Lower Shoalhaven River Drainage Remediation Action Plan

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Executive Summary

The Shoalhaven River floodplain has extensive acid sulphate soil deposits. These soils produce highly acidic water that appears in the sediments and in nearby flood mitigation drains. The majority of these drains are managed by Shoalhaven City Council and include infrastructure such as levees, floodgates and culverts.

This report describes landscape management issues and remediation options associated with acid sulphate soils in flood mitigation drains of the Broughton Creek and Crookhaven River floodplains. The report details various strategies that could be used to improve water quality in the flood mitigation drains and the adjoining drainage sub-catchments which will lead to improved water quality in the waterways.

An evidence-based approached was applied to rank the drainage sub-catchments using field data. An action plan is provided or each of the prioritised drainage sub-catchments. Immediate and long-term action plans are presented and the influence of sea level rise is discussed. It is important to note that the draft action plans presented require detailed consultation with local landholders prior to commencing on-ground works.

Acid sulphate soils are considered one of the worst soils in the world. These soils were formed in estuarine floodplains 4,000 to 6,000 years ago when the ocean levels were higher and present day floodplains were tidal backswamps. When wet these soils are harmless, however when exposed to atmospheric oxygen the soils quickly acidify creating high concentrations of sulphuric acid and heavy metals. Acid sulphate soils impact fish, oysters and other aquatic flora and fauna as well as man-made structures such as culverts and bridges. The Shoalhaven and Crookhaven River floodplains have been categorised as having high risk acid sulphate soils.

Drainage of the Shoalhaven and Crookhaven River floodplains has been ongoing since 1840. The existing drainage system and infrastructure has largely been in place since the 1970s. Research into the impacts and effects of acid sulphate soils in the Broughton Creek catchment commenced in 1994. While initial research focused on limiting acid production, recent studies have investigated remediation strategies for acidic groundwaters and adjacent flood mitigations drains. Previous investigations indicated that the most acidic conditions were located along Broughton Creek with limited acid impacts recorded in the Crookhaven River floodplain. As such, during 2001 the Broughton Creek floodplain was recognised as a major acid hotspot in NSW.

Research has shown that it is very difficult to limit further acid production once the soil is acidified. Since the majority of the floodplain soils are already acidic, most remediation strategies focus on (i) containing the acid within the soil, (ii) neutralising the acidic water onsite before it is discharged into the estuary, or (iii) encouraging low oxygen conditions onsite. On-ground project examples elsewhere in NSW have effectively reduced acid drainage and most projects include a combination of remediation strategies.

As resources are limited for on-ground works, it is necessary to determine the highest priority sites for remediation. For this study an evidence-based prioritisation method was used to rank the flood mitigation drains and larger drainage sub-catchments of the Broughton Creek and Crookhaven River floodplains. The method used field data on floodplain drainage, catchment characteristics, acid concentrations, soil parameters, asset condition, sensitive receivers and drainage capacity to objectively rank the 39 drainage sub-catchments identified. The top 10
highest priority drains were all located in the Broughton Creek catchment. The top 6 worst affected drains contribute over 80% of the total acid being discharged into the estuary.

Action plans were developed for each of the 39 drainage sub-catchments. These plans outline the recommended on-ground works required to reduce or eliminate acid drainage from the site. The actions plans recommend one option or a combination of remediation options previously detailed, including immediate on-ground recommendations (5-10 years) and longer term (>10 year) plans for each site. Approximate costs for each remediation strategy are also provided.

To address potential issues over the next 35-70 years, the impact of climate change, particularly sea level rise, was examined. For each drainage sub-catchment the impact of rising sea levels as predicted for 2050 and 2100 were assessed. This analysis calculated the effect of changed tidal levels on backswamp connectivity, levee overtopping, infrastructure elevations and reduced drainage. While the forecasted increases in high tides are a concern in some regions, the greater issue for land management is elevated low tides which will reduce drainage from low-lying backswamps. While this will impact agricultural productivity, it is likely to reduce acid drainage. The Numbaa Swamp and Saltwater Swamp on the Crookhaven River floodplain, and the Far Meadow and Jaspers Brush Swaps on the Broughton Creek floodplain are areas of particular concern highlighted in the report.

The results from this study, including action plans, require detailed stakeholder consultation prior to implementation on-ground. Several of the recommended strategies are different to existing land practices but detailed engineering plans or changes to land tenure could result in win-win outcomes. Results from the landholder surveys suggests that training in acid sulphate soil management and remediation techniques would be beneficial and may assist in developing long term outcomes.

![Figure EX1. Schematic of drainage sub-catchments (a) and priority rankings (b) developed in the study.](image-url)
1. Introduction

Acid sulfate soils (ASS) lie beneath the majority of eastern Australia’s coastal floodplains. The Shoalhaven River floodplain contains extensive areas of acid sulfate soils, with the Broughton Creek floodplain nominated as an acid hotspot (DECC, 2008) (Figure 1.1). According to the acid sulfate soil risk maps described by Naylor et al. (1995), approximately 6,600 hectares of land in the Lower Shoalhaven River floodplain has a high risk of acid sulfate soil.

The Broughton Creek and Crookhaven River catchments are low-lying agricultural floodplains with extensive man made drainage networks that discharge runoff via one-way floodgates to the tidal estuary (Figure 1.2). Construction of the drainage infrastructure in the Lower Shoalhaven River floodplain began in 1840 with Berry’s Canal. The first floodgates were installed in 1872 and were widely implemented during the early 20th century when 210 km of drainage channels were constructed. Since then, additional drainage infrastructure has been constructed across the floodplain, including smaller backswamp drainage canals and the deepening and straightening of existing drains.

The network of main flood mitigation drains, levees and structures is the responsibility of Shoalhaven City Council (Council). Main flood mitigation drains managed by Council are those that discharge immediately into the open estuary. An extensive network of backswamp drainage channels are not managed by Council, but are the responsibility of local landholders. Figure 1.2 presents Council flood mitigation drains along with all other non-Council drains.

The construction of deep (> 0.5 m) drainage systems on coastal floodplains increases the generation and export of acidity from ASS (Johnston et al., 2003). The discharge of acidic and deoxygenated runoff is exacerbated by floodgates, which prevent tidal waters from inundating low-lying areas of the floodplain (Glamore, 2003). Floodgates also maintain low drain water levels, creating a strong hydraulic gradient between the groundwater and the drain. This results in the transport of acid from the groundwater to the drainage channel and onwards to the estuary.

Within estuaries the tide, salinity and freshwater flows change daily. During dry times, acidic plumes are naturally neutralised, or ‘buffered’, by bicarbonate (HCO₃⁻) diffusing into the estuary from the ocean. However, rainfall events can flush the estuary of salinity and bicarbonate. During these periods, acidic runoff contaminates the estuary, often resulting in fish and oyster kills. At these times, individual acidic plumes from separate drains can join to form larger plumes in the estuary. The size and impact of the individual plumes is dependent on local topography, rainfall and soil acidity (Rayner, 2010).

Acid sulfate soil drainage has been identified as a significant contributor to poor water quality in the Shoalhaven estuary (Sammut and Melville, 1994; Pease, 1994; Blunden, 2000; Glamore, 2003; Morgan et al., 2005; Winberg and Heath, 2010). This process has resulted in impacts to the local shellfish, prawning and fishing industries (Winberg and Heath, 2010; Nash and Rubio-Zuazo, 2012). Shoalhaven City Council (2002) and Morgan et al. (2005) outlined areas of the Broughton Creek and Crookhaven floodplains where acid sulfate soils and associated impacts have been observed. Broad scale management options for selected areas were previously proposed, however further technical scoping and assessment of remediation benefits on a catchment wide scale have not been investigated.

The purpose of this study was to develop floodplain priority action plans for acid sulfate soil affected drains across the catchment. Although the overall outcome was to produce remediation
Figure 1.2: Shoalhaven River floodplain drainage and waterways
action plans for Council managed flood mitigation drains, all floodplain drains were included in the analysis to ensure all acidic areas, potential or actual, were identified. To date, remediation plans for the Shoalhaven River floodplain have been focused on individual drains, not catchment wide/floodplain characteristics. In contrast, this study assessed historical evidence and designed plans for each sub-catchment drainage area based on drain characteristics, acid contributions and sensitive ecological receivers using field data. This strategic approach to floodplain planning enables key sites to be targeted now and into the future.

The study methodology included:
- Review of existing floodplain on-ground works and research for ASS;
- Assessing floodplain hydrology and drain acid contribution;
- Conducting an analytical assessment of floodplain priorities to identify potential high impact remediation sites;
- Reviewing key ecological features in the Shoalhaven estuary;
- Reviewing and surveying floodplain asset condition;
- Assessing climate change vulnerability; and,
- Consulting with stakeholders to determine their level of training and willingness to adopt proposed management strategies for ASS.

The integration of existing assets, ecology, landholders, and management plans as presented in this report provides the basis for acid sulfate soil remediation actions in the Shoalhaven River estuary. Climate change vulnerability was also identified via calculations of sea level rise.

Background information, study outcomes and recommendations are presented in the main body of this report. In brief:
- Chapter 2 outlines the drainage history of Lower Shoalhaven River and introduces key acid sulfate soil concepts;
- Chapter 3 details the distribution of acid sulfate soils on the Broughton Creek and Crookhaven River floodplains;
- Chapter 4 presents the methodology used in this investigation to calculate the priority acid drainage areas;
- Chapter 5 summarises the various short-term and long-term remediation strategies;
- Chapter 6 presents drainage areas in ranked priority, and the individual short-term and long-term action plans for each drain.
- Chapter 7 discusses climate change impacts on floodplain drainage; and,
- Chapter 8 lists recommendations for moving forwards.

Detailed datasets and analyses of each priority factor are presented in the report appendices. All data values and sources used to determine drain remediation priorities and action plans have been included where possible. The attached appendices are:
- Appendix A: Technical literature review
- Appendix B: Floodplain drainage assets
- Appendix C: Hydrology
- Appendix D: Acid sulfate soil distribution
- Appendix E: Hydraulic conductivity distribution
- Appendix F: Water quality
- Appendix G: Sensitive environmental receivers
- Appendix H: Landholder survey
- Appendix I: Application of prioritisation methodology

Original data sources should be consulted for further information and clarification.
2. Background

This chapter outlines the geological and modern drainage history of the Lower Shoalhaven River floodplain and presents the fundamentals of acid sulfate soil generation, mobilisation, export and environmental impacts. Understanding these processes is critical to interpreting available data, identifying of high acid risk areas, and implementing effective remediation strategies.

2.1 History of the Shoalhaven River floodplain

The Shoalhaven River is located 160 km south of Sydney on the tectonically stable south coast of New South Wales (NSW). The river drains a catchment of 9,260 km$^2$ and in its lower reaches incises into Permo-Triassic sandstone and siltstones of the Sydney basin. The lower catchment consists of a main river channel with floodplains on the north and south riverbanks. The northern floodplain drains the Broughton Creek catchment, stretching from Berry to Bolong in a north to south orientation. The Crookhaven River floodplain encompasses the southern side of the main Shoalhaven River channel stretching from Nowra to Greenwell Point in an east to west orientation. Both the Shoalhaven River and Broughton Creek are highly channelized and are considered to have almost completely in-filled the pre-existing estuarine embayment (Roy, 1984). The estuarine alluvial plains that characterise Broughton Creek and Crookhaven floodplains presently support pastureland for various agricultural activities (Woodroffe, 2000).

The evolution of the Shoalhaven River system, from early stages of development to its current mature stage, resulted in increases in both the tidal range and tidal amplitude throughout the estuary. According to Roy (1984), estuary infilling creates sinuous channels with smooth, level banks promoting the attenuation of tides and enhances mixing within the water column. Broughton Creek has tidal fluctuations with a range greater than 1.0 m up to Berry, more than 20 km from the mouth of the Shoalhaven River (Pease, 1994). In the estuarine reaches of Broughton Creek, salinity varies substantially due to floodwaters and intermittent openings of Shoalhaven Heads (Glamore, 2003). Since 1822, much of the flow of the Shoalhaven River has been diverted through Crookhaven Heads, via Berry’s Canal (Bayley, 1975).

The modern drainage history of the Shoalhaven River floodplain began in the mid-19$^{th}$ century and has been continually modified until the present day. Significant floodplain drainage works undertaken throughout the 20$^{th}$ century have mitigated flood effects and saline intrusion onto the Broughton Creek and Crookhaven River floodplains. Whilst constructed works were initially managed by landholders, management of flood mitigation infrastructure became the responsibility of Shoalhaven City Council following completion of the drainage works. Key events and works undertaken on the Broughton Creek and Crookhaven River floodplains include:

- 1840: Construction of Berry’s canal began.
- 1872: First floodgates installed to restrict saltwater that threatened farms on the Crookhaven Floodplain.
- 1879: Crookhaven Heads dredged by bullock teams to provide improved drainage and lessen flood damage.
- 1901: 210 km of drains with floodgates constructed on Broughton Creek floodplain
- 1949: Majority of major drainage works completed.
- 1965 to 1972: Additional deepening, straightening and floodgating of drains in accordance with flood mitigation policy funding.
- 1991: First evidence of acid drainage identified when an 8 km stretch of Broughton Creek experienced a ‘black water’ event where the water turned clear (August, 1991).
- 1992: Second large acid event observed (February, 1992)
A schematic of floodplain evolution indicating the influence of extensive drainage works is presented in Figure 2.1.

**Figure 2.1: Schematic of floodplain evolution following European settlement**
2.2 Background to Acid Drainage

2.2.1 What are Acid Sulfate Soils?

Acid sulfate soil is the common name of soils and sediments containing iron sulfides, the most common being pyrite (FeS$_2$) (DERM, 2009). Acid sulfate soils (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, oxidation occurs due to climatic, hydrological or geological changes. The oxidised layer produces sulfuric acid and is termed an actual acid sulfate soil (AASS).

2.2.2 Formation

ASS are predominantly located within 5 metres of the surface and are found extensively on Australia’s coastline (DERM, 2009). Pyrite is formed in reducing environments where there is a supply of easily obtained decomposed organic matter, sulfate, iron and reducing bacteria (Figure 2.2). The deposition of these sands and muds occurs in low-lying coastal zones characterised by low energy environments, such as estuaries and coastal lakes. Acid sulfate soils that are of concern on Australia’s coastal floodplains were formed during the past 10,000 years (the Holocene epoch).

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

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

Figure 2.2: Pyrite formation (NRM, 2011)
2.2.3 Acidification

The pH scale (Figure 2.3) 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 pH 5 soil and 1,000 times more acidic than a pH 7 soil (QLD NRM, 2011).

![pH scale](source: QLD NRM, 2011)

Potential ASS are oxidised to form Actual ASS by clearing of coastal land for agriculture, resulting in extensive drainage and a lower groundwater table, introducing gaseous oxygen to the soil matrix. When pyrite is exposed to atmospheric oxygen, the iron sulfides react to form sulfuric acid and numerous iron cations ($Fe^{2+}, Fe^{3+}$). 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 2.4). Depending on the pyrite content of the soil, acidity levels can fall below pH 4.5. At this pH, iron and aluminium concentrations become soluble and can greatly exceed environmentally acceptable levels.

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

The construction of deep drainage channels drains water logged and flood prone areas, enabling agricultural practices. However, in an estuarine floodplain, drainage channels also allow tidal water to potentially inundate pasture and groundwater. To reduce tidal inundation, one-way floodgates are commonly installed. The tidal floodgates restrict saline intrusion, and may provide livestock with a source of drinking water (Figure 2.5).

In areas affected by acid sulfate soils, deep drainage channels and one-way floodgates combine to increase acid sulfate soil oxidation, create acid reservoirs, and restrict neutralisation of acid by tidal waters. Floodgates and drainage structures are usually designed to maintain drain levels at the low tide mark to drain backswamp areas and reduce pasture water logging (Glamore, 2003). Since the pyritic layer is normally at the mid to high tide level, by maintaining drain water elevations lower than the pyritic layer (such as the low tide elevation), one-way floodgates increase the gradient between the drain water and the surrounding acidic groundwater (Glamore, 2003).
The difference in hydraulic gradient created by the tidal floodgates promotes the transport of oxygen into sulfidic subsoil material and the leaching of acid by-products into the drain (Blunden, 2000). This is particularly evident following large rainfall events when floodgates quickly establish low drain water levels and the groundwater table is elevated (Glamore and Indraratna, 2001).

The depth of a drain (or drain invert) in relation to the acidic layer influences the potential for 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 mobilisation.

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

2.4 Acid Discharge

While drain water can be highly acidic on a day-to-day basis, large plumes 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.

During dry conditions salinity concentrations increase with decreasing catchment runoff. Saline or brackish water contains natural neutralisation agents, buffering any acid discharged.
Typically, low volumes of acid are discharged during these dry periods, and the natural buffering capacity of the open estuary is high, creating low acid risk conditions (Figure 2.6).

During or immediately following a flood event, 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 2.7).

After the floodwaters have receded, tidal levels slowly re-establish. During this dry period, floodplain pastures are saturated and groundwater levels remain elevated, resulting in a steep gradient between drain water levels and the surrounding groundwater. This process mobilises acid from the soil towards drainage channels and receiving waters (Figure 2.8). 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 2.9).
Wet Periods
- Freshwater dominant
- Acid flow high, low concentration
- Limited tidal prism
- Highly diluted

Figure 2.7: Wet periods characterised by high dilution

Figure 2.8: Influence of one-way floodgates on groundwater elevation under normal (top) and flood (bottom) conditions (Glamore, 2003)
2.5 Environmental Impacts

The discharge of acidic plumes with low pH and high concentrations of soluble metals can have devastating impacts on the environment. Acid plumes can be compounded by multiple drains combining in the open estuary to form a 'super-plume’. Coupled with detrimental environmental impacts are economic losses due to the impacts on aquatic (i.e. oyster, prawns etc.) and terrestrial (i.e. reduced agricultural production) industries.

The NSW Department of Environment and Climate Change (DECC, 2008) (now NSW Office of Environment and Heritage (OEH)) 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.

Asao (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 oxyhydroxide 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.

**KEY POINTS FOR ACID SULFATE SOILS**

- Pyrite (acid sulfate soil) is a natural soil, which when left undisturbed, does not produce acid;
- Acid is naturally buffered by bicarbonate (present in seawater);
- Drainage of soil containing pyrite results in pyrite oxidation and acid formation with a pH below 4;
- Deep drainage channels constructed in acid sulfate soils increase acid export;
- A by-product of acid production is high concentrations of iron and aluminium;
- One-way floodgates maintain low drain water levels which results in a large gradient between the drain and surrounding groundwater, leaching acidic water into the drain;
- Acid drainage is greatest following flood events; and,
- Acid plumes with high metal content are highly toxic to aquatic flora and fauna.
3. Acid Sulfate Soils in the Lower Shoalhaven River Estuary

Mapping of acid sulfate soil distributions in the Shoalhaven was undertaken by the NSW Department of Agriculture in the 1970s (Read, 1974). It was not until two large acid discharge events in 1991 and 1992 that acid sulfate soils in the Shoalhaven River floodplain were further investigated (Woodroffe, 2000). Detailed mapping by the former Department of Land and Water Conservation generated acid sulfate soil risk maps for much of the state, including the Shoalhaven River Estuary (Figure 3.1). Early work by Pease (1994) highlighted the distribution and severity of acid sulfate soils on the Broughton Creek floodplain. This work coincided with research (White and Melville (1993), Wilson (1995), Sammut (1993), Sammut et al. (1996) and White et al. (1997)) being undertaken on northern NSW floodplains, identifying the environmental impacts of acid discharges on estuaries.

It was not until the NSW Department of Agriculture undertook soil investigations in 2002 and 2006 that pyrite distribution across the Broughton Creek and Crookhaven River floodplains was assessed on a catchment wide scale (Lawrie and Eldridge 2002, 2006). Whilst all the major drainage areas of the Crookhaven River floodplain were investigated by Lawrie and Eldridge (2006), only four acid ‘hot-spots’ were targeted on the Broughton Creek floodplain (Lawrie and Eldridge, 2002).

Acid sulfate soil distributions on the Broughton Creek and Crookhaven River floodplains are summarised below. The depth to the actual acid sulfate soil (AASS) layer on the Broughton Creek and Crookhaven River floodplains is presented in Figure 3.2. The depth to the potential acid sulfate soil (PASS) layer on the Broughton Creek and Crookhaven River floodplains is presented in Figure 3.3. Further information regarding acid sulfate soil distributions, groundwater hydraulic conductivity and discussion of data sources can be found in Appendices D and E.

3.1 Broughton Creek Floodplain Acid Sulfate Soil Distribution

The depth of the AASS and PASS layers, as well as soil chemistry was found to vary considerable across the floodplains although some similarities were observed. Generally, the northern Broughton Creek floodplain is characterised by a sulfidic layer between 0 m and — 0.5 m deep, whereas the southern extent of the floodplain has a deeper PASS layer between —1.2 m and — 1.5 m deep (SCC, 2002).

SCC (2002) reported that the elevation of AASS on northern properties was below — 0.5 m AHD, with some shallower sections at approximately —0.25 m AHD. Due to local topography, these elevations relate to a soil depth to AASS of between 0.9 m to 1.75 m deep. Conversely, properties at the southern extent of the floodplain were observed to have much deeper PASS occurring at/or below —1.35 m AHD, or between 1.85 m to 2.1 m depth. Lawrie and Eldridge (2002) observed the middle area of the Broughton Creek floodplain to have complex vertical distributions of acidic soils. Whilst PASS was observed to occur between —0.25 m and —0.75 m AHD (0.6 to 1.6 m below soil surface), jarosite was observed in the top 50 cm of soil at several locations. The presence of surface jarosite coincided with surface acid scalds.

Data availability identifying actual and potential acid sulfate soils was varied. Whilst some drainage areas of the Broughton Creek floodplain have been investigated in detail, other drainage areas of the floodplain had very limited soil data. All available data sources were consolidated to assess acid distribution on Broughton Creek. Some drainage areas require further soil investigation prior to implementation of any remediation strategy.
3.2 Crookhaven River Floodplain Acid Sulfate Soil Distribution

Soil profile information collected by Lawrie and Eldridge (2006) found strong evidence of acid sulfate material in the following drained areas:

- Worrigee;
- Terara;
- Numbaa; and,
- Saltwater.

In general, the extent of high risk acid on the Crookhaven River floodplain is less than that on Broughton Creek. Subsoil descriptions suggest widespread sulfidic material, however evidence of aeration and oxidation is less common (Lawrie and Eldridge, 2006). Soil profile data analysed by Lawrie and Eldridge (2006) indicated that there was some variation in the elevation of the sulfidic layer across each drained area, making it difficult to predict the amount of stored acid within the soil.

The topography of the Crookhaven River floodplain is generally lower than the northern Broughton Creek floodplain. Subsequently, groundwater levels are closer to the surface creating a narrower AASS layer than Broughton Creek soils. The northern Crookhaven River floodplain features particularly high groundwater levels, and deeper potential acidic layers, lowering the risk of acid production and discharge.

Data used to determine actual and potential acid sulfate soil distributions on the Crookhaven River floodplain was sourced from Lawrie and Eldridge (2006). The investigations undertaken by Lawrie and Eldridge (2006) specifically targeted acid soil and can therefore be used with confidence. Although the sampling undertaken had a low spatial resolution, the full floodplain was investigated and all Crookhaven drainage areas were assessed. Further soil investigations may be required for some drainage areas prior to implementation of any remediation strategy.

### ACID SULFATE SOIL DISTRIBUTION

- Actual and potential acid sulfate soils are widespread across the Broughton Creek floodplain;
- The depth to acid soil layers on the Broughton Creek floodplain is generally
  - Deep in the southern area of the floodplain;
  - Shallow in the central reaches; and,
  - At a moderate depth in the northern extent.
- The extent of actual acid sulfate soils on the Crookhaven River floodplain is less than that of Broughton Creek;
- A shallow groundwater table across the Crookhaven floodplain has maintained pyrite as a potential acid source, not an actual acid source;
- The Crookhaven River floodplain generally contains a lower acid risk.
Figure 3.1: NSW Government acid sulfate soil risk map
Figure 3.2: Depth to Actual Acid Sulfate Soil layer
Figure 3.3: Depth to Potential Acid Sulfate Soil Layer
4. Drain Prioritisation Methodology

Identifying and prioritising the remediation of acid drainage areas that will provide the greatest environmental benefit is the overall aim of this project. Identifying the magnitude of existing (or potential future) environmental impacts due to ASS of each drainage unit is critical in designing an objective and evidence based action plan. This chapter outlines the key factors included in the proposed prioritisation strategy. It also provides a brief discussion on risk management and then summarises the key components that were applied to generate the action plans (provided in Chapter 5). Detailed descriptions of each variable are provided in Appendix I.

A multi-criteria analysis methodology is often applied to risk based assessments. Analysis and combination of the contributing factors were combined to produce an acid risk for each drainage sub-catchment; enabling drainage areas to be prioritised for remediation. A similar methodology has been previously applied to assess fire risk (Vadrevu et al., 2010; Chen et al., 2003), flood risk (Meyer et al., 2007; Raaijmakers et al., 2008; Meyer et al., 2009), landslides (Abella and Van Westen, 2007), earthquake vulnerability (Rashed and Weeks, 2003), and a wide range of other environmental decision applications (Kiker et al., 2009). NSW DPI (2007) prioritised floodgate modification across NSW based on upstream channel length and habitat.

There were 38 Council maintained flood mitigation drains and one non-Council floodgated drain (upper Crookhaven Creek) identified across the Broughton Creek and Crookhaven River floodplains. Each drain has a range of factors that contribute to its ability to generate and produce acidic discharges. Following research recently undertaken by Glamore et al. (2012), key parameters were identified as mechanisms for acid impacts. These factors are:

- Drainage
- Catchment hydrology
- Asset condition
- Groundwater (hydraulic conductivity)
- Water quality
- Acidic Soils

For this study, sufficient data was gathered for each factor to generate a risk matrix. This information was then normalised to compare and rank drainage sites against each other. A summary of the risk as applied to each factor is outlined in Figure 4.1. Other factors not directly related to acid generation were also considered. Additional issues which were incorporated when designing short and long-term of remediation strategies were:

- Sensitive Receivers
- Climate change
- Landholder support
4.1 Drainage

The extent and capacity of drainage across a sub-catchment influences the acid export potential of an area. The longer the total network of drains across a floodplain, the greater the potential for acid sulfate soils to be drained and oxidised. This is referred to as the ‘drainage density’. A higher drainage density results in increased risk and subsequently a higher priority ranking.

Drain dimensions (width and depth) are also critical factors with respect of acid oxidation and mobilisation. A wide drain that is deeply incised into the acidic soil layers (AASS and PASS) poses a greater potential environmental impact than a narrow drain with a higher invert.

Drain dimensions and condition are provided Appendix B.

4.2 Catchment Hydrology

The quantity of acidic water discharged from a drain is determined by the drainage catchment area. The greater the drained catchment area, the greater the flow in comparison to other drainage areas. Flow, in combination with poor water quality, provides the pollutant flux (flux = discharge x concentration) from a drain. Generally speaking, a drain with a higher flow has the potential to discharge a higher pollutant flux, having a greater impact on the environment.

Catchment flows for this study were generated using the Australian Water Balance Model v2002 (AWBM) (Boughton, 2004). The catchments for Broughton Creek and Crookhaven River floodplains were divided into steep catchments and flat floodplain catchments. Each drain sub-catchment was delineated using LIDAR data and divided into steep and flat where appropriate. The 5 m AHD contour was used to divide steep and flat areas. An area of catchment currently gauged by the NSW Office of Water was used to calibrate the AWBM model for steep catchments. Auto-calibration was used for the low, flat floodplain areas of the catchments. Ninety-nine (99) years of daily rainfall data at Berry was used to create a prediction of daily
discharge for each drain. Daily flows were analysed to produce percentile exceedance statistics for each drain to enable a normalised ranking. The 98th percentile exceedance flows were used to rank each drain.

A full description of sub-catchment modelling methodology and predicted flow statistics is presented in Appendix C.

4.3 Asset Condition

The condition of Council’s flood mitigation assets was surveyed by Shoalhaven City Council between 2010 and 2011. Both drain and structure condition was included in the survey. Asset condition was summarised as:

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

When assessing floodgate structures, condition reporting was only undertaken on the ability of a floodgate to restrict tidal intrusion and maintain efficient drainage. If a floodgate had been previously modified for an auto-tidal gate, the condition of the auto-tidal gate was not surveyed. A survey by SCC and WRL in July 2013 showed that all auto-tidal gates except P3D5G1 installed in Broughton Creek are no longer functional, or were never commissioned or are in poor/very poor condition.

Asset condition survey for all drains and structures is detailed in Appendix B.

4.4 Landholder Willingness

Landholder willingness is a major component of the prioritisation processes. Although interim (short-term) remediation strategies are aimed at minimal disturbance to the landholder and agricultural practices, the majority of long-term remediation strategies involve changing of current land use practices of a portion or all of a drainage area. A willing landholder greatly influences the potential remediation strategy that is achievable, particularly in the long-term.

Existing land productivity also influences potential future land management strategies. Some areas have high soil salinity from previous natural tidal inundation resulting in poor agricultural yields. Other agricultural areas are extremely low lying (below 0 m AHD) and have a history of poor drainage and extended inundation. These areas are candidates for changing land use practices whereby poor quality land is utilised for wet pasture management or transformed to a natural wetland or saltmarsh system. Future risk to climate change and sea level rise may also influence landholder willingness to vary existing land use management strategies.

A survey of landholder knowledge regarding acid sulfate soils and willingness to adopt various remediation strategies was undertaken using a survey distributed in October 2013. Full results of the landholder survey are not presented in this report due to protection of privacy. Statistical analysis of survey results was undertaken, finding that further education is required to fully inform landholders about acid sulfate soil remediation. Landholders were generally opposed to remediation strategies that impact their existing agricultural practices.

The distributed newsletter, survey, and analysed responses are presented in Appendix H.
4.5 **Groundwater**

The ability of water to flow through the soil matrix is known as the hydraulic conductivity (K) of a soil. A high hydraulic conductivity implies a greater potential groundwater flow rate. On the Broughton Creek and Crookhaven River floodplains, a high soil hydraulic conductivity increases the potential for acid to be transported from the soil into drainage channels and the estuary. Areas with a high hydraulic conductivity are subsequently assigned a high priority. Overall, hydraulic conductivity data is spatially sparse across both floodplains.

Information regarding hydraulic conductivity in the Shoalhaven River estuary is detailed in Appendix E.

4.6 **Water Quality**

Acid discharge events occur after large wet weather events. During dry periods, drain water quality is an indicator of potential acid event discharges, however the measurement of actual wet weather flow, and acid discharge is preferred. Measurement of post-flood discharge and water quality enables the total acid flux of a drain and the contribution of each drain to overall estuarine water quality to be determined.

Following the 1991 and 1992 acid events on Broughton Creek, an intensive water quality monitoring campaign was initiated with regular monitoring at major drains on Broughton Creek until 2001. Since 2001, a reduced number of monitoring locations are maintained.

Wet weather pH measurements were used where possible to rank drain water quality for prioritisation. Where wet weather data was unavailable, dry weather drain or groundwater pH data was used. Catchment modelling was used to determine when wet events occurred and which pH value corresponded to wet weather discharge. A higher acid risk and ranking was applied to larger drainage areas with measured low pH discharges. As pH is a logarithmic measure of hydrogen protons (H\(^+\)), pH values were converted to H\(^+\) concentrations to ensure the acidity of each measurement was correctly included into the priority risk assessment.

Water quality data for each drainage sub-catchment is detailed in Appendix F.

4.7 **Sensitive Receivers**

The proximity of each drainage area to sensitive environmental receivers is an important factor to consider when assessing the benefits of remediation. The Shoalhaven River estuary contains significant environmental and economic values that are impacted by poor water quality and acidic discharges. Some sensitive receivers, such as commercial oyster leases and seagrasses, are located adjacent to the discharge point of several drains and are subsequently highly susceptible to poor water quality.

A range of stationary sensitive receivers in the Lower Shoalhaven River estuary were identified as part of this study including:

- Oyster leases
- Macrophytes
- Endangered Ecological Communities (EEC)
- Riverbank stabilisation projects

These sensitive receivers were mapped and the proximity to each drain determined.
Potential aquatic habitat contained within each drainage area was also considered as part of each remediation strategy. 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 (NSW DPI, 2007; Winberg and Heath, 2010).

Mapping of sensitive receivers and drain proximity is detailed in Appendix G.

4.8 Acidic Soils

The extent of acidic soils across the Broughton Creek and Crookhaven River floodplains is a key component of the priority assessment. The depths to the actual and potential acid sulfate soil layers (AASS and PASS) are critical in identifying acid sources and the potential acid production of drainage areas. Relating acid layer depth to drain invert elevations enables high risk drains to be identified. A drainage area, which is deeply incised into the acidic layers, poses a higher risk for acid generation and mobilisation than a shallower drain constructed through the same acidic layer. Furthermore, the AASS and PASS layer elevation in relation to the low drain water elevation determines the potential acidic groundwater hydraulic gradient. The drain prioritisation process also considered drain width and length when assigning priority rankings based on soil acidity, as a long, wide drain has a greater acid generating potential compared to a short, shallow drain.

Mapping and presentation of acid soil data sources is presented in Appendix D.

4.9 Climate Change

Climate change in the Shoalhaven River estuary is likely to affect land use and flood mitigation management over the next 10 to 50 years. Sea level rise predictions indicate 0.4 m rise in average water levels by 2050 (DECCW, 2009). The impact of sea level rise was assessed across the Broughton Creek and Crookhaven River floodplains as part of this study. As long-term tidal levels increase, individual drainage areas become connected at higher elevations. Subsequently, climate change was assessed on management areas where the interconnectivity of future sea levels is predicted.

The elevation of existing infrastructure (levees, headwalls, and floodgates) was incorporated into the climate change assessment. The headwall elevation of existing structures is generally the lowest point on the Shoalhaven River banks and is the first point of overtopping in many drainage areas. Areas identified as being highly susceptible to sea level rise were given a higher priority for implementation of a long-term remediation strategy. Drainage areas that are likely to be unaffected by climate change in the short to mid-term (10 to 20 years) are logical candidates for implementation of interim remediation strategies.

Although increased high tide elevations are likely to impact the floodplain in the long-term, the major short-term impact will be reduced drainage. This is particularly relevant to low-lying areas where prolonged periods of inundation following wet weather events are expected by 2050. The Crookhaven River floodplain is likely to be worst affected by reduced drainage, with low-lying areas in Terara, Numbaa, Saltwater, Brundee and Greenwell Point. The backswamp areas of the Broughton Creek floodplain at Jaspers Brush Swamp, Back Forest and Far Meadow Swamp will also experience reduced drainage and increased inundation.
Climate change was incorporated into this study by considering both short and long-term impacts on each drainage area. The susceptibility of areas to both saline inundation and reduced drainage was assessed to guide the final remediation action plans. The impact of climate change was applied by characterising climate change susceptibility as:

- High = Significantly reduced drainage
- Medium = Saline inundation/overtopping and/or reduced drainage
- Low = General reduced drainage

Interconnected drainage areas are assessed for sea level rise in Section 8.

**DRAINAGE PRIORITISATION**

A range of environmental factors, or processes, contribute to the risk of acid production from a drainage area. These factors are combined to rank each drainage area in terms of the risk of acidic discharge. These factors are:

- Drainage
- Catchment hydrology
- Asset condition
- Groundwater hydraulic conductivity
- Water quality
- Acidic Soils

Other factors not used to determine acid risk, or drain priority/rank, but utilised to determine appropriate remediation strategies for each drainage area include:

- Landholder willingness
- Sensitive Receivers
- Climate change
5. Remediation Options

A range of short-term (~10 years) and long-term (> 10 years) strategies exist for the remediation of acid affected drains and floodplains. The applicability of each strategy is highly dependent on site specific factors such as; land use, hydraulic conductivity, catchment topography, landholder willingness, acid layer depth, drain condition, tidal amplitude and climate change. Some strategies include interim options for limiting acid production and discharge, whereas other options aim to permanently stop acid production and export. This chapter provides a brief description of short-term and long-term remediation strategies. Further information regarding each remediation strategy and design considerations can be found in the Acid Sulfate Soils Remediation Guidelines for Coastal Floodplains in New South Wales (Talau, 2007).

Approximate costs for the design, construction and implementation, and annual maintenance are provided at the end of this section (Table 5.1).

5.1 Interim (short-term) Remediation Options

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

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

A range of options are detailed below.

5.1.1 Groundwater Manipulation

Installation of weirs in drainage channels reduces the production of acid in the soil (Blunden, 2000). Higher drain and groundwater elevations reduce groundwater drawdown, thereby minimising the hydraulic gradient between groundwater and drainage channels.

Weirs are generally applicable in higher elevation locations on the floodplain where increases in drain water levels do not result in inundated paddocks or decreased agricultural productivity. Lawrie and Eldridge (2002) noted that the impact of weirs on agricultural activity is minimal, and Blunden (2000) found weir installation to be a successful strategy for minimising acid export in the upper Broughton Creek floodplain. The optimal weir crest elevation is dependent on the elevation of the acidic soil layer. Ideally the weir crest elevation is situated at, or above the elevation of the AASS layer. This minimises the potential for lateral flow of acidic water from the ground into the drain (Figure 5.1).

Weirs are often designed to reduce acid export whilst maintaining effective drainage during wet periods. Adjustable weirs are desirable to maintain agricultural productivity following flood periods, while raising the weir crest during dry periods reduces the groundwater hydraulic gradient and minimises acid export. Figure 5.1 shows how a weir reduces acid generation and export.

Talau (2007) listed a number of criteria that need to be considered for successful weir design:

- Suit local conditions;
- Maintain the efficiency of the flood mitigation system;
- Control different water levels;
- Low maintenance and durable;
- Comply with OH&S;
- Be vandal resistant;
- Be cost effective;
- Have landholder approval; and,
- Comply with legislation.

Figure 5.1: Weir implementation before and after
5.1.2 Tidal/Saline Manipulation

One-way floodgates prohibit tidal inundation, maximise pasture drainage, and maintain drain water levels at the low tide elevation. When acid sulfate soils are present, tidal floodgates increase acid discharge and restrict tidal buffering. Floodgate management and/or modification is widely practiced in NSW. Glamore (2003) showed that in the Shoalhaven River Estuary modified floodgates that permit two-way tidal flows significantly improve water quality and generally reduce the impact of acid sulfate soil drainage.

Specific benefits of floodgate modification include:
- Improved drain water quality through flushing and acid buffering;
- Reduced exotic drain vegetation; and,
- Increased fish passage (NSW DPI, 2007).

The extent of tidal restoration of a site is often dependent on site topography, tidal elevations, estuarine salinity and current land management practices. Maintaining tidal waters within the drain so as to not impact agriculture is often desired. Uninhibited tidal restoration is rarely undertaken, except when tidal amplitude is low, or agricultural land use practices are abandoned. The installation of auto-tidal gates permits tidal flushing up to a pre-determined elevation. Maximum inundation elevations are usually dependent on pasture topography of the backswamp.

Figure 6.2 shows how a modified one-way floodgate restores tidal flushing to an acid affected drainage channel.

a)

b)

Figure 5.2: Before and after floodgate modification a) One-way floodgate maintains low drain water levels while b) Modification of floodgate to enable tidal flushing introduces in drain acid buffering and higher drain water levels.
5.1.3 Acid Neutralisation (Liming)

When applied to pyritic soils, lime reacts with the soil to neutralise acidity. Lime is comprised of calcium hydroxide (CaOH) and is often applied directly to pyritic soils as a dry powder. This is commonly undertaken when pyrite levels are low or when pyritic soils are excavated and small scale neutralisation is required. Lime is seldom applied directly to pyritic soil as a broad acre solution due to the large quantities required for neutralisation and difficulties in integrating the lime into clayey soils.

The injection or application of lime to deep or shallow acid affected soils requires large quantities of lime mixed with water to form a slurry to facilitate pumping. Deeper lime injection requires the construction of a borehole network. Large scale application of lime on either the surface or sub-surface of acid affected soil is not a cost effective management strategy in the Shoalhaven due to the pyrite content in the soil. Liming is often used in conjunction with other remediation strategies which require earth works such as levee removal and drain reshaping.

5.1.4 Permeable Reactive Barriers (PRB)

Permeable Reactive Barriers (PRB) are a vertical barrier that allows groundwater to pass through. PRBs have been applied at various groundwater contamination sites due to the cost when compared to the cost of treating shallow aquifers (Regma et al., 2009). PRBs can remove contaminants by (i) sorption 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 acid affected groundwater 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 5.3). 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.

Application of PRBs is not a cost effective management strategy in the Shoalhaven due to the widespread distribution of acid sulfate soils. PRBs are applicable to smaller scale in-situ treatment of acidic groundwater or other sub-surface contamination.

![Figure 5.3: Permeable Reactive Barrier (PRB) application to neutralise acidic groundwater.](image)
5.2 Long-term Remediation Options

Long-term management options aim to completely rehabilitate acid affected sites and prohibit future acid production. These strategies mainly target changes to current land use practices.

Long-term, permanent management strategies are characterised by:
- Greater capital cost;
- Potential impact to agricultural/landholder;
- Minimal ongoing maintenance; and,
- Changed land-use practices/management.

Although longer term management options may result in significant changes to land use practices, application of these management options have the potential to be implemented over a portion of an acid affected area to maintain agricultural activities. These areas can be targeted for long-term remediation, while lesser affected areas are managed on a short-term, reactive time scale. This approach allows for agricultural productivity to continue, whilst addressing key areas of concern.

5.2.1 Wet Pasture

Wet pasture, or reflooding, involves retaining fresh surface water on pastures during dry periods by limiting drainage. Talau (2007) states that this option aims to contain acid and other oxidation products within the soil and surface water by raising water levels in the drain (Figure 1.1). This is usually achieved by installation of structures in the drainage channel such as a weir, and/or modification of pasture drainage pathways.

Johnson et al. (2003) showed that the acid export 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 hydraulic conductivity.

![Figure 5.4: Wet pasture management](image)

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5.2.2 Drain Infilling and Reshaping

Infilling, shallowing and reshaping drains can be an effective way of reducing acid export and many other negative impacts of over drainage, particularly in ASS backswamps (Johnson et al., 2003). Raising drain invert elevations while maintaining the effective drain cross-sectional area reduces acid seepage and maintains drainage. These drains are commonly referred to as ‘swale drains’.

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 strategy is applicable where the acid soil layer is sufficiently deep enough to enable an efficient drain slope from the back swamp to the estuary without the drain invert disturbing the acid layer.

Figure 5.5: Before and after swale drain construction
5.2.3 Land Raising

Raising of land by addition of fill (or reshaping) enables acid remediation strategies to be applied without affecting agricultural practices. Depending on the site, land raising would require significant volumes of soil to be transported and levelled across the pastures. This could be implemented where saline tidal inundation is likely to be detrimental to the upper soil profile, and agricultural practices (Figure 5.6).

![Figure 5.6: Schematic of partial land raising](image)

5.2.4 Reversion to Saltmarsh or Wetland

Prior to settlement, the Broughton Creek and Crookhaven River floodplains were a mixture of saltmarsh and wetlands (Bayley, 1975). Reversion of an acid affected site to a saltmarsh or wetland could effectively limit acid export and provide habitat for primary production. Similarly to land raising and wet pasture management options, remediation of a site to create saltmarsh or wetland could be undertaken over an entire acid affected drainage area, or on a portion of the floodplain. This strategy has been effectively applied at other acid affected sites in NSW, such as Tomago wetlands near Newcastle (Rayner and Glamore, 2010) and Big Swamp near Taree (Glamore et al., 2012).

Wetland or saltmarsh creation would require flow restrictions such as levees and floodgates to be removed or relocated. Where remediation of a portion of the floodplain to a wetland is to be undertaken, structures may be relocated to maintain existing agricultural land use conditions for the remainder of the drainage area. Where a site is to be converted to a wetland, regular tidal inundation would provide natural buffering of acid soils and maintain high groundwater levels. This management option has the greatest environmental benefit by increasing water quality, eliminating acid discharge, and providing aquatic habitat and fish passage. This option requires the largest change to existing land management.
Figure 5.7: Reversion to wetland
Table 5.1: Approximate remediation option costs*

<table>
<thead>
<tr>
<th>Option</th>
<th>Design Cost</th>
<th>Implementation</th>
<th>Maintenance (per annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weirs</td>
<td>$10,000</td>
<td>$10,000 to $30,000</td>
<td>$5,000 to 15,000</td>
</tr>
<tr>
<td>Floodgate modification</td>
<td>$10,000</td>
<td>$10,000 to $25,000 per gate</td>
<td>$5,000 to $10,000</td>
</tr>
<tr>
<td>Liming</td>
<td>$5,000</td>
<td>$15/m³ acid soil Dependent on acid content</td>
<td>None</td>
</tr>
<tr>
<td>Culvert relocation</td>
<td>$15,000</td>
<td>$60,000 to $100,000 per culvert</td>
<td>$8,000</td>
</tr>
<tr>
<td>Drain infilling</td>
<td>$15,000</td>
<td>Equipment establishment ($5,000) + unit rate ($10,000/500m)</td>
<td>None</td>
</tr>
<tr>
<td>Drain reshaping</td>
<td>$15,000</td>
<td>Equipment establishment ($5,000) + unit rate ($20,000/500m)</td>
<td>None</td>
</tr>
<tr>
<td>Permeable Reactive Barrier (PRB)</td>
<td>$40,000</td>
<td>$10,000/100m to $100,000/100m</td>
<td>$20,000</td>
</tr>
<tr>
<td>Wet pasture</td>
<td>$15,000</td>
<td>Potential: Structure relocation + Land acquisition + Drain infilling</td>
<td>None</td>
</tr>
<tr>
<td>Land raising</td>
<td>Design. Potential flood impact assessment.</td>
<td>Equipment establishment + fill + daily rate</td>
<td>None</td>
</tr>
<tr>
<td>Full reversion to wetland</td>
<td>$15,000</td>
<td>Land acquisition (per ha) + Drain infilling + Drain reshaping + Infrastructure removal + Infrastructure relocation</td>
<td>None</td>
</tr>
</tbody>
</table>

*Based on standard commercial rates
6. Drain Action Plans

Proposed short and long-term drain remediation action plans are presented for all flood mitigation drains on the Lower Shoalhaven River floodplain. A total of 39 drainage areas were identified and assessed (Table 6.1, Figure 6.1). Broughton Creek was identified as the worst affected area, containing the top 13 acid affected drains. Particularly, the Far Meadow, Jorams Creek and Berry areas were found to be the highest risk sub-catchments. Some areas of the Crookhaven River floodplain were found to be a potential acid risk, however the overall impact of Crookhaven drains is low.

The action plans presented in this section provide a preliminary outline of recommended remediation strategies. Action plans are presented in numerical order by drain identification number. Further investigation will be required to determine precise engineering specifications prior to implementing remedial works. Application of the prioritisation methodology and results are presented in Appendix I.

Figure 6.1: Approximate drainage sub-catchments
### Table 6.1: Summary of Drain Remediation Priority

<table>
<thead>
<tr>
<th>Drain</th>
<th>Ranking</th>
<th>Short-Term Remediation Option</th>
<th>Long-Term Land Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>P6D3</td>
<td>1</td>
<td>Tidal manipulation and weir</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P3D6</td>
<td>2</td>
<td>Tidal manipulation and paleo channel inundation</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P6D2</td>
<td>3</td>
<td>Tidal manipulation</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P6D4</td>
<td>4</td>
<td>Drain reshaping</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P6D8</td>
<td>5</td>
<td>Tidal manipulation and weir</td>
<td>Floodwater diversion</td>
</tr>
<tr>
<td>P3D2</td>
<td>6</td>
<td>Floodgate relocation and tidal modification</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P6D7</td>
<td>7</td>
<td>Tidal manipulation</td>
<td>Floodwater separation</td>
</tr>
<tr>
<td>P6D1</td>
<td>8</td>
<td>Drain reshaping</td>
<td>Ongoing maintenance</td>
</tr>
<tr>
<td>P6D5</td>
<td>9</td>
<td>Wet pastures</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P3D1</td>
<td>10</td>
<td>Floodgate relocation and tidal modification</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P3D7</td>
<td>11</td>
<td>Tidal manipulation</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P3D8</td>
<td>12</td>
<td>Tidal manipulation</td>
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</tr>
<tr>
<td>P3D4</td>
<td>13</td>
<td>Ongoing tidal modification</td>
<td>Wet pastures/wetland</td>
</tr>
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<td>P1D1</td>
<td>14</td>
<td>Tidal manipulation and weirs</td>
<td>Wet pastures</td>
</tr>
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<td>Floodgate relocation and tidal modification</td>
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<td>P5D1</td>
<td>16</td>
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<tr>
<td>P9D2</td>
<td>17</td>
<td>Tidal manipulation</td>
<td>Wetlands</td>
</tr>
<tr>
<td>P6D9</td>
<td>18</td>
<td>Preliminary investigation required</td>
<td>Drain reshaping</td>
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<td>Wetlands &amp; fisheries</td>
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<td>28</td>
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<td>Wet pastures/wetland</td>
</tr>
<tr>
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<td>29</td>
<td>None</td>
<td>Drain reshaping</td>
</tr>
<tr>
<td>P4D3</td>
<td>30</td>
<td>None</td>
<td>Drain reshaping</td>
</tr>
<tr>
<td>P8D2</td>
<td>31</td>
<td>None</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P5D2</td>
<td>32</td>
<td>None</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P4D1</td>
<td>33</td>
<td>Floodgate relocation and tidal modification</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P2D1</td>
<td>34</td>
<td>None</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P2D3</td>
<td>34</td>
<td>Preliminary investigation required</td>
<td>Wet pastures/wetland</td>
</tr>
<tr>
<td>P4D2</td>
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<td>None</td>
</tr>
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<td>P9D1</td>
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<tr>
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<td>Fish passage/Floodgate modification</td>
</tr>
</tbody>
</table>

The analysis to determine the priority rankings in the table above were done on a drain by drain basis. There are four catchments which feature multiple drains discharging from a single point. The following drains discharge via a single structure:
- P4D1, P3D1, P3D2 and P3D3 via P4D1G1
- P3D7 and P3D8 via P3D7G1
- P2D1 and P2D3 via P2D3G1
- P5D1 and P5D2 via P5D1G1