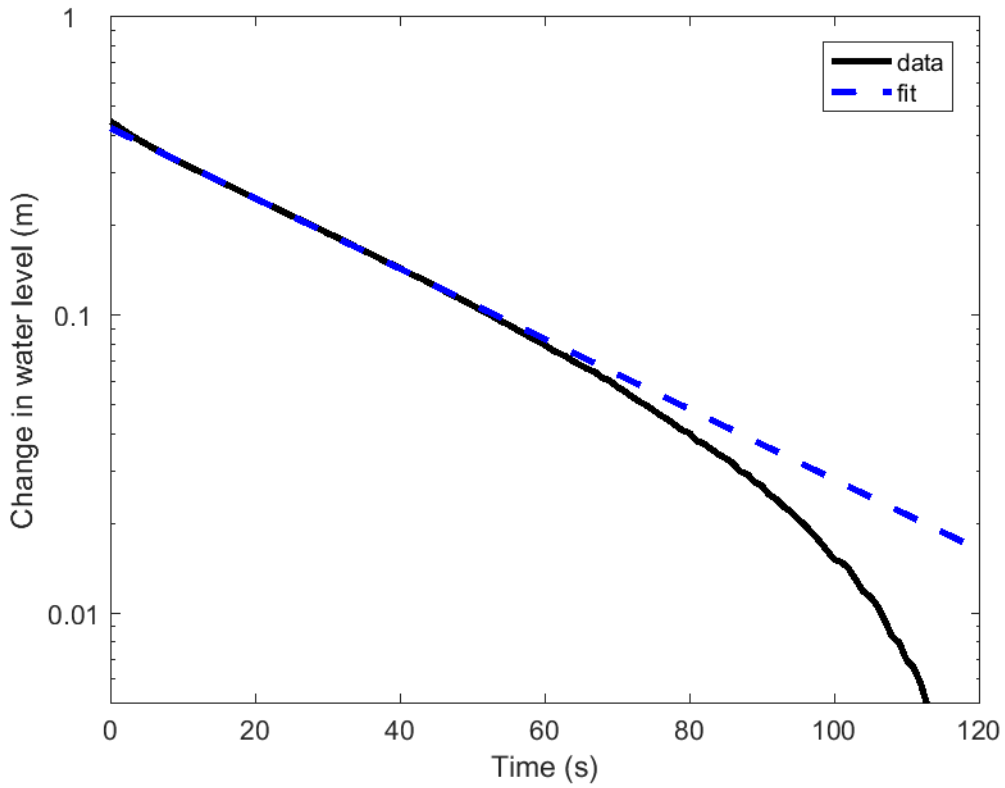

Figure A.13: The linear polynomial fit against recorded water level recovery data used to determine the actual displacement value (i.e. y intersect of the polynomial)

Calculation of hydraulic conductivity for the inverse auger and pit bail methods were completed using a slightly variant algorithm. The inverse auger calculations used the method outlined by van Hoorn (1979) and the pit bail calculations used the method outlined by Bouwer and Rice (1983) with a shape factor calculated using the Boast and Langebartel (1984) technique which takes into account the square shape of the sample pit.

As a quality assurance check, it was verified that the straight-line segment of the curve (see Figure A.14) was accurately determined by the algorithm for each water level recovery event. Where this was found not to be the case, adjustments to parameters within the algorithm were made iteratively until a suitable fit was found. In some instances, it was discovered that the change in water depth slowed when the recovering water level approached the water table (note the black data line in Figure A.13 tapers downward after 60 seconds). This is different to the examples outlined by Bouwer and Rice (1976) and Bouwer (1989). It is unlikely that this has an impact on the overall hydraulic conductivity measurement obtained as it only occurs once the larger proportion of water within the sample hole has recovered.

To validate the technique used for calculation of the hydraulic conductivity, a check was completed whereby hydraulic conductivity measurements calculated using Bouwer and Rice (1976) for the Hastings floodplain were also calculated using the Hooghoudt (1936) method as described by Dunn (1980). The comparison for results is displayed in Figure A.14 which shows only slight variations in the calculated hydraulic conductivity with measurements and a positive correlation of 0.84. This indicates that the Bouwer and Rice (1976) method provides a reliable result for determining hydraulic conductivity measurements.

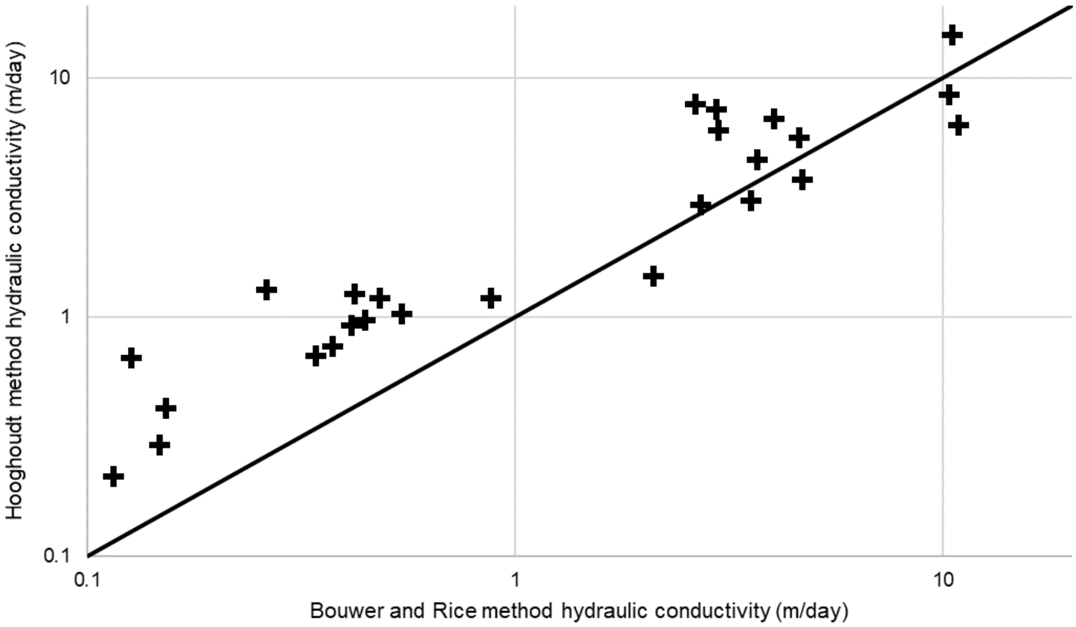

Figure A.14: Comparison of the Bouwer and Rice (1976) and Hooghoudt (1936) calculation techniques

A4 Analytical laboratory analysis

A4.1 Field acid sulfate soil testing

Samples were collected for each layer/horizon of the soil profiles and analysed by a NATA accredited laboratory. For each soil sample the following parameters were tested:

- Field pH (pH_F);
- Hydrogen peroxide reaction rate;
- pH after peroxide oxidation (pH_{FOX}); and
- Electrical conductivity (1:5 aqueous extract).

Testing for these parameters is standard practice to identify the presence of ASS and the degree of oxidation that has occurred within them, differentiating between potential ASS (PASS) and actual ASS (AASS). Further details on how to identify ASS using these parameters is outlined by Stone et al. (1998), Sullivan et al. (2018) and the Department of Environmental Regulation (DER) Western Australia (2015), and discussed in the following sections.

A4.2 Field pH test

This test measures the field pH of the soil (commonly denoted as pH_F). This can either be measured directly with a spear point pH probe directly into moist soils, or by testing the pH of a solution made by mixing 1:5 soil to de-ionised water.

Stone et al. (1998) suggest that the following conclusions can be made from results of this test:

- $pH_F \leq 4$ strongly indicates the presence of AASS (although there are some other limited conditions in which acidic soils can exist);
- $4 < pH_F \leq 5.5$ indicates acidic soils possibly from past or limited sulfide oxidation, but does not definitively identify the presence of AASS, as there are other common processes that can result in soils that are acidic; and
- pH_F alone cannot be used to identify PASS, which commonly has a near neutral pH

Eurofins laboratory completed this test using a 1:5 aqueous solution extract and measuring the concentration of hydrogen ions (H+) expressed in pH units at a temperature of 25ºC as per NEPM Schedule B3 (NEPC, 2011). Eurofins measurements of soil pH include 2.5% of measurement uncertainty.

A4.3 Laboratory hydrogen peroxide reaction rate test

In the field, during soil sample collection, a hydrogen peroxide reaction rate test was completed as per Sullivan et al. (2018) (see Section A3.1). As discussed, the results of the field peroxide test by itself does not definitively identify the presence of ASS but can help indicate the presence of oxidising sulfides. In addition to these tests, laboratory analysis of the hydrogen peroxide reaction rates was also completed (Figure A.15). In the laboratory a different methodology was used for determining the reaction rate to that which was used in the field and outlined by Sullivan et al. (2018).

Figure A.15: Example of a laboratory hydrogen peroxide test

During the laboratory reaction rate tests, samples were given a long time to react. In some instances, this was as long as two hours. During this time test tubes containing samples were placed within a

40ºC water bath to help initiate the reaction. Once the reaction was completed the laboratory added additional hydrogen peroxide to the test tube to ensure that all reactive compounds within the sample completely oxidised. Note, in-between each reaction the sample was allowed to cool to room temperature. It is important for the pH_{FOX} test that the sample is allowed to fully oxidise (see Section A4.4).

During the initial hydrogen peroxide reaction, laboratory technicians scored the reaction rate on a scale of 1 to 4 (as opposed to 0 to 5). Table A.7 describes each of these scores as outlined by Eurofins. The changes in methodology and scoring adopted by Eurofins resulted in some discrepancies for the reaction rate results. For this reason, only results from the field hydrogen peroxide reaction rate tests have been included with data from each soil profile.

Table A.7: Laboratory peroxide test scale adopted by Eurofins

Reaction Scale	Rate of Reaction
1	No reaction to slight
2	Moderate reaction
3	Strong reaction with persistent froth
4	Extreme reaction

A4.4 pH after oxidation

Following the hydrogen peroxide test, the pH of the soil/hydrogen peroxide mixture was measured (commonly denoted as pH_{FOX}) to observe any changes in the pH of the soil following oxidation. Note that it was ensured that the soil sample had fully oxidised and the reaction had completed before the pH_{FOX} test was undertaken so that the oxidated pH was calculated correctly.

Stone et al. (1998) provide the following guidance on the results of this test:

- $pH_{FOX} \leq 3$ is a strong indicator of PASS;
- $3 < pH_{FOX} < 4$ is likely an indicator of PASS, but additional laboratory analysis is required to definitively confirm the presence of sulfides;
- $4 < pH_{FOX} < 5$ does not confirm or deny the presence of sulfides, further testing is required;
- $pH_{FOX} \geq 5$ and minimal difference to pH_{FOX} is likely an indicator that no PASS is present; and
- The greater the difference between pH_{FOX} and pH_F the stronger the indication of the presence of PASS.

As with the pH_F test, Eurofins completed the pH_{FOX} test using a 1:5 aqueous solution extract measuring the concentration of hydrogen ions (H^+) expressed in pH units at a temperature of 25ºC as per NEPM Schedule B3 (NEPC, 2011). Eurofins measurements of soil pH include 2.5% of measurement uncertainty.

A4.5 Electrical conductivity

Electrical conductivity (EC) is a measure of the ability of soil to conduct electricity and is a method for determining the salinity of a soil (Tenison, 2014). EC was tested using a 1:5 aqueous solution extract at a temperature of 25ºC which is in alignment with NEPM Schedule B3 (NEPC, 2011). Results were expressed in µS/cm units. Laboratory measurements of soil EC include 12.7% of measurement uncertainty.

A4.6 Laboratory quality control

During laboratory testing, the following quality control checks were made in alignment with NEPM Schedule B3 (NEPC, 2011):

- Laboratory control samples (LCS);
- Method blanks; and
- Duplicate samples.

A laboratory control sample is a test completed where a control sample is created with a known concentration of the analyte being tested (e.g. electrical conductivity). The concentration should be within the range expected for the samples that are being tested. Laboratory control samples are reported as the percent recovery. It is expected that the percent recovery to be within 30% of the known concentration. A total of ten (10) laboratory control samples were completed with all inside the acceptable limits.

A method blank is a test where a control sample containing none of the analyte is tested to determine if any contaminants are introduced form components of the test such as reagents or glassware. For soil testing Eurofins uses clean sands and deionised water. A total of 15 method blanks were completed with all results showing no detectable contamination.

Duplicate samples (the same sample is tested twice) ensure that the measurements are accurate. The relative percent difference (RPD) of the two samples is calculated. Generally a RPD less than 30% is acceptable, however if the measured concentration is less than 20 times the limit of reporting (LOR) (the limit equipment can accurately measure concentrations), a RPD less than 50% is acceptable and if the concentration is less than 10 times the limit of reporting there is no limit for the RPD. In total, 253 duplicate samples were tested. Of these, one sample resulted in an RPD greater than 30%. This occurred for soil sample HA_24A_01 and was found to be due to the sample being heterogeneous.

A summary of the quality control samples for each batch sent for laboratory analysis can be found in Table A.8.

Table A.8: Summary of laboratroy quality control test results for each sample analysis batch

Sample Batch	Number of Samples	Laboratory Control Sample		Method Blanks		Duplicates EC		Duplicates pH		Duplicates Reaction Rate	
		Pass	Fail	Pass	Fail	Pass	Fail	Pass	Fail	Pass	Fail
678810	77	1				8		7		7	
681811	54	1		1		6	1*	6		6	
681796	71	1		1		7		8		8	
683941	59	1		1		4		6		6	
684877	36			1		3		4		4	
685800	56			1		4		6		6	
687374	73	1		1		8		7		7	
690017	40	1		1		4		4		4	
691176	38			1		5		4		4	
692477	49			1		4		5		5	
693050	33	1		1		4		3		3	
699930	29	1		1		3		3		3	
699859	21	1		1		2		3		3	
701125	24	1		1		2		1		1	
701255	81			1		8		9		9	
705545	53			1		2		6		6	
706738	54					6		4		4	
Total	848	10	0	15	0	80	1*	86	0	86	0

*A RPD of 160% was recorded due to sample heterogeneity. Sample 1 recorded 410µS/cm and sample 2 recorded 42µS/cm.

Appendix B Groundwater saturated hydraulic conductivity theory

B1 Saturated hydraulic conductivity

Coastal floodplains are characterised as having unconfined aquifers of shallow to intermediated depth (e.g. up to 10 m depth) (Glamore et al., 2016a). Unconfined aquifers are associated with the presence of a free-water table that can be influenced by a range of processes including direct rainfall, inundation due to flooding, evapotranspiration, and drainage to surface waters. The free-water table enables groundwater to flow in any direction, however the flow of groundwater to connected surface waters is predominantly horizontal (Oosterbaan and Nijland, 1994). The hydraulic conductivity of soil, often described as permeability (Dunn, 1980; Dent, 1986), is defined as the constant of proportionality in Darcy's Law, which describes the flow of a fluid (usually water) through a porous medium (e.g. the flow of groundwater through the unconfined aquifer of a coastal floodplain). The law was formulated by Henry Darcy (Darcy, 1856) based on the results of experiments on the flow of water through beds of sand, and is expressed as:

$$V = K\left(\frac{dh}{dx}\right) \qquad \textbf{Equation B.1}$$

where,

V = apparent velocity of the groundwater (m/d);
K = hydraulic conductivity (m/d);
h = hydraulic head (m); and
x = distance in the direction of groundwater flow (m).

In Darcy's equation (Equation B.**1**), dh/dx represents the hydraulic gradient (s) (the head loss per length of flow), which is the difference in energy (dh) over a small distance (dx), a dimensionless parameter. By rearranging, Equation B-1 the hydraulic conductivity can be expressed as $K = \frac{V}{s}$, and can thus be regarded as the apparent velocity (m/d) of the groundwater when the hydraulic gradient equals unity (i.e. dh/dx = 1) (Oosterbaan and Nijland, 1994). A schematic of an unconfined aquifer of shallow to intermediate depth is provided in Figure B.1. The K-value of saturated soil (K_{sat}) represents the average hydraulic conductivity, which depends predominantly on the soil size, shape and distribution of the pore spaces within the soil profile (Oosterbaan and Nijland, 1994).

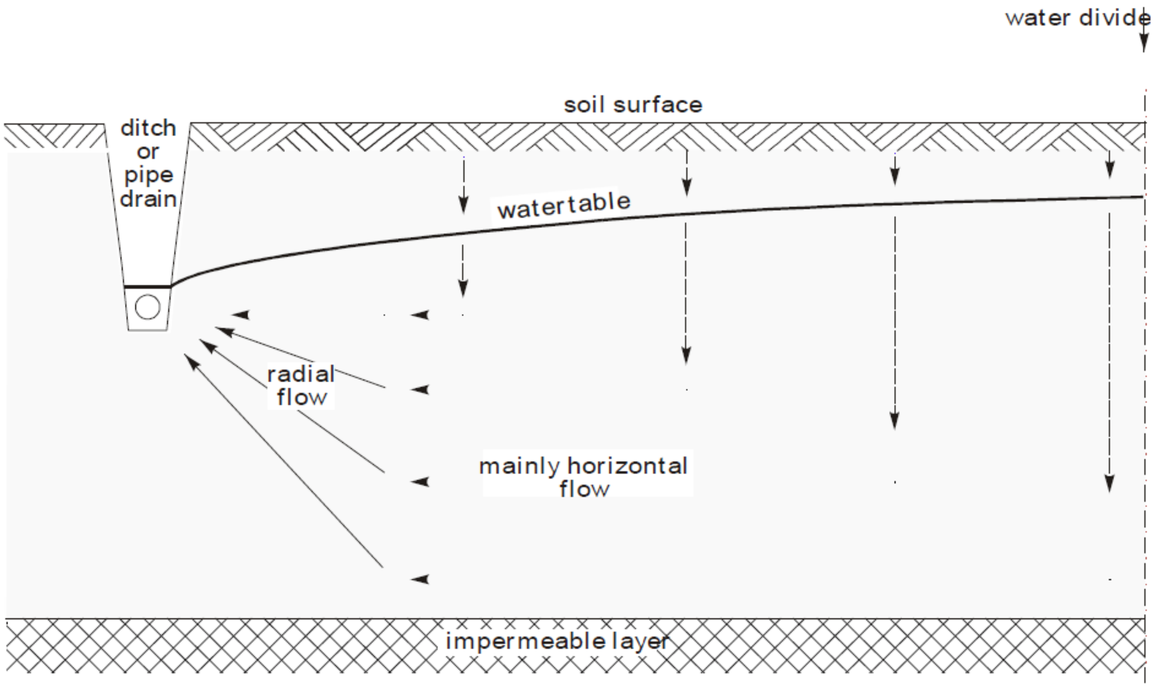

Figure B.1: Flow into an agricultural drain from a shallow unconfined aquifer (Oosterbaan and Nijland, 1994)

B2 Variability of saturated hydraulic conductivity

Understanding the saturated hydraulic conductivity (often referred to simply as 'hydraulic conductivity') of drained floodplain soils is an important factor used in assessing the severity of acid sulfate soils (ASS) and the potential risk to estuarine waterways (Johnston and Slavich, 2003). Spatially, the hydraulic conductivity of a soil profile can be highly variable in both the horizontal direction across different field and landscape scales and vertically at different depths (Johnston et al., 2009). This is due to the heterogenic properties of soil, particularly on coastal floodplains (Oosterbaan and Nijland, 1994; Johnston et al., 2009).

In coastal floodplains the spatial variability on a horizontal scale is caused by the intricate development of the floodplain involving factors such as changing sea levels and human interference (Hirst et al., 2009). Oosterbaan and Nijland (1994) describe how coarser soil particles (e.g. sands and gravels) are deposited as levees near riverbanks and finer particles (e.g. silt and clay) are deposited on the floodplain. Over time, as rivers or creeks meander and vegetation growth changes this creates complex lithological patterns across a floodplain resulting in varying hydraulic conductivity even within a single paddock. Indeed, Gupta et al. (2006) found when conducting an experiment testing hydraulic conductivity of adjacent eight metre square plots that there was significant spatial variation.

As part of this study, an investigation was completed to understand the spatial variability of hydraulic conductivity for different quaternary geology units. Hydraulic conductivity measurements across all floodplains were compiled (including data from literature and data collected as part of this study where the groundwater table was above the local mean low water spring level) and assigned a quaternary geological unit based on the location where the measurement was completed. The variability of the hydraulic conductivity for different quaternary geology units was then compared (Figure B.2). Results indicated that hydraulic conductivity measurements varied significantly within individual quaternary geology units and also across different quaternary geology units. This indicates that spatially hydraulic conductivity is extremely variable and that a specific quaternary geology unit at one location (e.g. a backswamp close to the ocean) may have a completely different hydraulic conductivity at a different location (e.g. a backswamp in the upper estuary) even if both locations have the same quaternary geology.

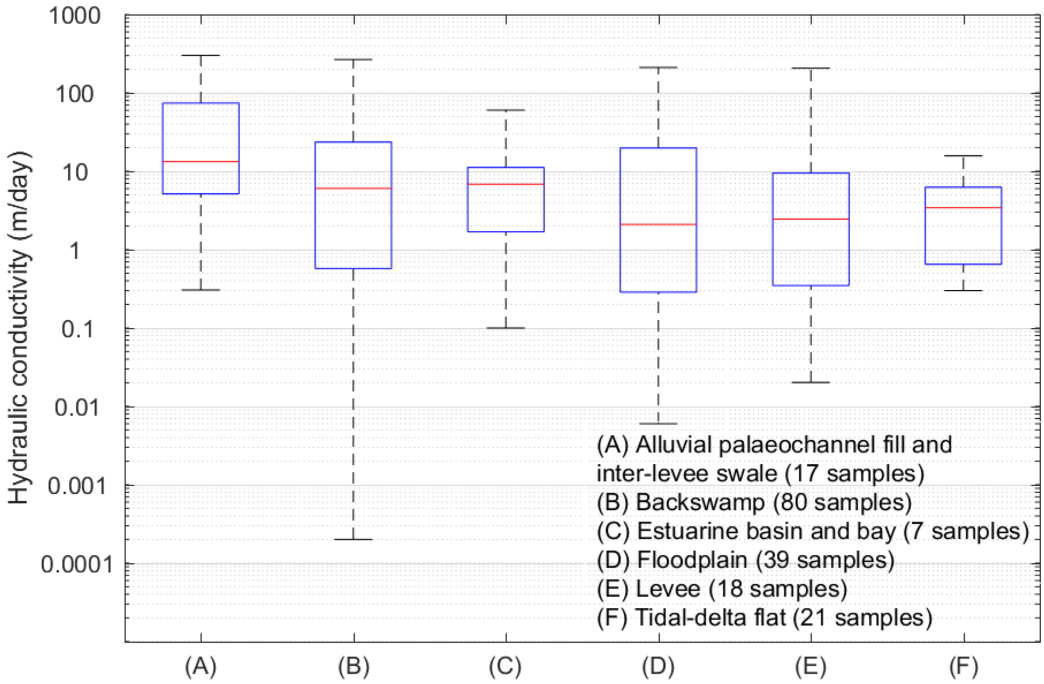

Figure B.2: The median (red line), 25% to 75% range (blue box) and total range (black whiskers) of hydraulic conductivity measurements for different quaternary geology units on NSW coastal floodplains

Human interference can further alter the hydraulic conductivity of the soil profile, thereby increasing the overall variability. Dent (1986) describes how agricultural drainage induces ripening of the soil structure. During this process the soil shrinks creating a series of inter-connected fissures or fractures in the soil profile that increases the hydraulic conductivity. In addition to this, decayed organic matter such as roots within the subsoil further act to increase the hydraulic conductivity of soil (Johnston et al., 2004). Known as macropores, these channels, sometimes greater than 20 mm in diameter, have been shown to result in hydraulic conductivity exceeding 100 m/day in certain locations (Johnston et al., 2004).

In addition to the horizontal spatial variability there is also evidence that hydraulic conductivity varies with depth (Dent, 1986). A common ASS profile consists of topsoil underlain by actual ASS (AASS) which in turn is underlain by potential ASS (PASS) (see Section 2 for further details). It is common for features such as macropores to be abundant in the AASS layer (due to drainage causing soil ripening) resulting in a significantly higher hydraulic conductivity when compared to the PASS layer. Further, in the AASS layer it is often found that macropores are coated in ferric iron which helps to sustain their structure (Dent, 1986; Johnston et al., 2002). Johnston et al. (2004) found that macropores cause significant increases in horizontal hydraulic conductivity (i.e. towards agricultural drains) due to their development in AASS layer. On the other hand, within the PASS layer, hydraulic conductivity is generally low due to the small particle size of clay and is only increased in the presence of old root channels or burrows and even then not nearly to the same extent when compared to the increase caused by the development of macropores in the AASS layer (Dent, 1986). It is generally accepted that hydraulic conductivity decreases with depth in the clays of coastal floodplains.

Due to this heterogeneity, physically measuring the hydraulic conductivity across coastal floodplains can only ever be indicative as it can vary significantly based on the landscape and depth. Subsequently, since hydraulic conductivity measurements across ASS affected floodplains can be highly variable, measurements should be taken as high-level estimates of the flow connectivity between shallow groundwater and subsurface drains and in turn the potential risk for ASS discharges.

B3 Impact of catchment hydrology on groundwater discharge

Groundwater flow on coastal floodplains can be influenced by the characteristics of its upstream catchment as well as the floodplain drainage network. The size of a catchment and the drainage density within a catchment are key factors that influence the rate and volume of groundwater discharge from a floodplain to the estuary. Independent of the variability of floodplain hydraulic conductivity (which is represented by the hydraulic conductivity (K) in Equation B.**1** (see Section B1)) these two factors will control the rate at which water flows from the ground.

For groundwater to flow it must have a hydraulic gradient, that is, there needs to be an effective difference between two water levels (or more specifically a difference in hydraulic energy/head) over a certain distance (dh/dx in Equation B.**1**). When this occurs water will flow from a location with a high water level to a location with a lower water level at a rate dependent upon the medium it is travelling through (i.e. the hydraulic conductivity). This is how floodgates work to lower the upstream groundwater table as they promote a water level within a drainage network to be at the low tide level. Larger hydraulic gradients promote faster groundwater discharge.

The size of a catchment is able to influence the hydraulic gradient on a floodplain and subsequently the groundwater flow. Following a runoff event, the water table on coastal floodplains rises (increasing the hydraulic head) and results in increased flow from the groundwater to the surface water drainage network (Figure B.3). Where a catchment is larger there are two (2) impacts on the groundwater:

1. There is a greater capacity for the system to raise the water table; and
2. There is a larger volume of water that is flowing across the floodplain and through the drainage network.

Together these factors result in an increase in groundwater flow from the floodplain (e.g. to the drainage network and then the estuary) following a runoff event by increasing the difference in water level between the groundwater table and within the drainage network (i.e. increasing dh in Equation B.**1**).

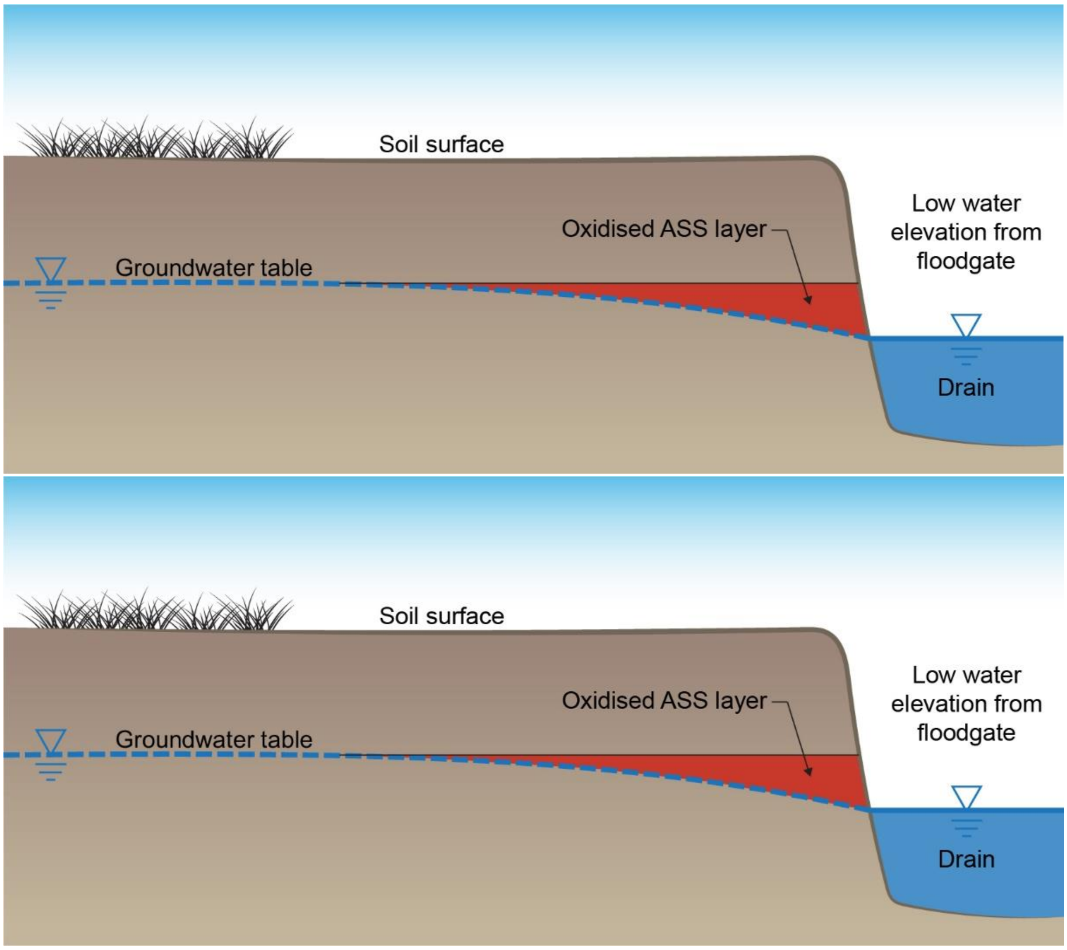

Figure B.3: Floodplain drainage during day-to-day conditions (top) and with an increased flow potential following a rainfall event (bottom)

In addition to the size of a catchment, the density of the drainage network in a coastal floodplain also impacts the rate and volume at which groundwater flows. Rather than changing the difference between the groundwater table and the water level in the drainage network (hydraulic head), a drainage network with a greater density decreases the distance over which water needs to flow to reach surface water drains (i.e. dx in Equation B.**1**), resulting in a faster recession of groundwater levels and increased groundwater discharge (Figure B.4).

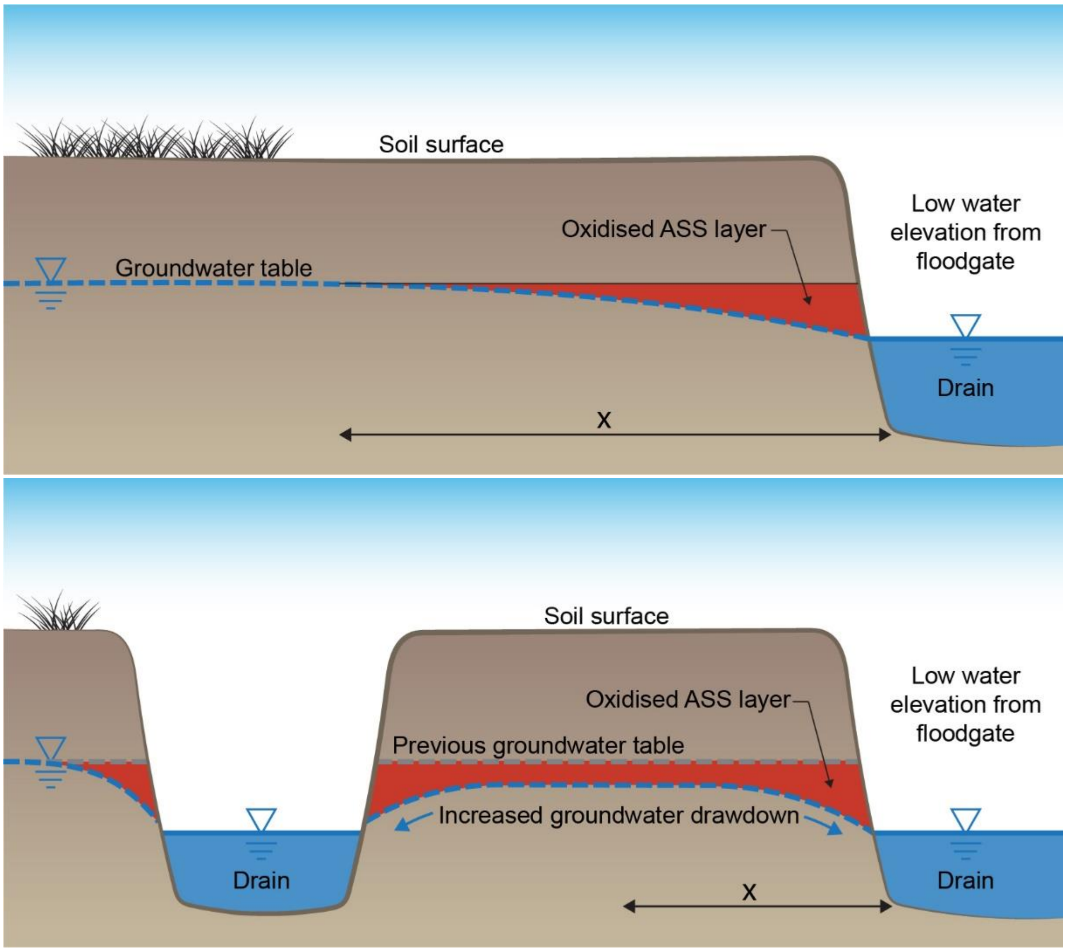

Figure B.4: Floodplain with limited number of drain (top) and an increased number of drains (bottom)

It is important to consider both catchment hydrology, floodplain drainage, and hydraulic conductivity when assessing the export of acidic water from coastal floodplains. In Equation B**.1** (Section B1), an increase in the hydraulic gradient (dh/dx) will result in an increase in the apparent velocity of groundwater. The hydraulic conductivity (K) will also affect the apparent velocity of groundwater. These two factors cannot be considered independently when assessing the capacity of floodplains to discharge acidic water. Subsequently, it is important to acknowledge the catchment hydrology as a key factor that influences groundwater flow in addition to hydraulic conductivity.

B4 Methods for measuring saturated hydraulic conductivity

Several field measurement techniques exist for measuring the in-situ hydraulic conductivity of soil. Due to the high variability of hydraulic conductivity each of these techniques have different pros and cons. The following section will provide a detailed description of hydraulic conductivity measurement techniques including:

- The auger hole method (slug test);
- The pit bailing method; and
- The inverse auger hole method.

These are the techniques that have been used for determining the hydraulic conductivity across coastal floodplains within existing literature and during the fieldwork investigations completed as part of this study. A brief description has also been provided for several other techniques that can be used to determine hydraulic conductivity.

B4.1 Auger hole method (slug test)

The auger-hole method (or slug test) is a technique whereby a cylindrical hole is drilled or bored below the water table in a shallow unconfined aquifer. Once the water table stabilises (after being disturbed from the initial drilling process) a portion of the water (or 'slug' of water) is removed from (or in some instances added to) the hole. The time it takes for the hole to recharge (or fall) and reach equilibrium at the initial water table is then measured. The method was initially developed by Diserens (1934) and has since been improved resulting in multiple theoretical methods for calculating the hydraulic conductivity value using the slug test technique (van Beers, 1970). The basis of each of these methods is determining the relationship expressed in Equation B.2 (Boast and Kirkham, 1971):

$$Q = AKy$$

Equation B.2

Where,

Q = the rate of flow into the hole (m^3/d);
K = hydraulic conductivity (m/d);
y = change in water level (m); and
A = a constant known as the 'shape factor' (m).

Different calculation methods used for determining the hydraulic conductivity using the slug test technique include:

- Hvorslev method (1951);
- Hooghoudt method (1936);
- Ernst method (1950); and
- Bouwer and Rice method (Bouwer and Rice, 1976; Bouwer, 1989).

Each of these methods vary in terms of assumptions and approximations, particularly regarding the calculation of the shape factor (A).

Table B.1 provides a brief summary of the assumptions for each technique. These methods are designed for use in auger holes within an unconfined aquifer. There are several other techniques available for use in a confined aquifer that are not relevant for this study (Fetter, 2001).

Table B.1: A summary of the different theoretical techniques used to calculate hydraulic conductivity from a slug test (Hvorslev, 1951; Boast and Kirkham, 1971; Bouwer and Rice, 1976; Dunn, 1980)

Technique	Summary of Assumptions/approximations
Hvorslev (1951)	Drawdown of the water table is negligible. Flow above the water table can be ignored. Head losses as water enters the hole is negligible. The aquifer is homogeneous and isotropic. The constant groundwater pressure is determined from the steady state when the change in water level is 37% of the initial water level.
Hooghoudt (1936)	Drawdown of the water table is negligible. Flow above the water table can be ignored. The aquifer is homogeneous and isotropic. Head loss occurs over an empirical length (L) defined as L=aH/0.19 where a is the hole radius and H is the water depth in the hole.
Ernst (1950)	Drawdown of the water table is negligible. Flow above the water table can be ignored. The aquifer is homogeneous and isotropic. The shape factor can be calculated based upon relaxation drawings, experimental data and a formula derived from them.
Bouwer and Rice (1976)	Drawdown of the water table is negligible. Flow above the water table can be ignored. Head losses as water enters the hole is negligible. The aquifer is homogeneous and isotropic. An effective radius (Re) is determined based upon empirical electrical resistance experiment data.

B4.2 Pit bailing method

The pit bailing method was initially developed by Healy and Laak (1973) and involves digging a larger diameter and shallower hole (in comparison to the slug test hole) which still penetrates below the aquifer. Bouwer and Rice (1983) expanded upon their own previous work and that of Healy and Laak (1973) to develop a method for the calculation of hydraulic conductivity. The theory behind this method is that features within the soil profile, such as macropores, are more likely to be intersected in the larger pit that is excavated resulting in an accurately represented profile contributing to the recharge rate of the pit once water has been removed. Johnston et al. (2009) argue that the pit bailing method is more suited to calculating the hydraulic conductivity on coastal floodplains due to:

- Being better suited to capture the spatial frequency of macropores;
- Being only influenced by shallow soil horizons;
- Allowing for visual inspection of the soil profile; and
- Being less prone to smearing which blocks pores preventing flow.

On the other hand, Johnston et al. (2009) also note that limitations of the pit bailing method include that:

- It is unrealistic to measure the hydraulic conductivity for soil horizons more than 0.7 m below the ground surface;
- It requires the groundwater to be close to the surface;

- Removal of water (or the 'slug') does not occur instantaneously; and
- Accuracy is dependent on uniformity of the pit.

As with the auger hole method (slug test), a number of techniques have been derived for calculating a discrete value for the hydraulic conductivity using the pit bail method. These are based upon different assumptions and approximations used for calculating the shape factor (a parameter which is dependent on the shape of the hole) and are outlined by:

- Bouwer and Rice (1983);
- Boast and Langebartel (1984); and
- Lomen et al. (1987).

These methods are all primarily based upon the same calculations as the auger hole method with different shape factors representing larger holes. Bouwer and Rice (1983) developed the method for circular holes with a large diameter. Lomen et al. (1987) developed a method to calculate the shape factor for circular holes with a large diameter and developed a method to calculate the shape factor for trapezoidal holes. Boast and Langebartel (1984) developed a technique whereby, in addition to large circular holes, the hydraulic conductivity value could be calculated for large rectangular or square holes with the aim of calculating flow rates into agricultural drains.

Johnston and Slavich (2003) investigated the use of the pit bailing method for measurement of hydraulic conductivity on coastal floodplains and developed a methodology which used a square pit that protruded into the shallow underlying aquifer. In their methodology they developed a criterion that classified approximate hydraulic conductivity ranges. This can be further extrapolated to indicate the risk level associated with export of acid from ASS into drains in terms of hydraulic conductivity as shown in Table B.2. This method acknowledges the uncertainty associated with hydraulic conductivity field measurements and instead of providing a discrete hydraulic conductivity value, it provides a category indicatively describing the hydraulic conductivity removing bias associated with the general variability in hydraulic conductivity.

Table B.2: Risk classification for approximate rates of saturated hydraulic conductivity (Johnston and Slavich, 2003)

Risk classification	Approximate Ksat (m/day)
Extreme	>100
High	15 to 100
Moderate	1.5 to 15
Low	<1.5

B4.3 Inverse auger hole method

The inverse auger hole method (commonly referred to as the Porchet method) is a technique whereby an auger hole is drilled or bored to a desired soil horizon above the water table, filled with a known volume of water and then the rate at which the water level drops is measured (Oosterbaan and Nijland, 1994; van Hoorn, 1979). The benefits of this method are that it can be completed in situations where the water table is at a significant depth below the ground surface and it can be used to target key soil horizons.

Assumptions of the inverse auger hole method are outlined by Noshadi et al. (2012) and include:

- The pressure head gradient due to ponded water in the hole is neglected;
- The capillary action of unsaturated soil is neglected; and
- The blockage of pores by trapped air is neglected.

Using these assumptions, van Hoorn (1979) developed a calculation technique to determine the hydraulic conductivity using the inverse auger method. It should be noted that van Hoorn recommended the test be repeated until successive measurement have a difference of less than 15% to ensure the correct hydraulic conductivity is accurately determined.

B4.4 Alternative methods

In addition to the techniques outlined previously, there are several other methods available for the calculation of hydraulic conductivity. A number of these have been outlined in Table B.3 which summarises different techniques found in literature for calculating hydraulic conductivity (Millham and Howes, 1995; Noshadi et al., 2012; Oosterbaan and Nijland, 1994). Note that it is generally accepted that field methods produce a better measurement of hydraulic conductivity than laboratory methods (USDA, 2018).

Table B.3: Summary of techniques for determining hydraulic conductivity (Millham and Howes, 1995; Noshadi et al., 2012; Oosterbaan and Nijland, 1994)

Method	Description
Infiltrometer	An infiltrometer is a device that can be used to measure the vertical hydraulic conductivity of soil. This technique does not require any excavation and only measures the hydraulic conductivity value of soil located at the ground surface. It involves using a metal ring mounted to a water dispenser. The rate at which water infiltrates into the ground is measured and used to calculate the hydraulic conductivity.
Tidal dampening (Transmissivity)	Using techniques developed by Ferris (1963), the time it takes for the dampened tidal signal from an estuary or the ocean (or a synthetic fluctuation) to pass through the groundwater can be measured and subsequently converted to a hydraulic conductivity.
Tracer test	Tracer tests involve dosing the groundwater with some form of tracer (such as Radon). Using multiple groundwater sampling locations, the time it takes for the tracer to travel between locations can be determined and subsequently the hydraulic conductivity.
Guelph Permeameter	This technique was developed by Reynolds and Elrick (1985) (see also Reynolds and Topp, 2008) and uses sophisticated field equipment to measure vertical and horizontal hydraulic conductivity in a similar way to the inverse auger method. It takes into consideration flow due to gravity, ponding depth, soil capillarity actions and well dimensions.
Electrical conductivity push tube	This method uses an electrical conductivity profiling tool which is often mounted to a large mobile vehicle (Healey, 2004). A probe is inserted into the ground which then measures the ability of the soil to conduct an electrical current. It is able to give the hydraulic conductivity at differing depths depending upon the surrounding soil including anomalies due to its heterogeneity.
Laboratory tests	There are a number of laboratory tests that can be completed to determine hydraulic conductivity. An example is the permeameter test which, using different hydraulic heads, can calculate hydraulic conductivity. Further details are outlined by Fetter (2001).
Grain size analysis	A number of equations for hydraulic conductivity based upon grain size and statistics have been developed including by Hazen (1893) and Krumbein and Monk (1943). Generally, they are related to soils with particle sizes classified as sands.
Desktop methods	An example of this technique is described by Dieleman (1974) whereby through analysis of hydraulic head and drainage flow data the hydraulic conductivity can be calculated using the Boussinesq equation. This specific method does require field data such as the depth of the impermeable layer and soil porosity.

B5 Inclusion of saturated hydraulic conductivity to the prioritisation methodology

B5.1 Discussion

The catchment prioritisation approach, as defined by Glamore and Rayner (2014) and refined by Glamore et al. (2016a), utilised the hydraulic conductivity in calculating a rate of acidic export from an ASS affected floodplain for use in a groundwater factor, which in turn is used to determine a risk rating of acidic discharges to an estuary. These previous studies have used hydraulic conductivity calculated using the Johnston and Slavich (2003) method exclusively. Using this methodology requires that the groundwater table be within 0.7 m of the ground surface. During a data gaps analysis of hydraulic conductivity data, it was determined that there was insufficient spatial coverage of hydraulic conductivity measurements to determine the groundwater factor for the floodplains being investigated within this study. Furthermore, due to drought conditions experienced during scheduled field investigations for this study (completed from August 2019 to March 2020), it was not possible to complete hydraulic conductivity measurements using the Johnston and Slavich (2003) approach at all measurement locations. It was therefore decided to expand the existing dataset being used to include hydraulic conductivity measurements from other techniques (such as the slug test) which could be used during drier climates including when the groundwater depth is greater than 0.7 m below the ground surface. To understand the impact of using these measurements to calculate the groundwater factor for catchment prioritisation, an investigation was completed comparing hydraulic conductivity values measured using the pit bail method to the slug test method. This investigation took into consideration data from five separate coastal floodplains located on the north coast of NSW (Tweed, Richmond, Clarence, Macleay and Hastings).

To compare the Johnston and Slavich (2003) pit bail method with the Bouwer and Rice (1976) slug test method, pits and auger holes were excavated directly adjacent to one another. Analysis of the pit bailing method was completed using the method developed by Bouwer and Rice (1983). Square pits were dug using the approach outlined by Johnston and Slavich (2003). To take into consideration the square shape of the pit, the shape factor outlined by Boast and Langebartel (1984) was used which allowed for the calculation of a discrete hydraulic conductivity value. Analysis of the slug tests was completed using the Bouwer and Rice (1976) methodology which calculates the shape factor using empirical data to determine the effective radius of influence that the removed slug of water has. For the purpose of calculations, it was assumed that the impermeable layer was at the base of the auger hole meaning that vertical flow into the base of the hole was considered negligible. Furthermore, since no screen was used for the calculations the portion through which water enters the well was set as the total depth of water within the hole. Further detail is provided in Section A3.2.

A scatter chart comparing the pit bail and slug test method hydraulic conductivity values is shown in Figure B.5. Results indicate that there is no correlation between the hydraulic conductivity measured between the two techniques. It is likely that this is due to a number of reasons including:

- The general heterogeneity of soils on coastal floodplains means two data points even directly next to each other can display significant differences (e.g. if one intersected a macropore);

- Slug test data is biased due to macropores resulting in significantly increased or decreased hydraulic conductivity in comparison to the average;
- Slug tests generally penetrate through more than one soil horizon which impacts on the overall hydraulic conductivity of the profile; and
- Slower removal (or bailing) of water in the pit bail method results in discrepancies when calculating the hydraulic conductivity value.

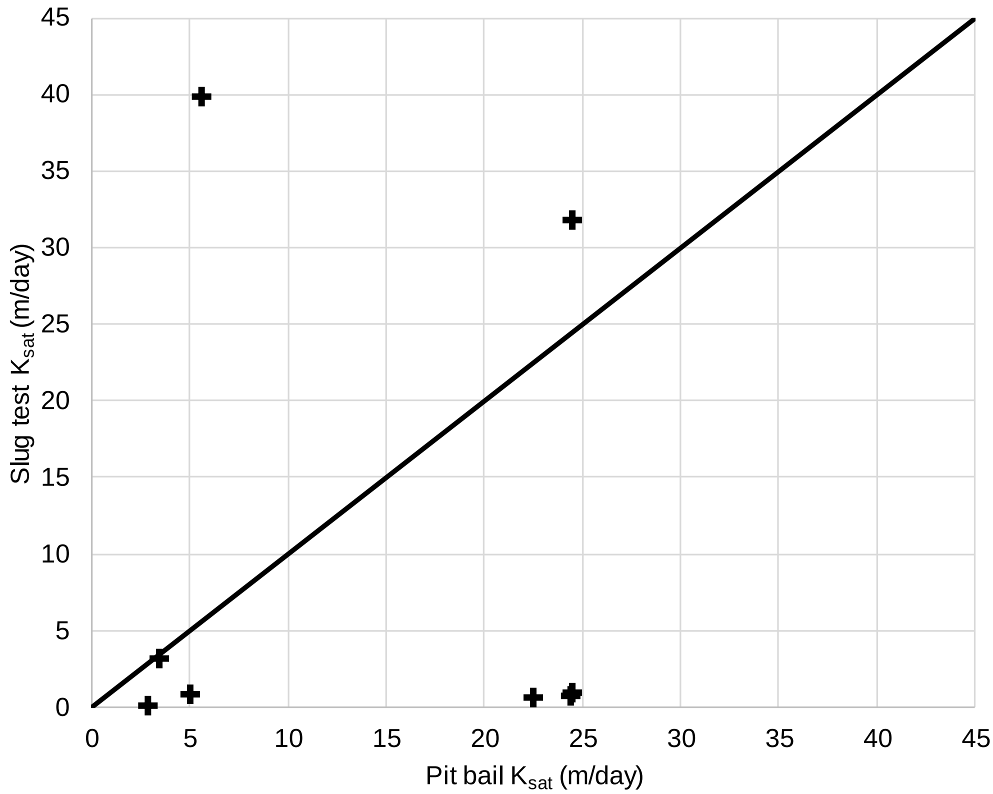

Figure B.5: Comparison of saturated hydraulic conductivity for measurements calculated using the pit bail and slug test methods immediately adjacent to each other

These results suggest that the methods are not comparable, however, this does not mean that hydraulic conductivity data obtained using the slug test method is unreliable. Indeed, extensive pit bail tests completed by Johnston et al. (2009) showed that within similar catchments the standard deviation of hydraulic conductivity using this method can be up to 130 m/day. This is using the same Boast and Langebartel (1984) technique to determine hydraulic conductivity for square or rectangular pits. The discrepancies shown in Figure B.5 fall well within this level of deviation with the range of the differences between slug test and pit bail methods found to be a maximum of 34.3 m/day.

To further supplement hydraulic conductivity data in situations where the water table was at significant depth below the ground surface (approximately 3 m or more), towards the end of field investigations the inverse auger hole method was used. A total of 24 inverse auger tests were completed (in comparison to 111 slug tests and 10 pit bail tests) during field investigations as a part of this study. This was implemented using a similar methodology to the slug test except water was introduced to the auger hole rather than being removed and the hydraulic conductivity value was calculated as outlined by van Hoorn (1979) (see Section A3.2). Due to the nature of this test, no direct comparisons to the other methods for obtaining hydraulic conductivity values was possible. Instead, the range of values for the inverse auger test has been compared with those from the pit bailing method and slug test in Figure B.6. This demonstrates that the inverse auger method is comparable to the slug test method.

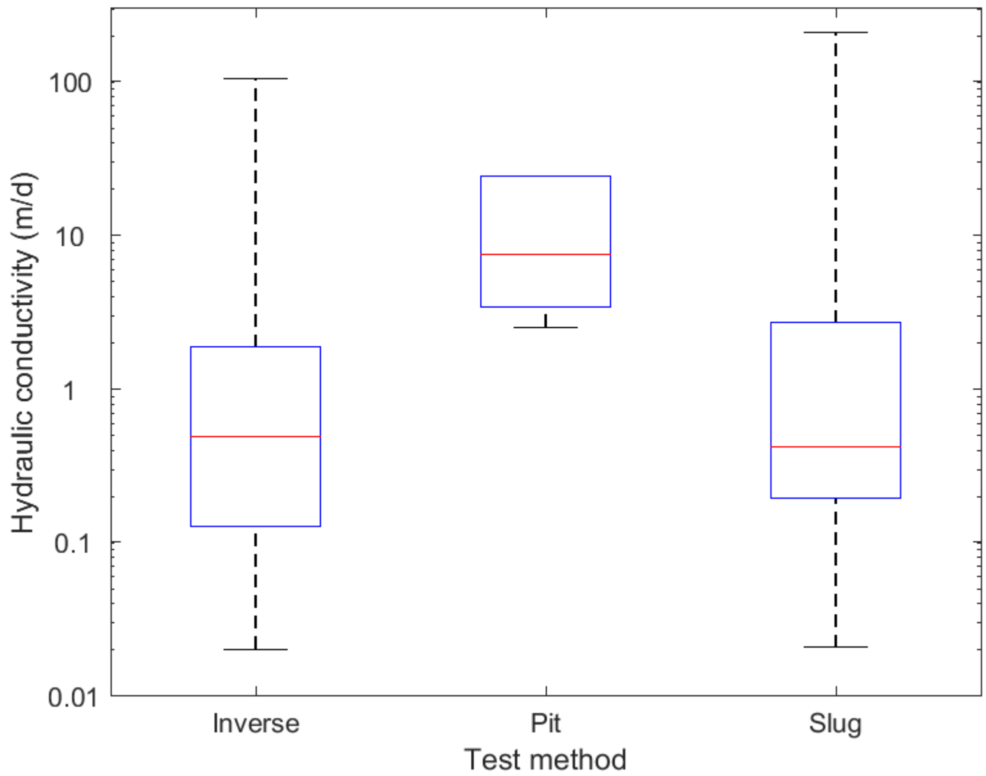

Figure B.6: The median measurement (red line), 25% to 75% range of measurements (blue box) and total range of measurements (black whiskers) for each of the different test methods for saturated hydraulic conductivity across five NSW floodplains. Note the number of measurement values for each method is 24, 10 and 111 for the inverse, pit and slug test, respectively

When comparing Figure B.5 and Figure B.6 it can be seen that the slug test and inverse auger methods, on average, produce a lower hydraulic conductivity when compared to the pit bail method. It is unclear whether this is due to the test methodologies (such as different target soil horizons) or whether it is due to natural variation due to the limited number of pit bail tests completed. When compared further with data from Johnston et al. (2009), which includes a range of values from 148 pit bail tests, the information suggests that the variation in test methodologies is the main driver in differing hydraulic conductivity measurements. This is shown in Figure B.7 which indicates that for coastal floodplains the hydraulic conductivity values tend to be between 2 - 40 m/day for the pit bail method in comparison to 0.02 - 5 m/day for the slug test method (see also Figure B.6). Note that the hydraulic conductivities presented in Figure B.7 have been calculated using the Bouwer and Rice (1983) method for round pits which tended to have slightly lower hydraulic conductivity values compared to the Boast and Langebartel (1984) method and would exacerbate the differences between the measurement methods.

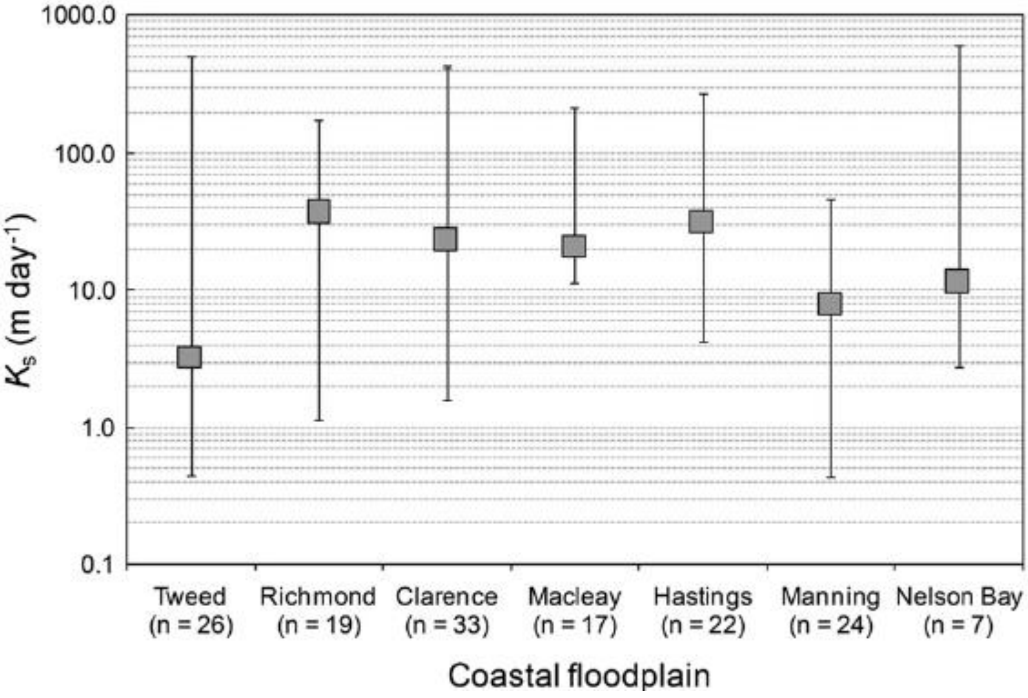

Figure B.7: The median (box) and range (whiskers) for the saturated hydraulic conductivity values measured across different NSW floodplains using the Bouwer and Rice (1983) calculation technique (from Johnston et al., 2009)

Generally, the slug test and inverse auger method target soil horizons at a greater depth compared to the pit bail method. This is a likely explanation for the differences between these test methods as deeper soil horizons tend to have a lower hydraulic conductivity (Dent, 1986). The result of including slug test and inverse auger method data for calculating the groundwater factor within the catchment prioritisation approach is that the acid export rates will be calculated across the entire soil profile which is contributing to acid export.

B5.2 Hydraulic conductivity selection

During the data collection field campaign, it was observed that often the water table within the sample hole was below the mean low water spring (MLWS) tide level of nearby waterways. This was due to the ongoing drought conditions that were prevalent at the time of data collection (from August 2019 to March 2020). The result of this was that sometimes the hydraulic conductivity measured using the slug test method was in a soil layer that is unlikely to contribute to export of acid via horizontal water movement. For this reason, it was decided that only hydraulic conductivity measurements where the water table was above the MLWS tide level would be used. Using this criterion, the hydraulic gradient from the measurement location to the estuary is only included for measurements within soil horizons that could facilitate acid export to the estuary. By using data from five separate NSW coastal floodplains (Tweed, Richmond, Clarence, Macleay and Hastings), Figure B.8 shows that reducing the dataset in this way does not have a discernible impact on the distribution of results despite the fact that instead off all 111 slug test measurements being used only 46 measurements where the water table was measured above MLWS tide levels, were used. This indicates that the data still represents the full section of the soil profile that is contributing to acid export.

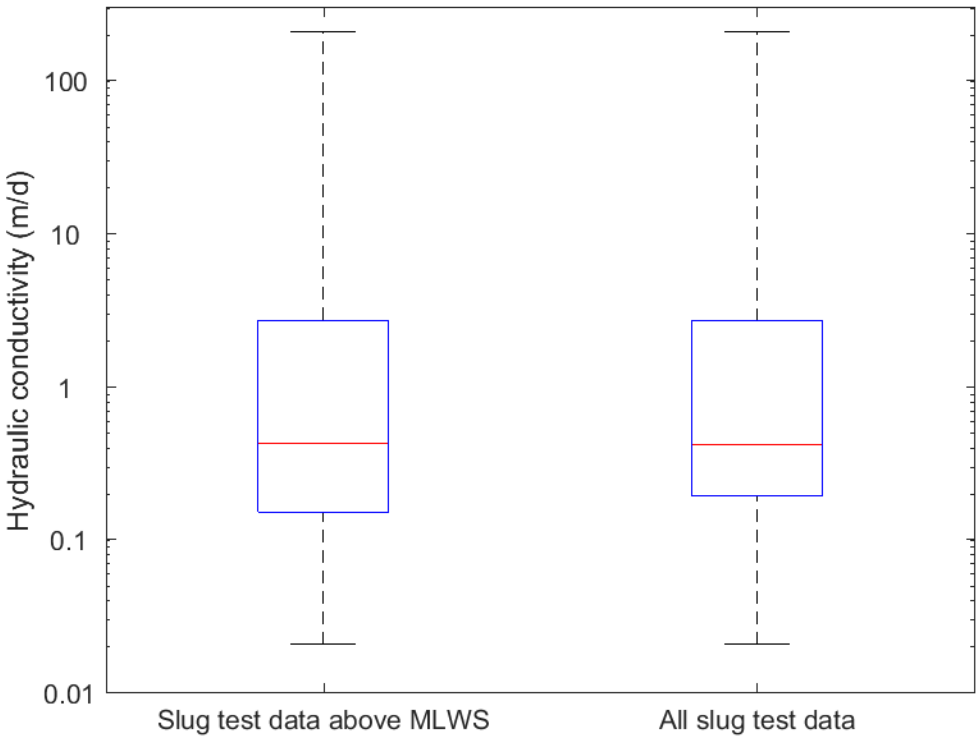

Figure B.8: The median measurement (red line), 25% to 75% range of measurements (blue box) and total range of measurements (black whiskers) across five NSW floodplains for slug test data where the water table was above MLWS tide (46 measurements) and for slug test data for all water table levels (111 measurements)

Johnston et al. (2009) suggests that methods such as the slug test do not accurately represent features in the soil profile such as macropores. While this is correct, it should also be noted that the pit bail method only represents the hydraulic conductivity of soil horizons closer to the surface, which are known to have a higher hydraulic conductivity, and does not account for the vertical variability of floodplain soils. Indeed, each method has a number of benefits and shortcomings for the calculation of hydraulic conductivity, particularly in relation to the overall variability of floodplain soils. To account for the vertical and horizontal variability of hydraulic conductivity in coastal floodplain soils it was decided that in addition to the pit bail method, as was used in the methodology for previous coastal floodplain catchment prioritisations (Glamore and Rayner, 2014; Glamore et al., 2016a), the slug test method when the water table is above the MLSW tide level and the inverse auger method would be used to calculate hydraulic conductivity. Furthermore, as proposed by Johnston and Slavich (2003), instead of a discrete hydraulic conductivity value being used, a categorisation from extremely low to extremely high was used as per Table B.4 whereby the overall variability of hydraulic conductivity is captured.

Table B.4: Modified risk classification for approximate rates of saturated hydraulic conductivity (modified from Johnston and Slavich, 2003)

Risk Classification	Approximate Ksat (m/day)
Extremely high	>100
High	15 to 100
Moderate	1.5 to 15
Low	<1.5
Extremely low	~0