RESTORING THE BALANCE

GUIDELINES FOR MANAGING FLOODGATES AND DRAINAGE SYSTEMS ON COASTAL FLOODPLAINS

Australian Government
Fisheries Research and Development Corporation
Land and Water Australia
Sugar Research and Development Corporation

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Disclaimer: The information contained in this publication is based on knowledge and understanding at the time of writing (November 2003). However, because of advances in knowledge, users are reminded of the need to ensure that information upon which they rely is up to date and to check currency of the information with the appropriate officer of New South Wales Department of Agriculture or the user's independent adviser.

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EXECUTIVE SUMMARY

Many coastal floodplains in Australia have an extensive network of floodgates, constructed drains and modified water courses. These are designed to mitigate the impacts of floods and large rainfall events. Floodgates prevent flood waters and tidal brackish water from inundating low areas of the floodplain. Constructed drains have converted prior wetlands into dryland farming areas. Whilst these developments have enhanced rural settlement and industries they have also caused unintended adverse impacts to fisheries, the ecology of estuaries and downstream water users.

The expanded drainage network has increased the generation and export of acidity from acid sulfate soils. Drainage systems can rapidly transfer acidity and deoxygenated water from backswamp areas to creeks and estuaries after rain. Floodgates and constructed drains have also blocked fish movement to upstream habitat areas and provide conditions that are conducive to the formation of poor water quality, particularly water with low dissolved oxygen.

These guidelines outline principles and strategies which can be employed to improve the environmental performance of coastal floodplain drainage systems, while retaining their benefits for agriculture. They have a particular focus on reducing drainage of acidity from areas with acid sulfate soils. The benefits, limitations and risks associated with management changes are described.

The guidelines emphasise the need to assess key features of coastal floodplain drainage systems before changing their management. Important features include the ranges of salinity and tides in the estuary, the elevation of land, the presence and depth of acid sulfate soils, the acidity of groundwater, the permeability of soils, and the changes that may have occurred in the type of native vegetation.

All stakeholders need to be involved in determining achievable management objectives. While some objectives have conflicting management requirements, many are compatible, enabling multiple objectives to be achieved. Management objectives can include preventing inundation of cropping land, reducing drainage of acidic groundwater, reducing low dissolved oxygen events, enhancing fish passage, enhancing fish habitat, managing aquatic weeds or restoring wetlands to conserve or enhance wildlife.

These objectives can be achieved by integrating three strategies for improved management. The first is to *modify floodgates* to enable controlled tidal exchange of drain water with fresh or brackish estuarine water. This will enable water quality improvements in the drain, allow fish greater passage, enhance fish habitat and enable the use of salt water to reduce aquatic weeds. Selecting a floodgate-opening strategy requires an assessment of the risks of overtopping drain banks and the most suitable opening device to provide the required degree of water level control. It will also require an assessment of subsidiary works (eg levees, penstocks) to prevent or control inundation and limit water movement.

The second strategy is to use *water retention* structures to reduce the seepage of acidic groundwater to drains in acid sulfate soil backswamps. These structures can also control unwanted intrusion of saline water, or reduce the risk of peat fires. Water retention strategies can also be used to reduce the drainage of acidic or deoxygenated surface water and aid the establishment of wetland pastures or wetland conservation areas.

The third strategy is *drain redesign.* This can include filling in unnecessary drains, replacing deep drains that intercept groundwater with shallow drains which remove only surface water, and land forming to shed surface water to shallow drains.

These guidelines are based on the best scientific understanding of the day. They will need to be applied adaptively given that social, economic and environmental circumstances are continually changing. They will require further development as our understanding of the processes continues to grow.

1. INTRODUCTION

PURPOSE

These guidelines are written for people who actively manage coastal floodplain drainage systems, including local government authorities, landholders, drainage unions, industry groups and community groups. The guidelines encourage a balance between the economic, environmental and social aspects of floodplain drainage. In many areas, floodgates and drainage systems will require substantial modification and active management to achieve an optimum balance. Some land use practices will also require change. In some locations incentives may be needed and trade-offs negotiated to offset the costs incurred in achieving balance.

SCOPE

The guidelines examine some of the adverse impacts of floodplain drainage systems, particularly to fisheries and estuarine water quality, and provide a framework for understanding how to reduce these impacts. At the same time they are designed to help land managers maintain agricultural production and prevent further degradation. There is no simple 'recipe' to achieve this. Each drain system has to be assessed and solutions devised to fit each unique site. As such the guidelines outline important questions that need to be answered in assessing each drain, and provide a range of management options that can be used to maximise benefits and manage risks.

These guidelines are designed to complement other extension material available at www.agric.nsw.gov.au/reader/floodgate-guidelines. A glossary to explain unfamiliar terms is located on page 45.

ACKNOWLEDGEMENTS

The guidelines are based on findings from seven years of research by NSW Fisheries and NSW Agriculture on the north coast of NSW. They represent the collaborative effort of many different organisations and individuals. Funding for these projects was provided by Land and Water Australia, Fisheries Research and Development Corporation, Sugar Research and Development Corporation and Acid Soil Action.

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Special mention of Clarence River County Council and staff is also warranted, particularly for their assistance identifying research sites and in designing, funding and installing various floodgate and drain modifications.

Many thanks to the following for their valuable contributions to the research projects and development of the guidelines: Thor Aaso, Matt Barwick, Peter Haskins, Phil Hirst, Graham Housefield, Rob Lloyd, Bernie Makins, Bob Smith, Michael Wood, Clarence Floodplain Project Committee, Department of Infrastructure, Planning and Natural Resources (NSW), NSW Sugar Milling Cooperative, Clarence River Fisherman's Cooperative, Southern Cross University, Richmond River County Council, and Wetland Care Australia.

2. DRAINAGE ON COASTAL FLOODPLAINS

The development of rural settlements and agriculture on many of the coastal floodplains of Australia involved the construction of an extensive network of drains. Drains were used to reduce the impacts of major floods, convert swampy land into agricultural land, and remove stormwater from agricultural land (Figure 1). Natural channels and tidal creeks were straightened and converted to drains while elsewhere new drains were excavated. Floodplain drainage systems allowed agriculture to diversify, improved production, increased land access and reduced health risks for both stock and humans (Figure 2). For example, cane growing in Northern NSW is a major agricultural industry which relies extensively on floodplain drainage, and current production is valued around $77 million per annum.

While there were many social and economic benefits of drainage, there have also been adverse impacts on the economic returns of downstream water users and industries, and on estuarine water quality and ecology (Figure 3). These impacts are largely a result of altered floodplain hydrology, drainage of low wetlands with acid sulfate soils, loss of fish and bird breeding habitats and the fast delivery of poor quality water to estuaries (Figure 4). Commercial estuarine fisheries in NSW, including oyster production, are also substantial industries which are highly dependent upon water quality and habitat, and production is currently valued around $46 million per annum.

2.1 Acid sulfate soils

Australia's coastal floodplains are underlain by more than 40,000 km^2 of potential acid sulfate soils. These soils account for half the total area of some individual floodplains and are generally buried beneath alluvial sediment. Potential acid sulfate soils are soils that contain iron sulfides, principally in the form of the mineral pyrite. These soils can generate large amounts of acidity, iron and aluminium when they are exposed to air, either by excavation or by lowering the watertable via drainage or drought. When leached from the soil, these products can

Figure 1. A floodplain drain being cleaned using a dragline excavator. (Photo: NSW Sugar Milling Cooperative)

Figure 2. Sugar cane along the edges of a drain. Floodplain agricultural industries rely on drainage to shed surface waters. (Photo: Frederieke Kroon)

Figure 3. Fishing boats moored in an estuary. Commercial and recreational fishing industries depend on water quality and fish habitat. (Photo: Rob Lloyd)

Figure 4. Plume of acidic water entering an estuary – a result of drained acid sulfate soil.

Figure 5. Floodgates set in a concrete culvert headwall - a common sight on coastal floodplains. Floodgates allow drainage outflow, but prevent inflow of salt water or floodwaters. (Photo: NSW Agriculture)

Figure 6. Floodwaters (centre left) are prevented from filling a natural backswamp by floodgates. Floodgates and flood mitigation works have helped reduce the frequency and severity of coastal flooding.

cause acidification and/or deoxygenation of drainage water and receiving waters. Acid sulfate soils are more likely to pose a hazard when they are close to the ground surface.

Acid sulfate soil drainage water has severe detrimental effects on the health of fish, prawns, oysters and other aquatic organisms and can cause fish kills. Over-drained or poorly managed acid sulfate soils can also reduce grazing productivity and degrade soil health.

2.2 Floodgates

One-way hinged flap gates, called floodgates, are a common feature of coastal floodplain drainage systems (Figure 5). Floodgates prevent saline tidal water and river flood waters from inundating low-lying land (Figure 6). They also allow ebb tide drainage to the local low tide level. Unfortunately, floodgates also have many unintended side effects. They provide an environment which is conducive to the development of poor water quality, block fish and prawn movement and enable accumulation of products which can reduce downstream water quality.

Some features of a typical drained coastal floodplain are shown in Figure 7. Variations of this diagram are used throughout the guidelines to illustrate important points.

COASTAL FLOODPLAIN FUNCTIONS

Coastal floodplains are complex and dynamic places. They are constantly responding to influences from both the land and the sea. They are depositional areas for sediments and contain a wide diversity of landscapes and habitats ranging from fertile levees and backswamp wetlands to estuarine channels and islands. In terms of the human life span they appear quite stable, but seen in the context of longer periods they are constantly changing, accreting or eroding according to sea level and long term climatic influences.

Coastal floodplain wetlands play an important role in estuarine ecological function. Stores of carbon they contain are released into estuaries periodically, which helps provide the basis of the estuarine food chain and contributes to the ecological productivity of the estuary. They also act as buffer zones, particularly when floods deposit sediment and nutrient rich water on the floodplains and backswamps. They provide essential habitat for estuarine / inshore fish and prawn stocks, with many of the commercially and recreationally significant species using these habitats at different points in their life cycles.

Artificial drainage has profoundly altered the hydrology and ecological functioning of our coastal floodplains, particularly backswamp wetlands. The quality of the ecological functions provided by backswamp wetlands has been degraded, in turn affecting the health of adjacent estuarine systems. Floodplain drainage has helped generate more acidity in acid sulfate soil areas and importantly, provides a means for rapid transport of this acidity to estuaries. Floodplain drainage has also altered carbon export rates and can increase the magnitude and duration of estuarine deoxygenation that occurs after flood events.

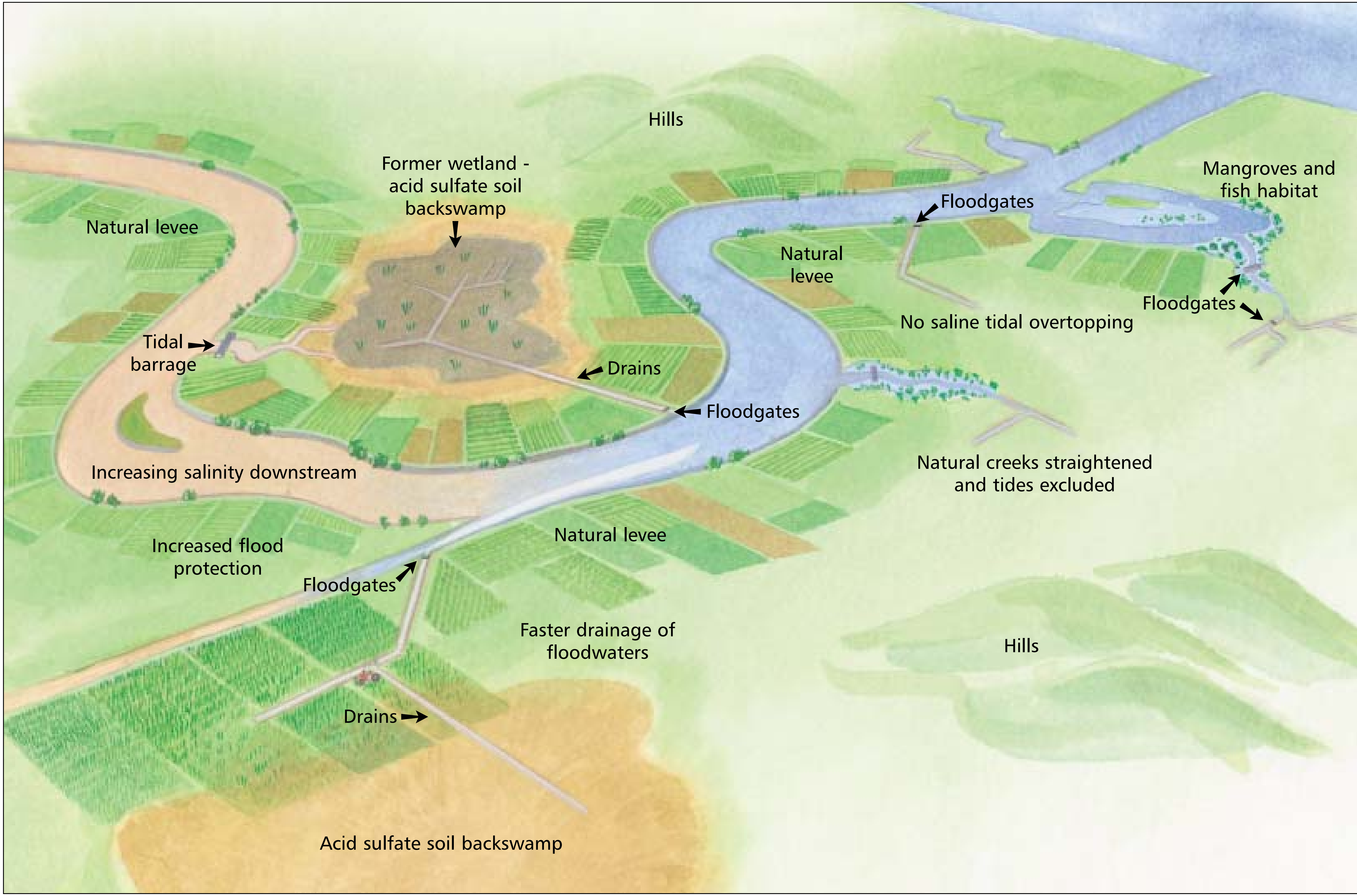


Figure 7: Floodplain diagram 1 – Typical features of a drained coastal floodplain

3. WHY WE NEED TO CHANGE

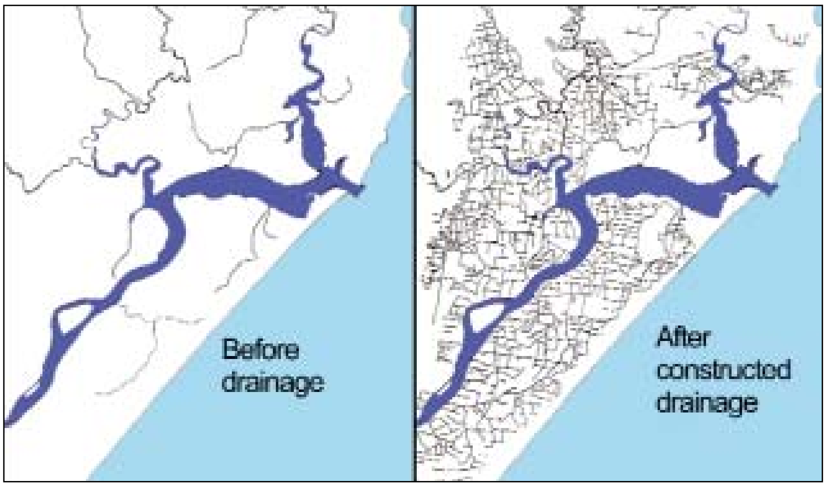


Figure 8. Natural and artificial drainage on a typical northern NSW floodplain. The amount of intact wetlands on coastal floodplains has been greatly reduced by drainage.

Figure 9. A drained wetland with scalding from acid sulfate soils (far right). The loss of surface vegetation from scalding greatly reduces agricultural productivity. Over-drainage of acid sulfate soils is a primary cause of such scalds. Fires, overgrazing, salinity and death of vegetation from deep flooding can be contributing factors. (Photo: Clarence River County Council)

Figure 10. A drain discharging highly acidic water with toxic concentrations of metals (iron and aluminium) from an acid sulfate soil backswamp.

3.1 Traditional drains and floodgates

Thousands of kilometres of drains have been constructed in coastal floodplains in NSW (Figure 8). The main function of these drains has been to remove water from swamps, wetlands and low areas following rain or floods to improve agricultural productivity and reduce the negative effects of flooding. Only a very small proportion of coastal floodplain wetlands and estuaries remain unaffected by drainage works. Drainage of floodplain wetlands in particular did not always provide the expected agricultural benefits (Figure 9) and has led to many environmental and economic impacts.

3.2 Impacts of drainage

In many instances drains are deeper than they need to be to remove surface waters from the land. Traditionally the drains are cleared of weeds and silt using excavators which can further deepen them. In acid sulfate soil (ASS) areas these over-deepened drains can collect acidic groundwater, forming a reservoir of acid which is flushed into the estuary after rain. Seasonal water quality can be very poor with high acidity and toxic metals (Figure 10).

It is well established that drainage in ASS areas has increased the magnitude, duration and frequency at which acidic products are transported to estuaries (Figure 11). Apart from readily visible impacts like fish kills, acid sulfate drainage water can cause many hidden impacts. These include impacts on fish and prawn migration and damage to the skin and gills which increase susceptibility to infections and diseases such as 'red spot' (Figure 13). Acidity and aluminium from acid sulfate soil leachate is known to be detrimental to the early life stages of several fish species as well as the Sydney rock oyster *(Saccostrea commercialis)*. Oyster production can be severely affected and prawns are especially intolerant to acid water during moulting.

Figure 11. A large acid plume caused by flocculation of iron and aluminium which often occurs when acidic drainage water mixes with estuary water.

While it is important to note that many floodgated drains are not acidic, other water quality problems, such as low dissolved oxygen and elevated nutrients, are relatively common.

3.3 Impacts of floodgates

Almost all drains on coastal floodplains in Australia have floodgates. The vast majority of floodgates were designed to be passive structures and are not actively managed.

Small tidal creeks and channels on the floodplain are vital habitat areas, important for the reproduction, recruitment and early growth of many commercial and recreational fish and prawn species. The majority of such creeks and channels now have floodgates and in many instances have been physically modified and straightened.

While floodgates act as barriers to incursion of saline tidal water, they also act as physical barriers to juvenile fish and prawns. Research on various coastal rivers in NSW has shown that juveniles of commercially and recreationally significant species such

Figure 12. In low-lying areas drains are sometimes pumped to assist water removal. Lowering drain water levels by pumping in ASS areas which have high soil permeability can increase drain water acidity and enhance acid export (see Figure 31).

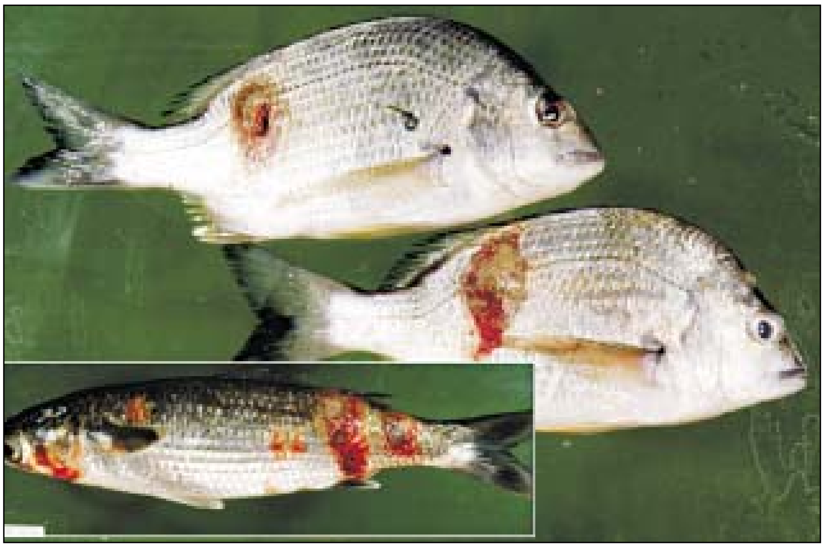


Figure 13. Bream and mullet with lesions caused by 'redspot' disease. 'Redspot' disease in fish has been linked to acid drainage water, which causes skin damage and allows a fungus to invade the skin, causing lesions. (Photo: Richard Callinan)

Figure 14. Dead fish in an estuary due to poor water quality. Acid and / or deoxygenated drainage water often causes such fish kills. (Photo: Jesmond Sammut)

as yellowfin bream *(Acanthopagrus australis)* and school prawn *(Metapenaeus macleayi)* are almost absent in gated systems, but occur in high numbers in non-gated systems.

Floodgates consequently play a role in the depletion of estuarine fish and prawn stocks, as they deny juvenile fish and prawns access to habitat and food upstream of these structures.

This is particularly so for migratory species such as Australian bass, yellowfin bream, schoolprawn, sea mullet and flat-tail mullet. Frequent opening of floodgates and allowing fish passage and access to former or new habitat areas will have long term positive benefits for fisheries resources.

Drainage systems with floodgates have many direct and indirect impacts on water quality and the environment (summarised in Figure 15) which can include

- impacts on juvenile fish and prawn migration
- reduced fish passage and recruitment of juvenile fish behind floodgates
- increased incidence of 'redspot' disease in fish and other sub-lethal effects upon fish and oysters (Figure 13)
- fragmentation and loss of fish habitat
- increased fish kills from acid or deoxygenation (Figure 14)
- increased export of acid / toxic metals from acid sulfate soils
- enhanced 'black water' impacts and rapid transport of 'black water' to estuary
- increased acid discharge as a result of drain pumping in high permeability acid sulfate soils (Figure 12)
- nutrient accumulation
- increased monosulfidic black ooze (MBO) formation in drains and transport to estuary
- wetland loss and reduced birdlife
- more fires in backswamps leading to loss of organic topsoil and scalding.

The long term cumulative effects of these various impacts clearly establish the need to improve current management of drainage systems.

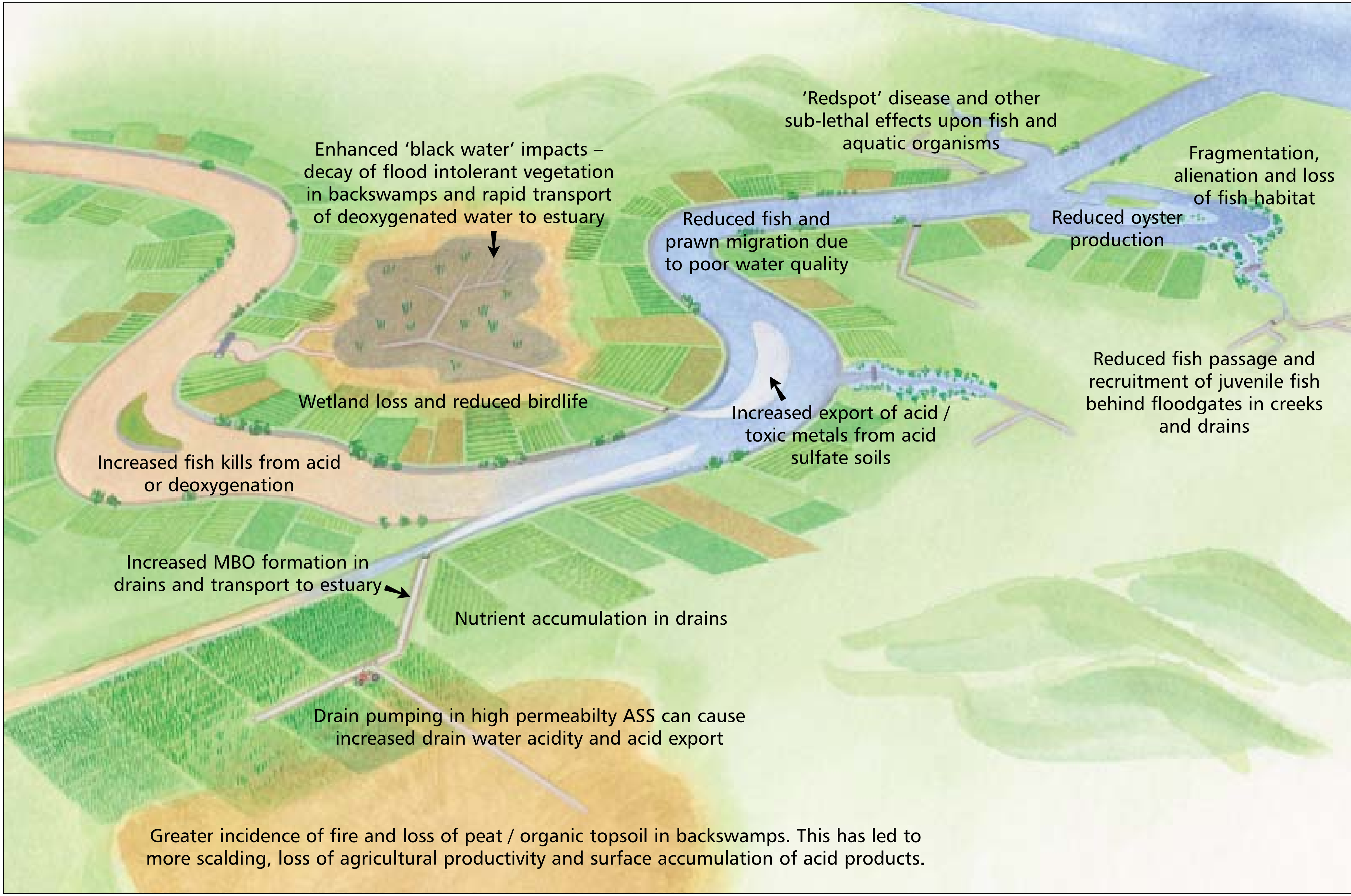


Figure 15: Floodplain diagram 2 – Some impacts of floodplain drainage

4. PREPARING FOR CHANGE

– A GUIDE TO ASSESSING YOUR DRAIN

Improving the management of your drain requires clear aims and some understanding of your particular drainage system. This section provides information on determining management objectives and outlines some questions that need to be answered in order to assess your drain and understand the likely effects of management changes.

4.1 Determine your management objectives

Past emphasis of drainage has focused on flood protection and land based economic enterprises. No doubt this will continue to remain very important. However, there is increasing recognition of the need to better account for the requirements of downstream users and the environment. Modifying and actively managing floodgates and drainage systems can reduce some of the negative impacts of drainage and help create more balanced outcomes.

Before embarking on active management of floodgates or drainage systems, you need to decide *what* you want to achieve and *how* your management will achieve it. The most common objectives of active management of floodgates and drainage systems are to

- improve drain water quality
- enhance fish passage and habitat
- maintain agricultural production and existing flood mitigation functions.

Other objectives can include

- aquatic weed control
- restoration of bird habitat
- wetland restoration
- enhanced aesthetic appeal.

In some instances landholders in drainage systems will have different priorities from each other. When setting objectives it is worth remembering to:

a) Define your objectives and priorities clearly as these provide the foundation for successful management.

b) Involve all stakeholders when setting objectives and priorities.

c) Choose objectives that are measurable.

Drainage systems in some locations can be successfully managed to achieve multiple objectives simultaneously. However, it is important to appreciate there will be drainage systems in other locations where a clear win-win-win is just not possible – you will need to make a choice. In such cases you will need to decide the *primary* objective, guided by the site characteristics. This may involve some trade-offs and compromise amongst stakeholders to achieve the best balance of outcomes. In many instances, some expert assistance will be required to assess the site characteristics and provide help with setting management objectives. See the section on Further Information (p. 46) for contact details of organisations with expertise in this field.

4.2 Understand your drainage system

Different drainage systems have different management requirements. There are three main kinds of methods for managing drainage systems.

1. Floodgate opening / water exchange devices that allow intentional flushing and exchange with estuarine water.
2. Retention structures that can be used to strategically retain water for a variety of purposes.
3. Infilling and shallowing of constructed drains.

The method you choose will depend on certain key features of your drainage system and your management objectives. Before making any management changes you need to examine your drainage system and understand how these key features may affect your management options. Accessing appropriate technical assistance and planning support is important at this 'assessment' stage.

There are a number of important questions you need to answer to understand the key features of your drainage system:

- Where is your drain located in the estuary?
- Where is your drain in the landscape?
- How high is the land next to the drain?
- What type of soil is next to the drain?
- What is the quality of your drain water?
- What is the capacity of the estuary to dilute drain water?
- What structures and landuse are present?
- Is *Melaleuca quinquenervia* (paperbark tea-tree) encroaching into ASS backswamps?

Each of these questions is discussed in more detail below. Figure 16 integrates some of these features using example drains and explains how these features might influence management options.

FEATURE 1. WHERE IS YOUR DRAIN LOCATED IN THE ESTUARY?

The location of the drain in the estuary will affect the tidal range and salinity levels. In most estuaries the tidal range decreases upstream from the ocean (Figure 17). A drain close to the river entrance is likely to experience a greater tidal range and higher salinity than one further upstream. High tide levels influence the risk of overtopping adjacent land. Low tide levels are also important as they influence the amount of groundwater seepage from acid sulfate soils (see Figure 31).

Salinity in estuaries on Australia's east coast is highly variable and affected by freshwater outflow and proximity to the ocean. Salinity levels at any given point in an estuary can change rapidly with rainfall and tides. Water near the bed of the river or water course can be much more saline than water near the surface. During droughts or dry seasons, salt concentrations in the estuary can increase markedly, ranging from less than 5 dS/m to greater than 40 dS/m (seawater is about 52 dS/m). During wet periods when the estuary is discharging rainfall runoff, the river water salinity will generally be low.

Before opening floodgates it is important to know a) whether salt levels in the estuary are increasing or decreasing and b) the salt concentrations upstream and downstream of the mouth of the drainage system. Salinity levels can be readily determined using inexpensive hand-held meters.

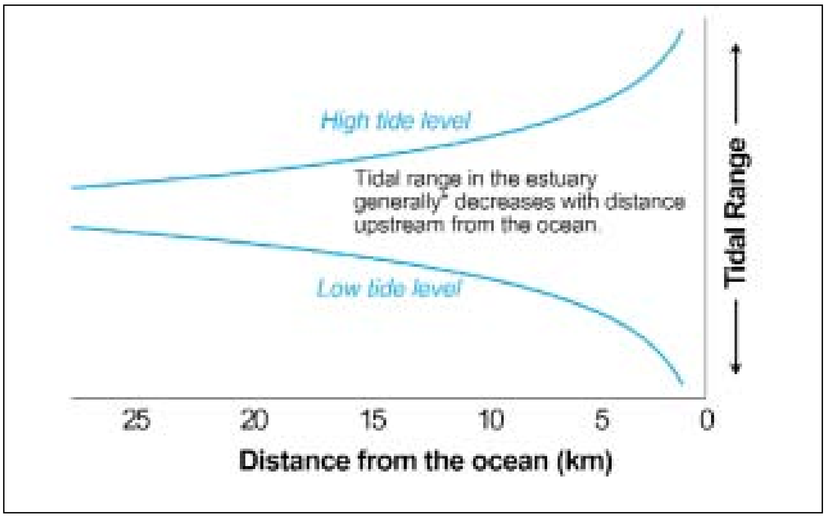


Figure 17. Tidal range tends to decrease with distance from the ocean (*Not in all cases).

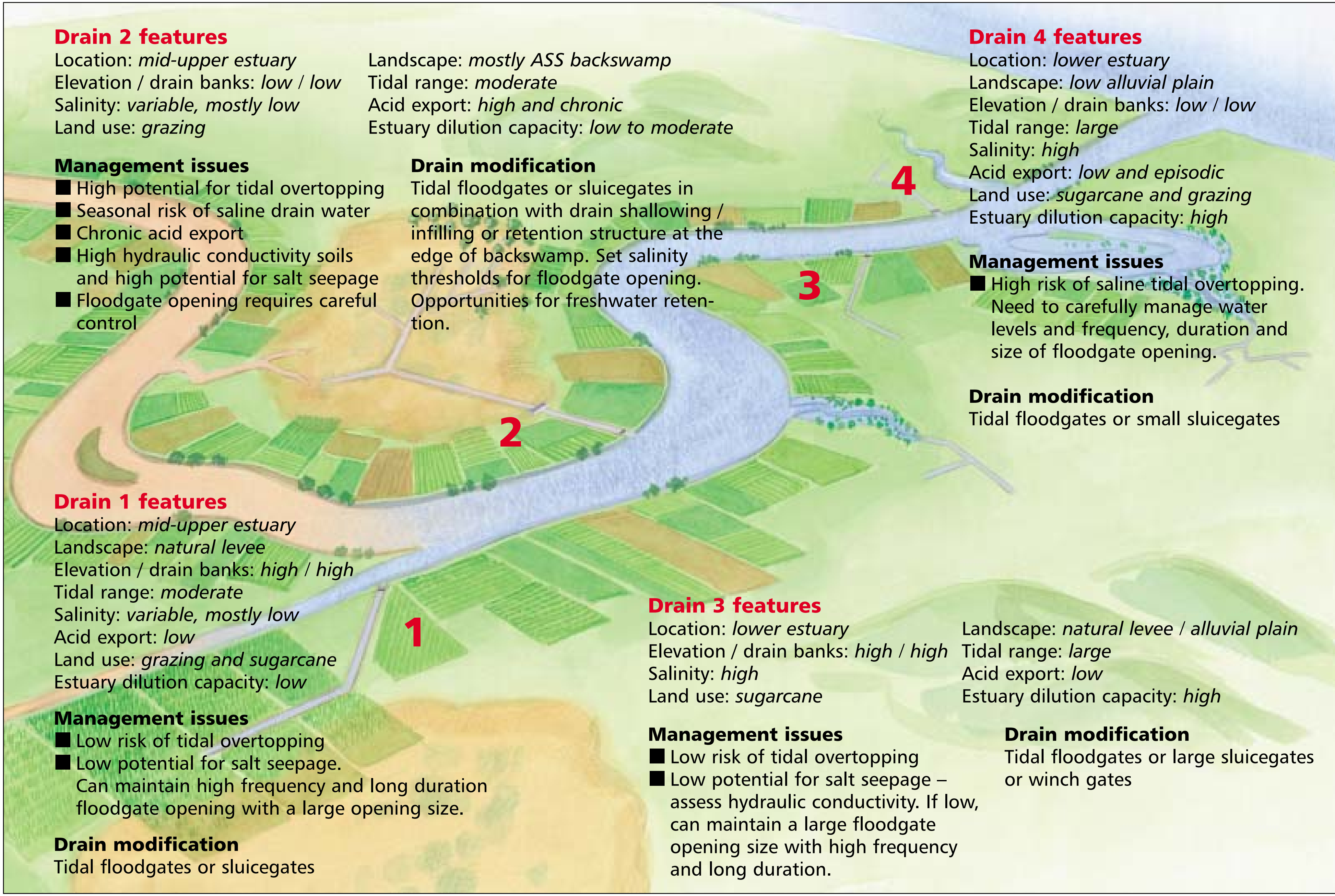


Figure 16: Floodplain diagram 3 – Understanding how the features of your drainage system can influence management options

FEATURE 2. WHERE IS YOUR DRAIN IN THE LANDSCAPE?

The type of floodplain landscape a drain is situated in (i.e. a backswamp or natural levee) will influence many attributes of the drainage system. Backswamps typically have low elevations and are more likely to contain ASS near the surface. They are also likely to be former wetlands and prone to long periods of inundation during wet seasons (Figure 18). Some now produce very poor drainage water quality.

Natural levees are usually located close to river channels and typically have higher elevations. Any ASS they contain is generally buried beneath alluvium and less likely to create acid water quality problems. Most drains intersect both landscape types.

FEATURE 3. HOW HIGH IS THE LAND NEXT TO THE DRAIN?

The height of land next to the drain determines whether tidal overtopping can occur when floodgates are open. Local experience is an important source of information on drain heights and overtopping, but you may need to do some survey work to determine exact land elevations. Information needs to be site specific and in relation to local tidal dynamics. It is a good idea to monitor and compare tide heights at key locations along the drain such as the drain mouth and low points. High drain sides provide greater opportunity for floodgate opening as they allow tidal water to be contained within the drain where it will pose little risk of flooding agricultural land.

Figure 18: Floodplain backswamps have low elevations and are prone to inundation from flooding or tidal overtopping. (Photo: Clarence River County Council)

FEATURE 4. WHAT TYPE OF SOIL IS NEXT TO THE DRAIN?

The soil type next to the drain will influence how you manage your floodgates. The severity of and depth to ASS is crucial, as is the hydraulic conductivity of the soil. ASS are often more severe and closer to the surface in backswamp landscapes (Figure 19). Hydraulic conductivity influences the rate at which acidic groundwater flows through the soil to the drain, and also the extent to which salt water seeps from the drain into adjacent soil and groundwater. Soils with a high hydraulic conductivity will be more prone to lateral water movement in both directions. There is more detail about lateral seepage on pp. 29-30.

While hydraulic conductivity is generally low in most floodplain soils, it can be high at some sites, particularly some ASS backswamps. It may need to be assessed on a site-by-site basis. Assessment of soil hydraulic conductivity requires some technical expertise, though simple field-based methods have been developed. Further information on these methods is available on the guidelines website (see p. 46).

ASSESSING ELEVATION

Some landholders assess the risk of overtopping by letting fresh river water into the drain during a high tide equal to the maximum likely to be allowed. When the estuary is fresh, any overtopping that may occur in this process does not generally pose a problem.

This method has limitations, but can provide useful information to the drain managers about relative land and tide elevations.

Figure 19. An example of acid sulfate soil containing yellow jarosite mottles. This was taken from a backswamp where the surface topsoil and peat had been lost through fire, creating a large acid scald. Sites like this can be a major source of acidity. (Photo: Rebecca Lines-Kelly)

Figure 20. A stand of paperbark tea-tree (*Melaleuca quinquenervia*) that has encroached into an acid sulfate soil backswamp after drainage. Orange stains from iron-rich acid groundwater are visible on the surface.

FEATURE 5. WHAT IS THE QUALITY OF YOUR DRAIN WATER?

There is enormous variability in drain water quality. Some drains have chronic acid discharge, some export acid infrequently and many others have little or no acid water, but may have other water quality concerns such as low dissolved oxygen or elevated nutrients. Water quality can determine management objectives. For example a drain with chronic poor water quality and high acid export may be better managed to contain acidity, with fish passage being a second order priority. In contrast, a drain with only episodic poor water quality and connected to significant fish habitat may be better managed to maximise fish passage.

FEATURE 6. WHAT IS THE CAPACITY OF THE ESTUARY TO DILUTE DRAIN WATER?

The capacity of the estuary to dilute and assimilate poor quality water from drainage systems depends on the volume of water in an estuary, the amount of tidal exchange and the estuary water chemistry. Sea water contains bicarbonate which can neutralise some acidity in drainage waters, but concentrations of bicarbonate usually decrease upstream. Acidity consumes bicarbonate which affects bicarbonate sensitive aquatic animals such as molluscs and crustaceans including oysters, prawns and crabs. Some locations are more vulnerable to poor quality discharge water than others. Lower estuary locations can generally dilute poor water quality more effectively than upper estuary locations.

FEATURE 7. WHAT STRUCTURES AND LANDUSE ARE PRESENT?

Existing structures and landuse within a drainage system need to be taken into account when deciding what management options are possible. Other features to consider include

- size of the drainage system and its sub-catchment
- origin of drains (ie whether constructed drain or a modified natural water course)
- linkages to drained wetlands and habitat value of the drain
- linkages to other drainage systems
- existing water extraction licences from drains.

FEATURE 8. IS *MELALEUCA QUINQUENERVIA* (PAPERBARK TEA-TREE) ENCROACHING INTO ASS BACKSWAMPS?

In some ASS backswamps, but certainly not all, significant expansion of the area of *Melaleuca quinquenervia* (Figure 20) has occurred following drainage. Such encroachment has the potential to reduce the area of pasture or open wetland available for grazing production.

Recent research has shown this encroachment also has the potential to increase acidity in the near surface soil and groundwater beneath *M. quinquenervia*. This can result in extra acidity in drainage and shallow surface water. It may be necessary to determine if this situation applies to your ASS backswamp. If it does, then strategically reducing the amount of water draining from such areas can improve water quality.

5. WHAT YOU CAN DO TO IMPROVE MANAGEMENT

Well-informed management of floodgate and drainage systems can yield many benefits to water quality, fish and the estuarine environment. The three main management options discussed here include:

- floodgate opening
- retaining water (p. 32)
- drain infilling / shallowing (p. 39).

This section outlines some of the benefits of these management options and also examines potential risks and how these risks can be managed.

After examining the key features of your drainage system you will be well placed to assess the implications and suitability of the different management options.

5.1 Opening floodgates

Floodgates can be modified in a number of ways to allow exchange with estuarine water during non-flood periods. This is referred to as 'floodgate opening'. The main types of modifications include sluice gates, tidal floodgates and various kinds of winch gates (Figures 21 to 23). New designs continue to be created. Each design has advantages and disadvantages and provides varying degrees of security in water level control. All designs still allow normal drainage of inundated farmland after flooding. A detailed review of floodgate modification devices and designs is available as workshop proceedings from the guidelines website (see p. 46 for details).

When used, these modifications can enhance fish passage and habitat, improve in-drain water quality and provide the opportunity for controlled inundation of lowland with river water. When planning to open floodgates, consult with your state water licensing authority and local flood mitigation body regarding relevant approvals.

(Photo: Frederieke Kroon)

5.2 Benefits of opening floodgates

As a general rule, the extent of the benefits is largely related to the frequency and duration of gate opening. Benefits include

- improved fish passage and habitat
- better water quality
- reduced acidity, iron and aluminium
- higher and more stable dissolved oxygen levels
- less monosulfidic black ooze in drains
- fewer nutrients and algal blooms
- healthier drain bottom sediments
- improved weed control in drains
- enhanced wetlands.

Figure 21. Tidal floodgates. As the tide rises the float lifts and automatically closes the gate, which then seals tight due to water pressure. (Photo: Frederieke Kroon)

Figure 22. River water flowing through an open sluice gate. This one operates with a worm drive mechanism. (Photo: Michael Wood)

Figure 23. Vertical winch gates (above) and horizontal winch gates (below). Both are opened via a cable and pulley system attached to a stationary winch on the bank. (Photos: Rob Lloyd and Alan Cibilic)

FLOODGATE MODIFICATION DEVICES

TIDAL FLOODGATE

Attributes: Various designs exist. Consist of an aperture within the existing floodgate with another smaller floodgate attached. This uses a float system to open and allow water exchange. Opens on the low tide and closes with the rising tide.

Water level control: Very good. Float can be adjusted to cut off inflow at desired level.

Advantages: Excellent water level control. Automatic operation. Amount of exchange and maximum height of inside water level can be adjusted. Flood secure - automatic closure as outside water level rises. Can also be locked shut. Low costs to meet occupational health and safety requirements.

Disadvantages: Can cost more than a lifting device if the original floodgate is very large; however, the cost is usually similar or even cheaper for smaller gates. Minor risk of being jammed open (as with normal gates); however, the gates have proven to be self-cleaning at trial sites in the Clarence, Hastings and Hunter rivers. Requires a new gate to be made in some cases.

SLUICE GATES

Attributes: Consist of an aperture within existing floodgate with a sliding plate cover and capacity to vary the opening size. This opening can be vertical, horizontal or rotational in design.

Water level control: Very good. Aperture size can be adjusted to vary the amount of inflow and suit site conditions. Position of window in gate can also be varied (vertically) and will affect water level control.

Advantages: Excellent water level control during non-flood periods. Simple design. Variable aperture size. Minimal maintenance. Low cost. Low costs to meet occupational health and safety requirements.

Disadvantages: Requires manual operation and manual closure in event of flooding.

WINCH GATES

Attributes: Various designs including a winch and cable mechanism which allows the existing floodgate to be lifted open either horizontally or vertically, and a worm drive mechanism that opens the gates vertically.

Water level control: Depends on design. Horizontal winch gates have limited water level control and are either fully open or closed. Vertical lift gates have good water level control and can be set in any position, from fully closed to fully open.

Advantages: Can allow large, rapid inflow of river water. Can be fully raised to assist outflow after flooding.

Disadvantages: Require intensive manual operation. Horizontal winch gates have greater risk of overtopping when open. Large forces can be involved in winch and cable system. Variability in opening size only available with vertically opening systems. Vertical winch gates can experience closing difficulties due to friction. Requires manual closure in the event of flooding. Can have higher costs to meet safety requirements.

BENEFIT: IMPROVED FISH PASSAGE AND HABITAT

Results from research in the Clarence and Macleay Rivers indicate that both fish passage and water quality are greatly improved with frequent openings of floodgates. Aquatic species richness in drainage systems, including total number of species and total number of commercial species, increases significantly with increased frequency of floodgate openings (Figure 24).

More specifically, the number of juvenile fish and prawns, including yellowfin bream *(Acanthopagrus australis)*, school prawn *(Metapenaeus macleayi)*, sea mullet *(Mugil cephalus)*, and southern herring *(Herklotsichthys castelnaui)* increase significantly in drainage systems with actively managed floodgates, and become comparable to non-gated systems. Interestingly, juveniles move into all drainage systems, whether they are modified natural creeks, or man-made drains. Thus, opening floodgates at the right time (Table 1), for the right amount of time, will allow juvenile fish and prawns access to upstream habitat (Figure 25) and food, thereby enhancing the productivity of the fishery.

Different species of fish, as well as the different life stages of these species, have different swimming abilities and behavioural traits that affect their ability to move past open floodgates. Some species prefer to move during the day, others at night; some travel with the current, others against it. To maximise fish passage into managed drainage systems, floodgate modifications should ideally:

- have as large an opening as possible to reduce current flow
- cover as much of the water column as possible
- operate automatically during day and night tidal cycles.

Figure 25. Floodgates act as barriers to fish and can restrict their access to upstream habitat areas.

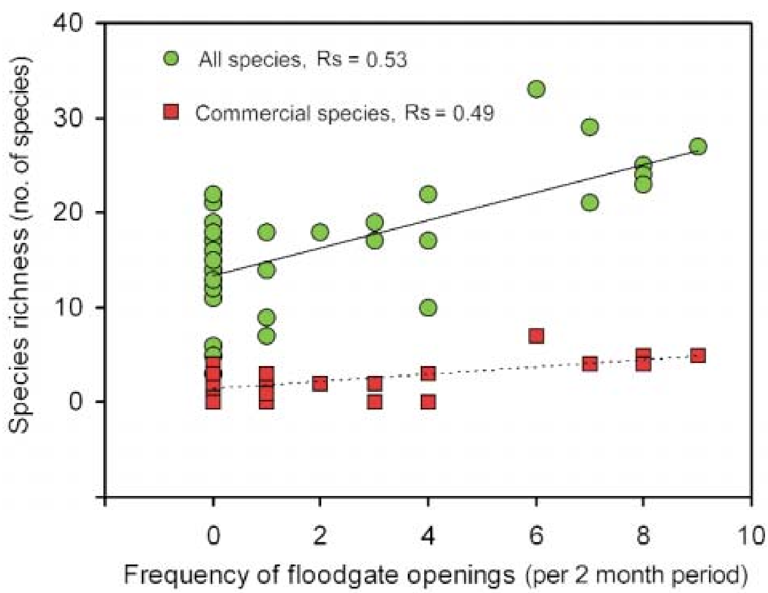


Figure 24: This graph shows that species richness, including the total number of species and total number of commercial species, increases significantly with increased frequency of floodgate openings. Both correlations are statistically significant at the >99% confidence interval. Results are from four constructed, man-made drainage systems with horizontal winch gates in the Clarence River, sampled bimonthly from July 2000 to May 2002.

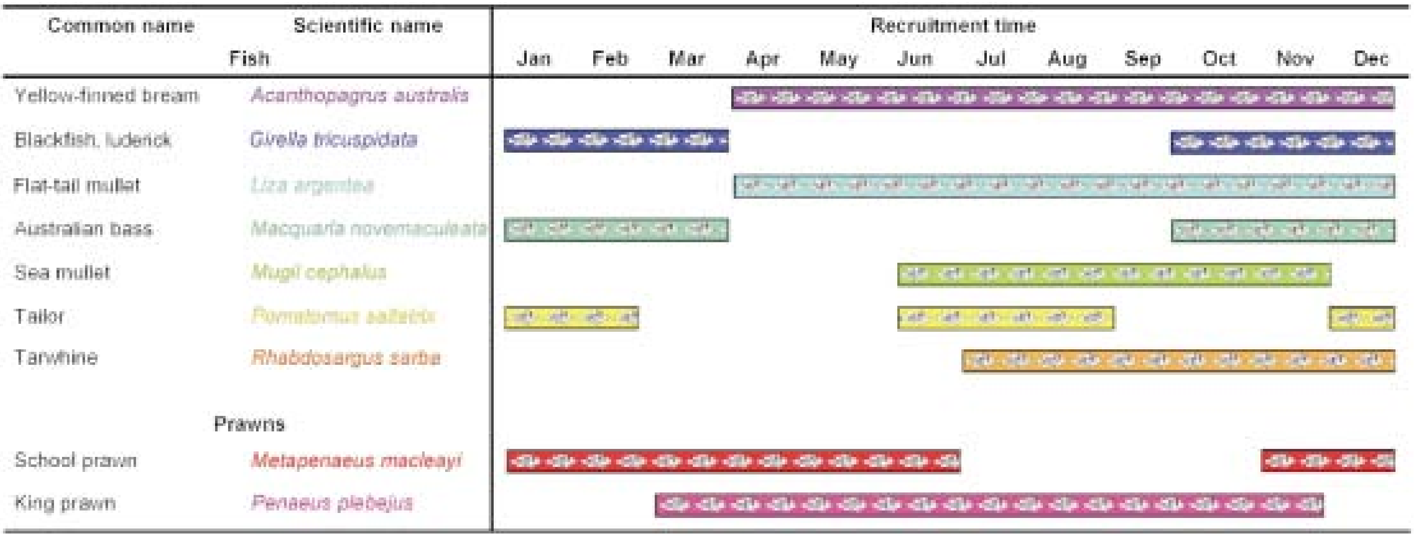


Table 1. Bars in the table indicate the months in which juveniles of important commercial and recreational fish and prawn species are most likely to move upstream into NSW and Qld estuaries and rivers. Check with your local Fisheries office for more detailed local times.

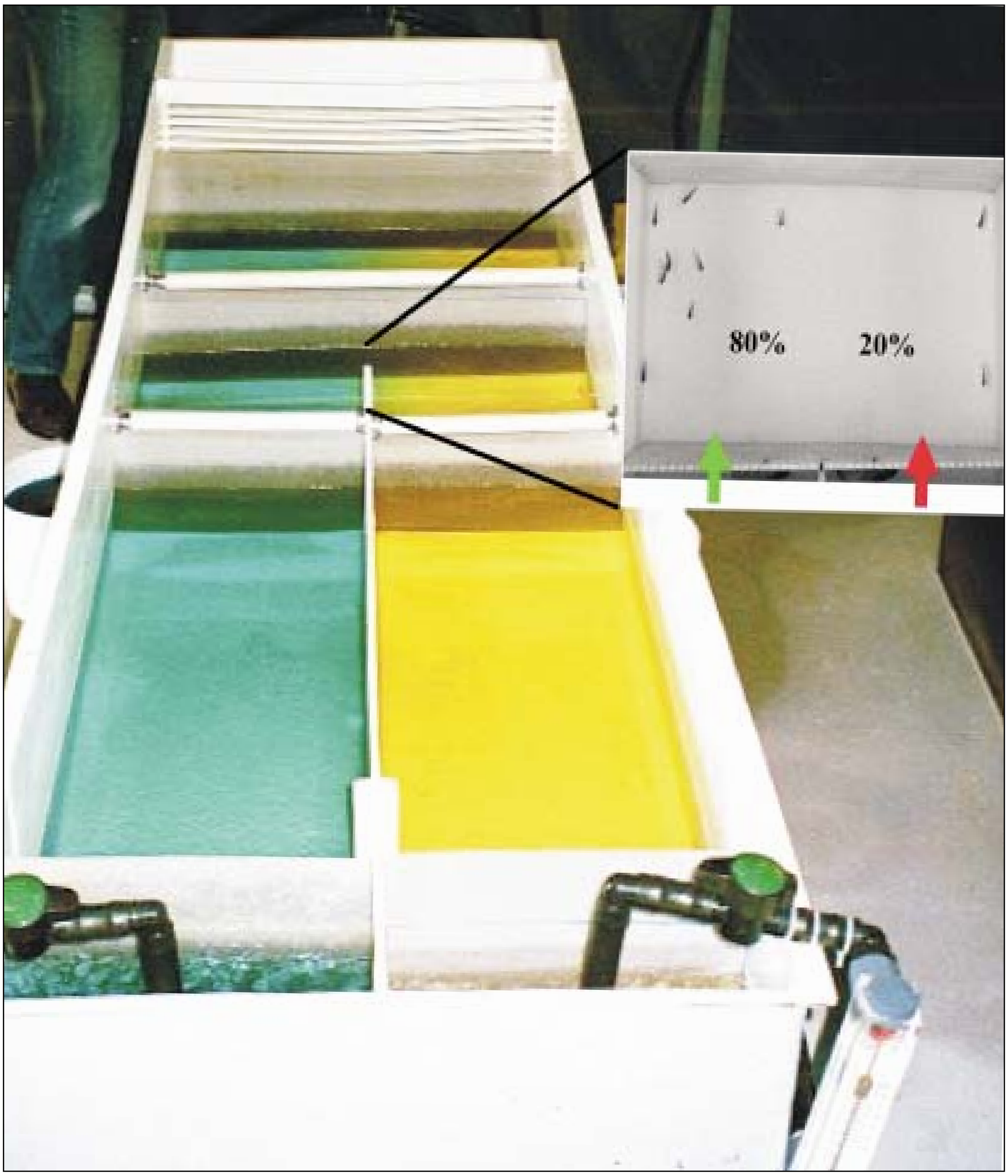
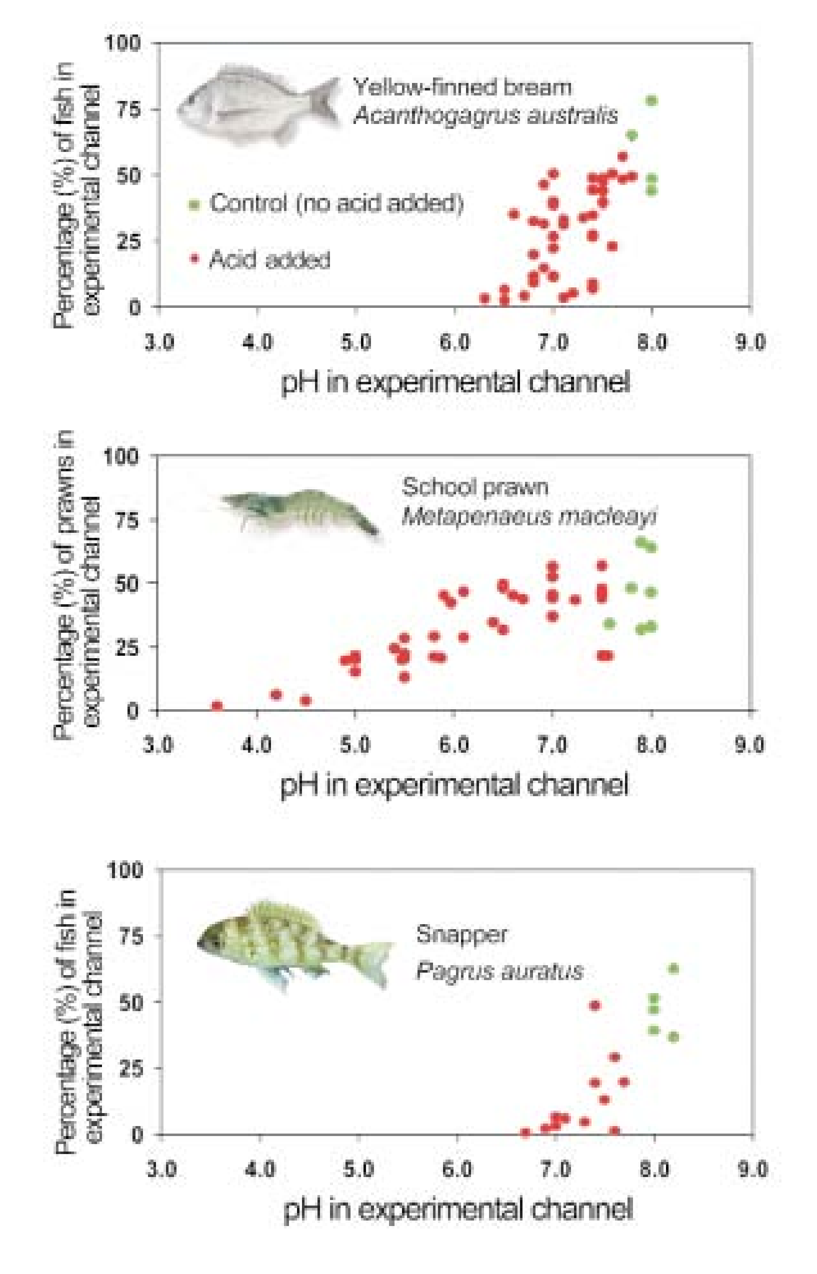


Figure 26: This picture shows a specially designed tank which exposed juvenile fish or prawns to two separate streams of water in one open area (see inset). One stream could be made acid (experimental channel) while the other remained unchanged. The fish and prawns were free to choose which stream they preferred. They were exposed to controlled acid levels with dilute sulfuric acid in many repeat experiments. Some results are shown in Figure 27. (Photo: Frederieke Kroon)

Figure 27. When given a choice, juvenile fish avoid acidified water. This figure shows the results from laboratory experiments, where juvenile fish or prawns placed in the tank in Figure 26, could choose between acidified and un-acidified water. The more acidic the water (ie the lower the pH), the fewer fish or prawns stay in the acidic water.



In addition to active management of floodgates, improving water quality coming out of the drainage system is vital to enhancing fish passage. NSW Fisheries studied the response of juvenile fish and prawns to different pH levels in laboratory experiments (Figure 26). These experiments were conducted to examine whether chronic acid sulfate run-off may affect migration of juveniles into potential nursery habitats. The results showed that juveniles of various species, such as yellowfin bream, snapper *(Pagrus auratus)* and Australian bass *(Macquaria novemaculeata)* avoid even slightly acidic water when given a choice (Figure 27). Schoolprawn, on the other hand, appear to be more tolerant of acidic water at least for short periods (Figure 27).

These results indicate that the acidic component of acid sulfate run-off alone can affect migration of juvenile fish and prawns. Such avoidance of acidified water may reduce the proportion of nursery habitat used, with possible negative effects on stock size. This highlights that improvements in water quality are crucial for enhancing and maintaining fish passage in floodgated drainage systems.

SHORT OR LONG OPENING PERIODS?

Research has shown that active management of floodgates improves fish passage. However, these improvements in fish passage quickly disappear when floodgates have not been opened for prolonged periods of time and/or when the frequency of floodgate opening decreases (Figure 24).

This is often the case, particularly with manually operated floodgates, as even well intentioned landholders managing floodgates are not always present or do not have time to open and/or close floodgates. Juveniles of the above-mentioned species that recruited into drainage systems with managed floodgates, disappear from these systems when floodgates are closed again. It is currently unknown whether this is due to migration out of the drainage system, or due to mortality related to a sudden and quick decrease in water quality (see next section). If the latter is the case, the cure may be worse than the disease as valuable recruits will be lost to the fisheries.

Hence, management of floodgates should be maintained once it has begun. To improve and maintain fish passage, installation of automated systems, rather than manually operated floodgates, is desirable.

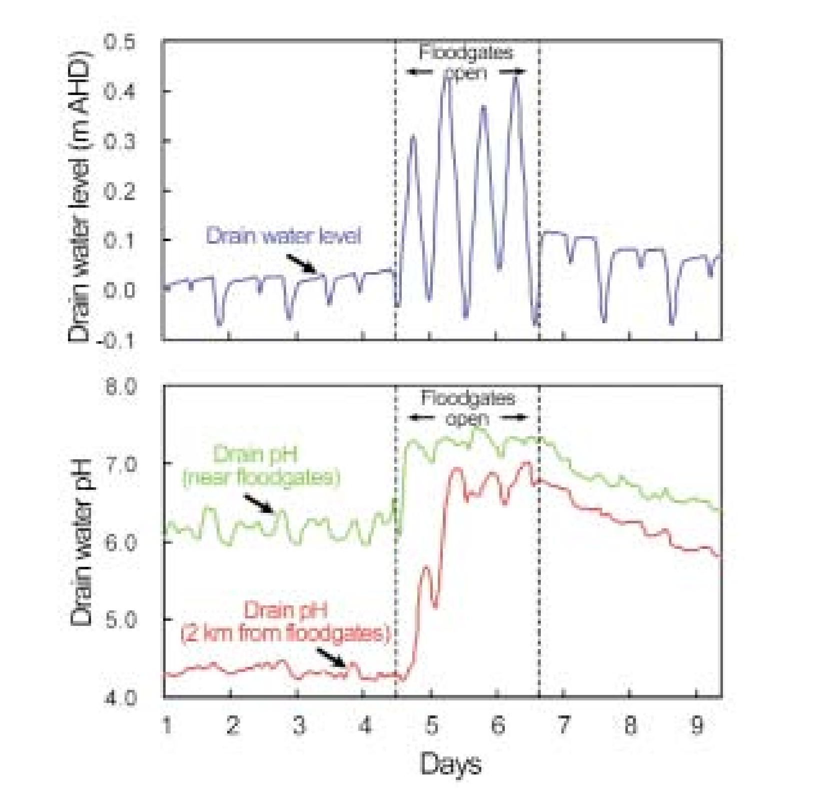


Figure 28. This chart shows a short term improvement in drain water pH in response to several days of floodgate opening. Note that pH values begin decreasing again as soon as floodgates are closed. Water quality improvements from short duration floodgate opening events are not very stable. Longer duration opening is more effective.

BENEFIT: BETTER WATER QUALITY

Opening floodgates can improve in-drain water quality because it allows river water to dilute drain water and can help neutralise acid stored in the drain. This can improve oxygen concentrations and pH levels. However once floodgates are closed again, drain water quality can rapidly revert to pre-opening levels (Figure 28).

The effectiveness of floodgate opening at improving in-drain water quality depends largely on how often the gates are open. In most cases the more often they are open the better. In some drainage systems the potential for saline tidal overtopping of adjacent agricultural land places constraints upon opening. In such systems it may be better to have smaller opening size using devices that provide greater control of water levels (ie sluice gate or tidal floodgate) and longer duration opening, rather than large, infrequent openings.

WATER QUALITY - WHAT'S 'NORMAL'?

Water quality in coastal floodplain drains varies greatly. Two parameters that are often measured, because of their vital importance to aquatic organisms, are pH and dissolved oxygen.

pH is a measure of acidity or alkalinity on a logarithmic scale of 1 to 14, with 7 being neutral. Most 'normal' estuary waters range from about 7 to 8.2 (Figure 30). Drainage waters from acid sulfate soils are often less than 4.0 and can fall below 3.0. Organic acids from decomposing vegetation can contribute to water acidity, but are generally not toxic. Some aquatic species are more tolerant to acid than others, but negative effects on the health of some fish species can be detected at approximately 5.8, depending also upon what else is in the water (ie aluminium). Research has shown some juvenile fish species can detect acid water and will avoid it when given a choice (see Figure 27).

The amount of dissolved oxygen in drain and estuary water varies according to daily cycles of photosynthesis and also depends on temperature (cold water can absorb more oxygen than warm water). Defining critical thresholds based on concentration is difficult because this depends a lot on the species and the water temperature. However, increased stress and decreased growth is evident in many fish species below about 5 mg/L, and estuarine fish kills are often associated with dissolved oxygen less than 2.0 mg/L.

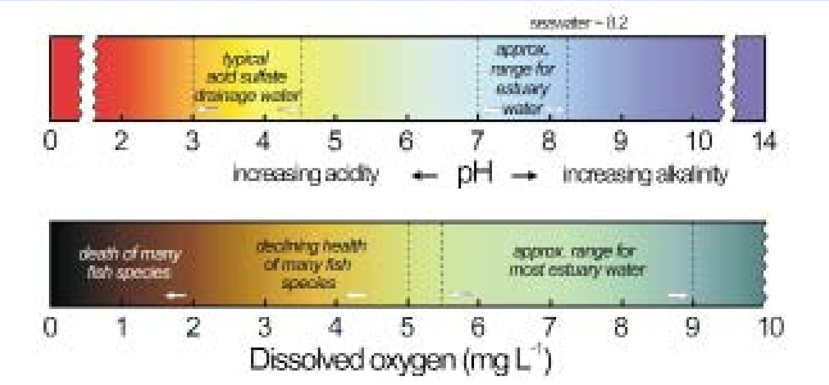


Figure 30: Important thresholds for pH and dissolved oxygen.

BENEFIT: REDUCED ACIDITY, IRON AND ALUMINIUM

Floodgate opening can dilute and neutralise acid drain water, reducing concentrations of iron and aluminium (Figure 29). However, floodgate opening is an 'end of pipe' solution and, by itself, it can have a limited effect at reducing chronic acid loads. This is particularly the case in ASS with high hydraulic conductivity where groundwater seepage is the major

Figure 29. Bright orange iron staining along the sides of a drain – an indicator of chronic acid conditions.

WHERE DOES ACID COME FROM?

In order to reduce acid export it is important to know where the acid comes from and how it gets to the drain. On coastal floodplains the acidity of concern is generated by acid sulfate soils (ASS). Large quantities of mobile iron and aluminium can be stored in ASS groundwater and are responsible for much of the acidity. Both metals can have lethal effects upon aquatic organisms, particularly in certain pH ranges.

The two main ways ASS-contaminated water enters the drainage system are surface runoff and groundwater seepage (Figure 31. Of the two, groundwater seepage is often the most significant and can lead to very acidic drain water with high iron and aluminium concentrations. The difference in height (or gradient) between the groundwatertable and the water level in the drain is an important feature, as this, combined with soil hydraulic conductivity, determines groundwater seepage rates. Therefore local low tide levels in the drain are also important - the lower they are the greater the potential size of the gradient.

Likewise, any drain pumping in high hydraulic conductivity ASS which lowers drain water levels below adjacent groundwater will increase gradients and acid groundwater seepage to the drain.

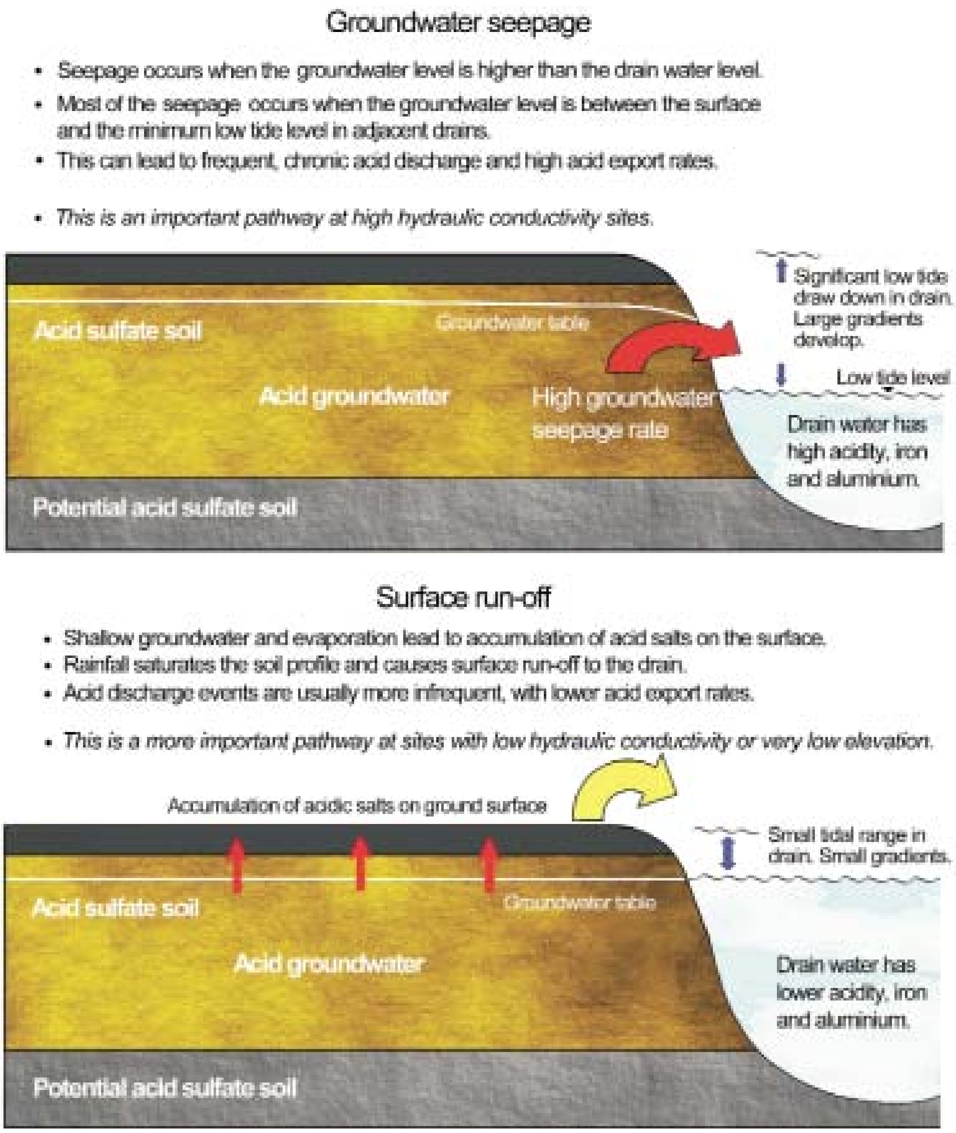


Figure 31. The two main ways acidity enters drains are groundwater seepage and surface runoff.

source of acidity entering the drain. This is because drain water levels can still draw down to low tide level, creating gradients that cause acid groundwater seepage (Figure 31). Where there is high acid groundwater seepage into the drain, the containment of acidity in the soil profile is a far more effective technique for improving drain water quality (see p. 33).

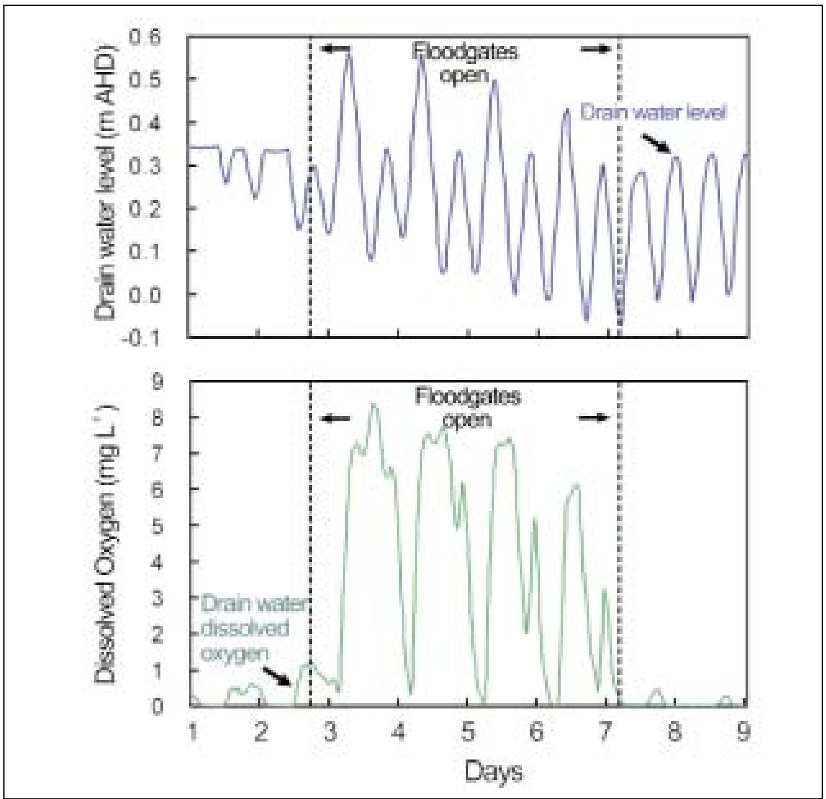


Figure 32. This chart shows a short term improvement in dissolved oxygen from floodgate opening. More stable improvements can be achieved by increasing the duration of opening using automatic tidal floodgates or sluice gates.

BENEFIT: HIGHER DISSOLVED OXYGEN LEVELS

Fish and prawn species depend on dissolved oxygen in the water to survive (Figure 30). Floodplain drainage systems often have low or wildly fluctuating dissolved oxygen concentrations due to high light conditions and high nutrient levels in the water encouraging large algal populations, particularly during warmer weather. Dissolved oxygen can plummet during the night when plant respiration takes over. Floodgate opening can help improve oxygen levels and moderate the fluctuations that can occur in drains, but maintaining the improvement depends on continued exchange with estuarine water. Once the floodgates are closed again, dissolved oxygen levels can quickly revert to previous levels (Figure 32).

There is considerable potential to improve the habitat and water quality in natural and artificial drainage channels, for example by decreasing temperature and light levels through shading. For further information see *'Riparian Land Management Technical Guidelines'* and *'A Rehabilitation Manual for Australian Streams'* available from the Land and Water Australia web site (see p. 47).

CASE STUDY - COMPLEXITIES AND THE IMPORTANCE OF UNDERSTANDING YOUR SITE

Infrequent floodgate opening in some drainage systems may lead to enhanced export of acidity. This is particularly the case at sites with high hydraulic conductivity soils, high groundwater acidity and large tidally influenced water level fluctuations in the drain adjacent to the ASS.

This was highlighted by a field experiment at a site with high hydraulic conductivity soils, where opening floodgates over four days caused recharge of near drain groundwater. When the floodgates were closed again and the drain water level fell, some of this groundwater discharged back into the drain, carrying acidic products with it. This emphasises the need for a clear understanding of the key process operating in any given system.

BENEFIT: LESS MONOSULFIDIC BLACK OOZE IN DRAINS

Monosulfidic black ooze (MBO) describes the black, organic gel-like sludges that form on the base of drains in ASS areas and contain high concentrations of monosulfides, a chemical compound of iron and sulfur (Figure 33).

These reactive monosulfides store acidity and are typically found in drains that are rich in iron and sulfate from ASS groundwater. The significance of MBO lies in its unique chemical characteristics and mobility. Due to its gel-like consistency and high water content, relatively low drain flow velocities can mobilise MBO into the water column. Once mobilised it depletes dissolved oxygen from water rapidly. Experiments have shown just 10 gm of fresh MBO can deplete the oxygen from 1 litre of water in a matter of minutes. After about three to four days the reactive compounds in the mobilised MBO can generate acidity in significant quantities and may lead to a large drop in pH. Some drains in ASS areas can have large accumulations of MBO. If the accumulated MBO is discharged during a high drain flow event, this can cause severe, rapid deoxygenation of receiving waters.

Tidal flushing through open floodgates can help reduce MBO accumulations by limiting the conditions that lead to its formation. This occurs by reducing the time that high concentrations of iron and sulfate are in the drain water, changing the redox conditions of sediments in the base of drains and by enhancing in-drain flow velocities.

BENEFIT: FEWER NUTRIENTS AND ALGAL BLOOMS

The water behind closed floodgates is often stagnant and favours the accumulation of organic matter and nutrients in low flow periods. Many floodplain drains have high nutrient levels which reduce water quality, promote episodic algal blooms (Figure 34) and large daily fluctuations in dissolved oxygen. Opening floodgates and promoting increased tidal exchange, drain flushing and biological activity will reduce the accumulation of nutrients and organic matter over the longer term.

Figure 33. This photo shows MBO (the black material) in the base of a drain after scraping away the surface sediment. The inset is a vertical core in perspex taken from the bottom of a drain. It shows base sediments (grey layer) covered by MBO (black layer) and topped with iron flocs (orange layer). High drain flow velocities can scour the MBO layer and mobilise it into the water column, consuming oxygen and producing acidity. (Photo: Mitch Tulau. Inset: Scott Johnston)

BENEFIT: HEALTHIER DRAIN BOTTOM SEDIMENTS

Sediment on the bottom of drains is often anaerobic due to lack of flushing and accumulation of organic matter. Crabs and other bottom sediment dwelling organisms, which are an important food resource for fish, cannot survive in such poorly oxygenated sediments. This creates a negative feedback loop as burrowing organisms like crabs normally play an important role in keeping sediments oxygenated through turning the sediment over. Regular, long term opening of floodgates will help improve the oxygen content of bottom sediments and improve its habitat value for sediment dwelling organisms.

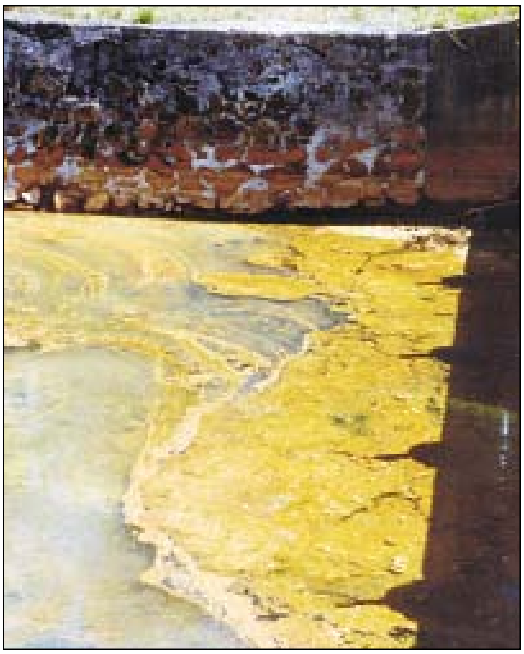


Figure 34. Algal blooms are a common sight in stagnant drain waters. This can cause large cyclic fluctuations in dissolved oxygen with high concentrations during the day and no oxygen at night.

Figure 35. Aquatic weeds in a drain before (left) and after (right) floodgate opening. (Photos: Frederieke Kroon)

BENEFIT: IMPROVED WEED CONTROL IN DRAINS

Aquatic weeds can reduce water flow in drains. They also favour the formation and accumulation of MBO (Figure 33). Salt water in drains can help control many aquatic weeds (Figure 35). Vegetation response to floodgate opening depends on the species and salt concentrations of ingress water.

BENEFIT: ENHANCED WETLANDS

Opening floodgates can also be used as a means of opportunistically ‘harvesting’ water from the river (when it is fresh) for backswamp wetlands. In backswamp grazing systems this can lead to seasonal increases in productivity (see p. 35) and help provide drought refuge and bird habitat. Prior to floodgate and levee construction, small scale flooding due to river flows used to occur naturally on a seasonal basis in many backswamp wetlands.

5.3 Risks of opening floodgates

There are several risks in opening floodgates

- flooding
- increased salt levels
- saline water overtopping
- lateral salt seepage.

RISK: FLOODING

The two main risks of flooding result from operator failure and mechanical failure. Manual floodgate opening devices, like winch gates or sluice gates, require a person to close them. If this fails to occur during high river water levels, flooding can result.

All mechanisms which allow for the opening of floodgates, including existing flap gate hinges, can be jammed open by debris in the drain or river. Devices with a fixed aperture size, such as sluice gates, are less prone to jamming. A regular maintenance and inspection routine can help avoid unwanted device failure. A debris barrier can be used to stop debris from the river entering the gate and jamming it open.

RISK: INCREASED SALT LEVELS

Most coastal floodplain drainage systems are influenced by saline water. Shallow groundwater in former estuarine sediments can also be saline. Many agricultural plants have low tolerance to excess salts in the root zone (Figure 36). Increased salinity in drains may affect their utility for stock watering purposes. Salinity management on the floodplain is perhaps one of the most important issues to understand and cater for from an agricultural perspective. There are two main risks, saline water overtopping drains, and lateral seepage from drains into soil.

RISK: SALINE WATER OVERTOPPING

Overtopping of saline tidal water is probably the greatest concern for landholders interested in opening floodgates, because the salt water can destroy agricultural productivity. Overtopping of saline water on a dry soil surface can have severe negative consequences, depending on the soil type and water salinity levels. Once overtopping occurs there can be rapid movement of water over the surface away from the drain and infiltration down the soil profile. Once in the profile the salt is likely to be slow to leach out, depending on the soil and groundwater characteristics.

Overtopping can be prevented by careful site specific assessment of each drain and the use of appropriate strategies to control water levels in the drain. Four key pieces of information are needed to prevent salt water overtopping

- knowledge of local land elevations next to the drain, particularly the low points
- water heights in the drain
- local tidal height predictions (available in tide charts)
- salinity levels in the estuary.

Controlling the drain water level is the key to preventing overtopping. Tidal anomalies occur relatively frequently on the east coast of Australia, so tides can often be significantly above the level predicted by tide charts. For this reason, floodgate opening devices that allow greater surety of water level control, such as sluice gates and tidal gates, are preferred in drainage systems prone to overtopping.

BEWARE IN SUGARCANE OR CROPPING AREAS WITH MOLE DRAINS!

Salt seepage can be rapid along mole drains. Know your drain water levels and ensure saline drain water does not enter mole drains.

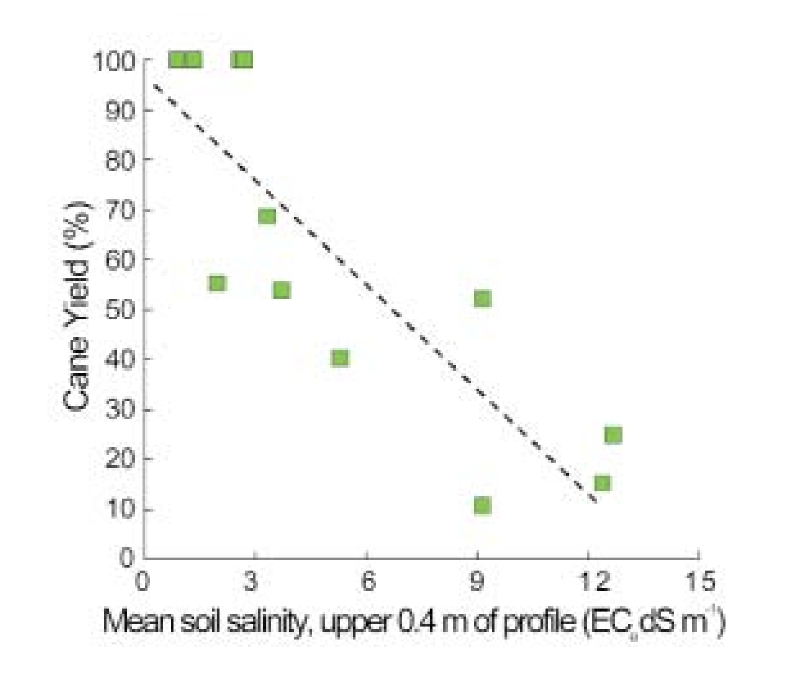


Figure 36. This chart shows a decrease in cane yield in response to increasing topsoil salinity. Managing salinity is an important issue for floodplain agriculture.

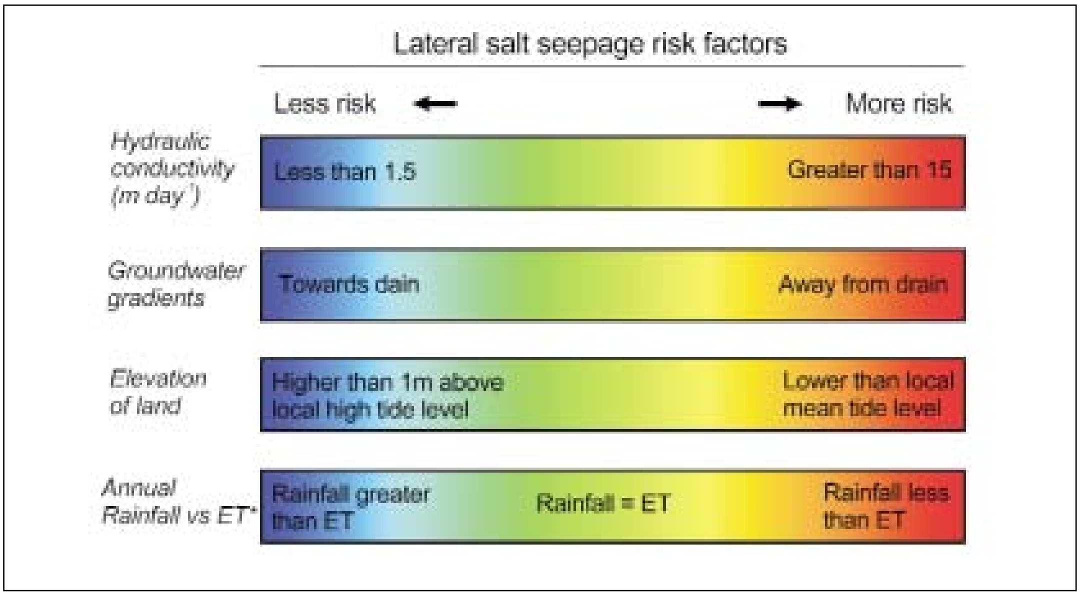
RISK: LATERAL SALT SEEPAGE

Lateral seepage of saline drain water into the groundwater adjacent to the drain does occur. However, research at a number of different sites in NSW and Qld has shown that in cases where the soil hydraulic conductivity is low, lateral seepage is confined largely to a few metres next to the drain bank.

The extent of seepage depends largely on the hydraulic conductivity of the soil and the long term slope of the groundwater gradient. The hydraulic conductivity of soils on coastal floodplains within the inter-tidal range is generally quite low. Long term groundwater gradients often flow towards the drain in many coastal lowlands and are

Figure 37. Marine salts or acid salts? Salts from seawater and ‘acid salts’ from underlying acid sulfate soils can appear identical on the surface and are difficult to distinguish without analysis.

Figure 39. Some of the factors which influence the risk of salt seepage from a drain into adjacent soil. *ET is evapotranspiration.



influenced by elevation and the balance between rainfall and evaporation. Both of these factors limit the risk of lateral salt seepage. Figure 39 lists some of the main factors that influence the likely extent of salt seepage.

However, opening floodgates can change the groundwater gradient by raising drain water levels. Importantly, there are some cases where the hydraulic conductivity of the soils can be very high. In these soils lateral seepage can extend much further into the soil (Figure 40). In such cases, if the drain water has salt concentrations higher than the local groundwater, and the groundwater gradient flows away from the drain, increased salinity in the shallow groundwater and in the rootzone can result. Figure 41 provides a step by step guide to assessing and managing the risk of lateral salt seepage.

Figure 38. Acid groundwater flowing through large soil pores rapidly filling an excavated pit. Even though this acid sulfate soil has a clay texture, it has high hydraulic conductivity and rapid lateral movement of groundwater due to the network of interconnected pores and cracks. (Photo: Thor Aaso)

HIGH OR LOW HYDRAULIC CONDUCTIVITY SOILS?

How can you tell the hydraulic conductivity of your soils? The only way to be 100% sure is to have it tested by someone with expertise. The rate at which a hole dug into the soil fills with groundwater is a reliable indicator. If the infill rate is rapid (minutes) then you may have high hydraulic conductivity soils. Hydraulic conductivity often varies with depth in the soil profile. Further information about testing for soil hydraulic conductivity is available on the guidelines website (see p. 46).

While it is a common perception that sandy soils conduct water very well, the hydraulic conductivity in sandy soils on the floodplain can often be limited by poor structure and fine dispersed clay blocking pore spaces around the sand grains. In contrast, it has been shown that some ASS backswamps with fine textured clay soil can have very high hydraulic conductivity (more than 100 m/day) due to many large pores in the soil associated with old root channels (Figure 38).

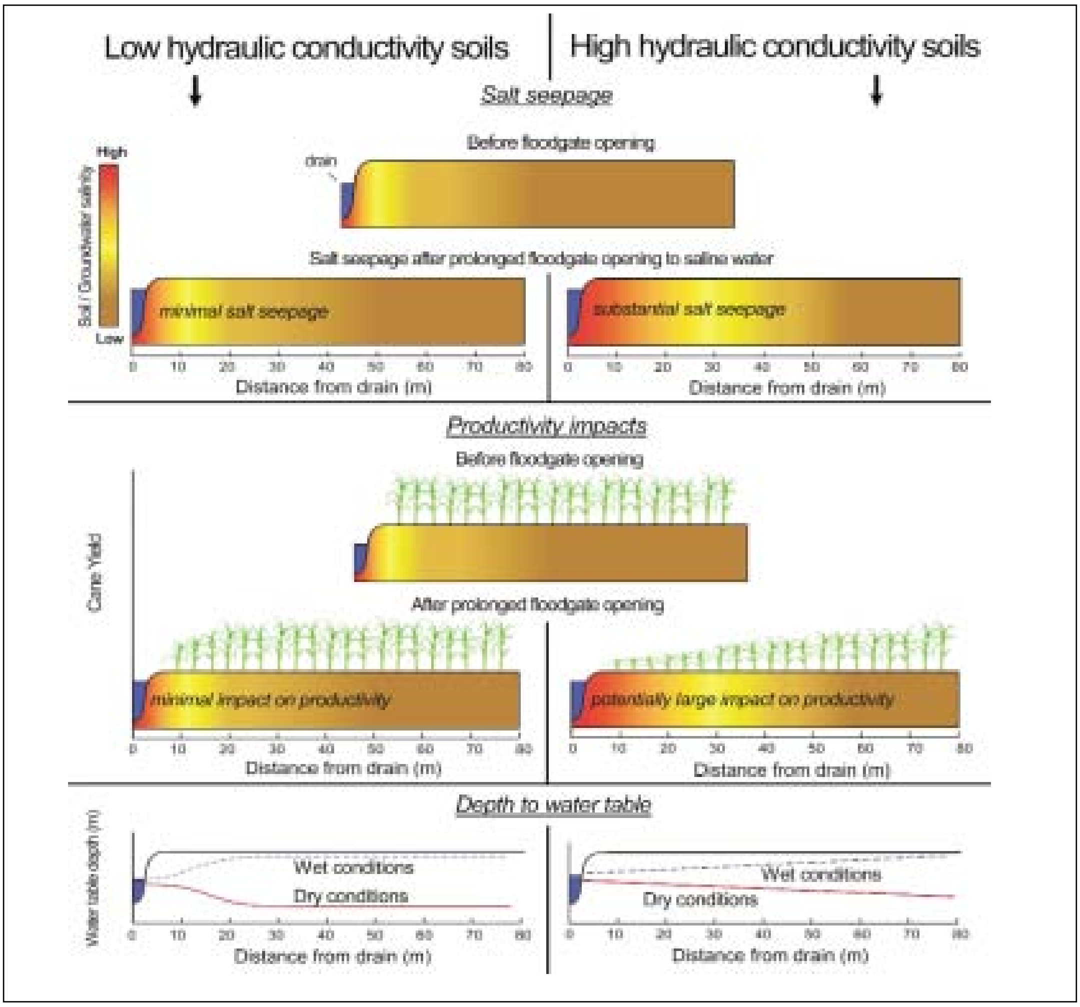


Figure 40. This diagram shows differences in the potential extent of salt seepage and productivity impacts before and after prolonged floodgate opening in relation to distance from the drain in low and high hydraulic conductivity soils. The typical behaviour of the watertable during wet and dry conditions in low and high hydraulic conductivity soils is also shown.

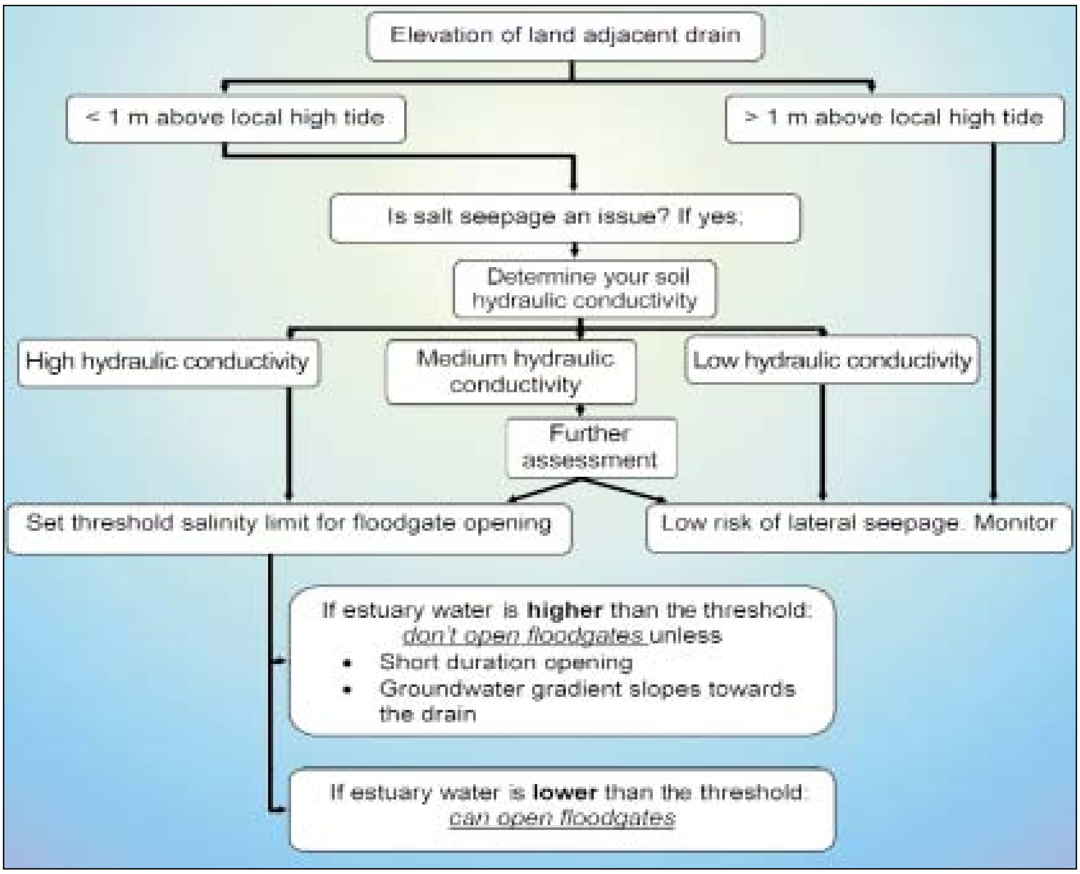


Figure 41. A flow chart illustrating some steps to identify and manage the risk of salt seepage. Suggested limits for hydraulic conductivity are; Low = <1.5 m/day, High = >15 m/day. As a general guide, salinity thresholds can be based on background groundwater salinity levels.

Figure 42. A large set of penstocks in a drain on the Clarence River floodplain. This set is located near the river levee on the floodgate headworks. Penstocks can be used to retain water in the drain. (Photo: Rob Lloyd)

Figure 43. dropboard culverts are a simple way to retain water to a desired level. Leaving a space between the boards and the pipes helps provide better drainage of overtopping waters. (Photo: Rob Lloyd)

5.4 Retaining water in drains

In-drain water retention structures are a flexible water management tool that can be used for diverse purposes. These structures form a partial barrier in the drain and can include penstocks, dropboard culverts and weirs (Figures 42 to 44). They are best located upstream from the floodgates, as this provides more flexible water level control and limits flooding problems.

They can be used to manipulate drain water levels to reduce effluent groundwater gradients and help contain acidic groundwater in the soil profile. They can allow water to be retained on low lying land at a desired level. They can also be used to exclude or confine saline water to a section of the drain where it can be more easily managed. The capacity to confine saline tidal water in this fashion may allow for greater gate opening frequency in some drainage systems.

When planning to retain water, consult your State water licensing authority, Fisheries authority and local flood mitigation body regarding relevant approvals.

RETENTION STRUCTURES

PENSTOCKS

Attributes: Consists of a sluice gate or vertical lift gate placed on the landward side of a culvert.

Advantages: Good seal, good water level control and rarely fail. Low maintenance if made from stainless steel.

Disadvantages: Cost. Can jam open on outflow if vertical winch type gate. A screw thread design prevents this. Manual operation.

DROPBOARD CULVERTS

Attributes: Consists of boards placed in slots in front of any culvert on the landward side.

Advantages: Good water level control. Depth can be adjusted to desired level.

Disadvantages: Often have some leakage. Boards can be difficult to remove under a significant head of water. Hand operated. Generally suitable only for low volume drains.

WEIRS / FIXED SILL

Attributes: Consists of a partial block low in the drain. A wide variety of designs exist with many potential materials (ie sandbags, rock/fill, concrete, steel).

Advantages: Can provide guaranteed minimum water level retention capacity. Potential to vary depth of water retention, depending on design. Low maintenance. Can be low cost, depending on materials.

Disadvantages: Can be difficult to vary once installed, depending upon design. Difficult to remove from drain, depending on design.

Note: a significant disadvantage of retention structures is they inhibit fish passage. See page 39.

5.5 Benefits of retaining water in drains

These may include

- reduced acid export
- increased grazing productivity of backswamps
- enhanced wetlands
- lower fire risk
- less export of 'black' water
- reducing impacts of *Melaleuca quinquenervia* (paperbark tea-tree).

BENEFIT: REDUCED ACID EXPORT

If the main way acid enters a drain is groundwater seepage (see Figure 31), then an in-drain retention structure can be a very effective means of reducing acid export. Acidic groundwater seeps into drains when

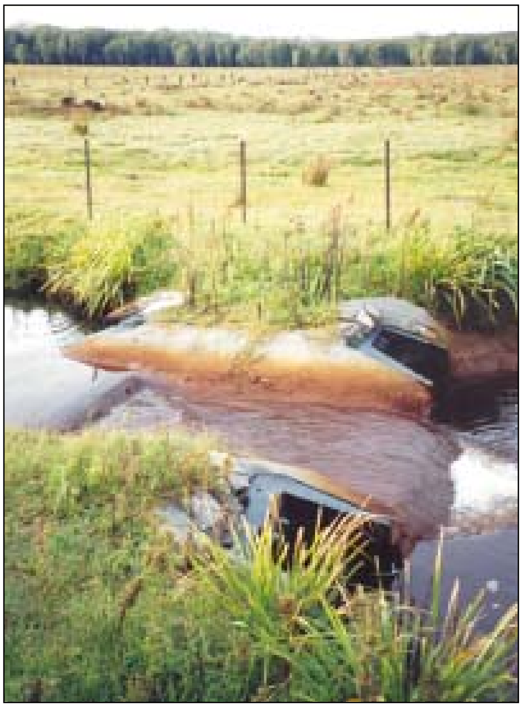


Figure 44. Weirs provide more permanent water retention. This one is used to maintain high drain water levels and reduce acid groundwater seepage.

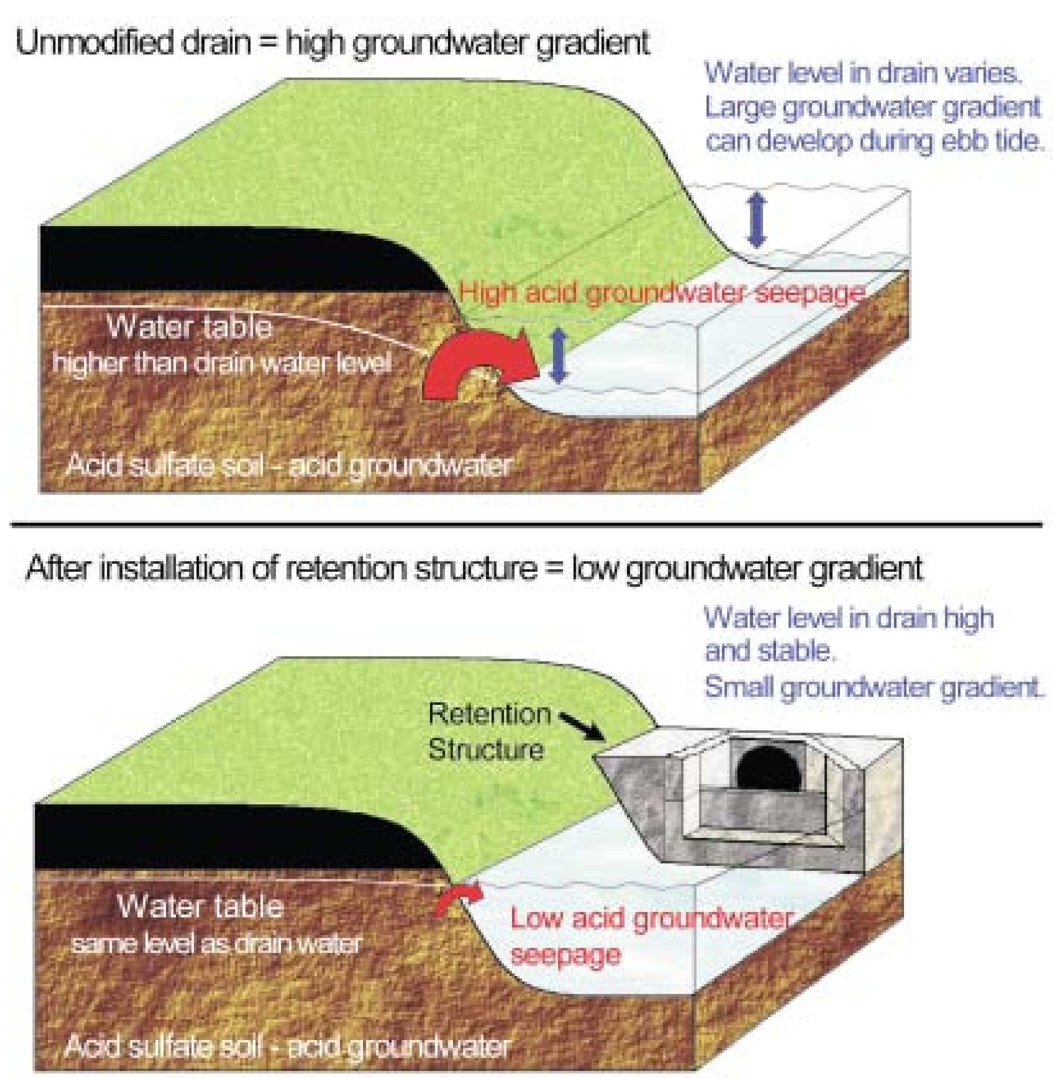


Figure 45. This diagram demonstrates the principle of containing acid groundwater by keeping drain water levels high using a retention structure.

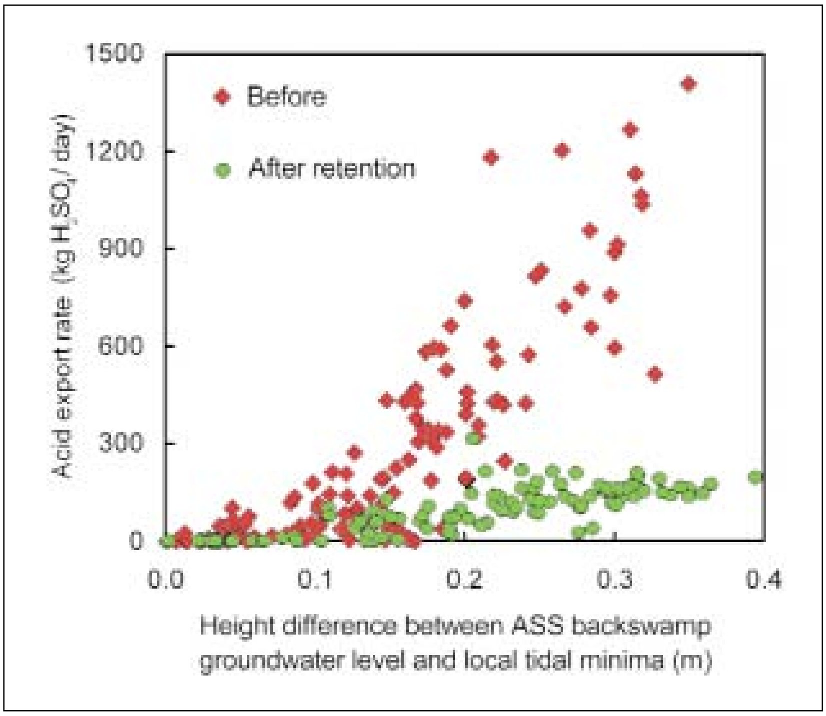


Figure 46. This chart compares acid export rates in a drain before and after the installation of a weir. It shows that acid export rates from groundwater seepage were greatly reduced after the weir was installed. The weir height was set close to the backswamp surface level, which still allowed surface water drainage, but reduced groundwater seepage to the drain (see Figure 45). The results shown are based on several years of intensive monitoring of an experimental site on the Clarence River.

the groundwater level is higher than the drain water level (Figure 45). This means drain water levels can have a big effect on the groundwater gradient in the soil next to the drain. Keeping the drain water high and stable reduces this gradient and limits the amount of groundwater seeping into the drain, causing a significant reduction in acid discharge (Figure 46). Strategically located water retention structures can be used to keep drain water levels above or equal to the groundwater level.

However, if the main way acid enters a drain is surface runoff, then raising drain water levels to reduce groundwater gradients will be less effective. In this case a retention structure can still be used to reduce acid export, but it will need to be high enough to retain the acid surface water.

MODELS FOR MANAGEMENT OF ACIDITY

The following management systems involve manipulation of groundwater and drain water in ASS areas to reduce acid export, but apply to different landuse contexts.

Sugarcane management system = groundwater lower

This model is based on efficient drainage of surface water and keeping the groundwater level generally lower. This maximises the capacity to store rainfall in the soil profile, reduces waterlogging and reduces the time that groundwater seeps into the drain. This model requires laser levelling of the site, shallow drains, fewer drains, regular drain bank liming and liming of pump out water. It is a high cost model that applies to land used for high water use, deep-rooted crops. It works best in low hydraulic conductivity soils.

ASS backswamp grazing management system = drain water higher

This model is based on containing acid groundwater in the soil profile. When the surface water is largely gone or at the desired depth, the drain water level is kept high and stable, ideally higher than or equal to, the level of the adjacent acid groundwater. This helps contain acid groundwater within the soil profile. Evapotranspiration will lower groundwater after that point. This model requires a retention structure such as a sill, penstock, drop-board culvert or weir in the drain next to the ASS area. It is a low cost model that applies to land used for wet backswamp grazing and works in high or low hydraulic conductivity soils. The retention structure can also be used to exclude salt water coming into the swamp. It gives landholders improved flexibility in water level control when used in combination with floodgate opening, but is generally not compatible with sugarcane or cropping.

BENEFIT: INCREASED GRAZING PRODUCTIVITY OF BACKSWAMPS

Floodplain backswamps are highly dynamic and fragile areas. Their vegetation needs to be managed differently to traditional dryland pastures. Strategic use of water retention devices can assist grazing management in ASS backswamps. The devices allow landholders to mimic the natural wetting and drying cycles of backswamps which can yield productivity benefits in some systems (Figure 47). However, a balanced grazing regime in a wet-managed backswamp may reduce the capacity for set stocking rates year round, with productivity becoming more seasonal (Figure 48). Some plant species are better adapted to wetter conditions than others and it is important to match the species with the hydrology (Figure 49).

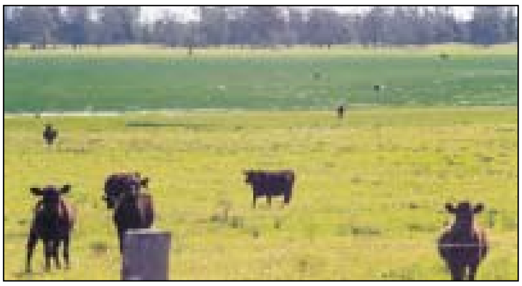


Figure 47. The dark green low area is a wet-managed backswamp. Skilfully managed wet backswamps can have very high seasonal productivity. (Photo: Peter Slavich)

Figure 48. Large seasonal changes in productivity occur in ASS backswamps due to droughts or rapid flooding causing vegetation death. Scalds (top) can be reclaimed (bottom) through water retention and wet management. (Photo: Phil Hirst)

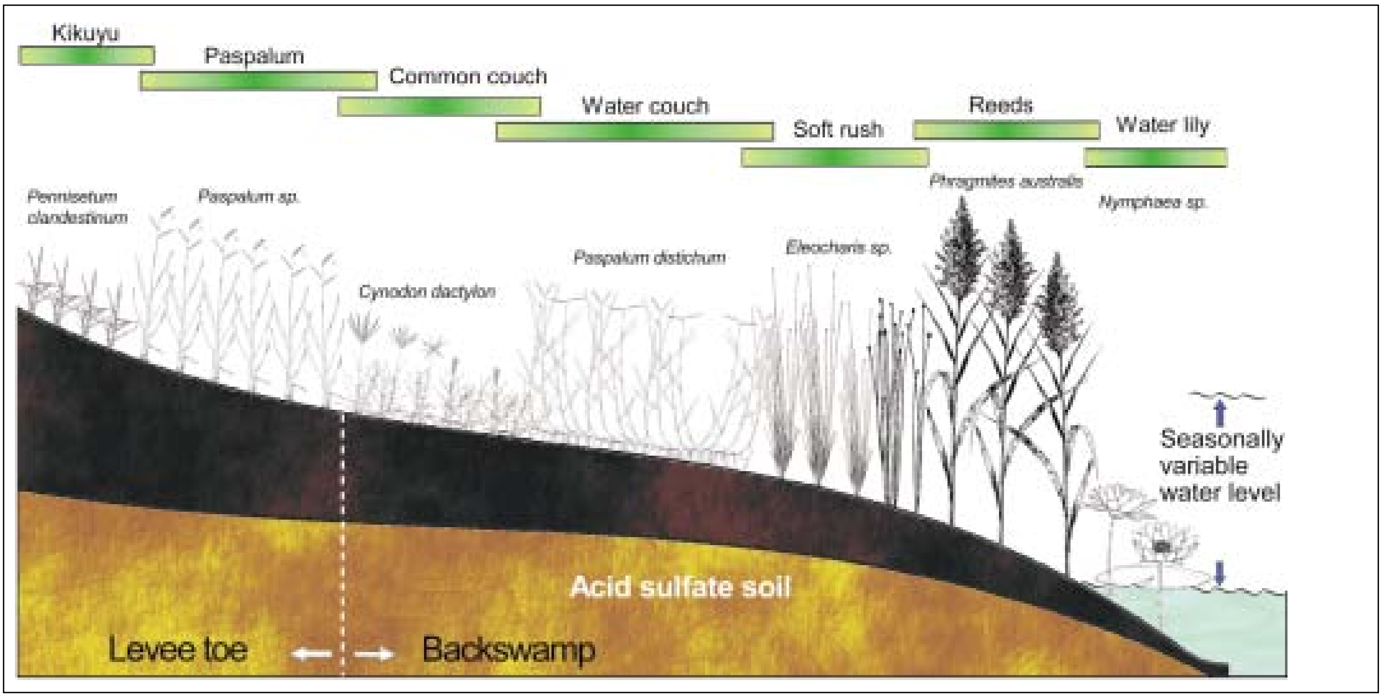


Figure 49. Distribution of backswamp pasture species changes according to topography and water depth / duration of flooding. Vegetation zones are dynamic and migrate according to seasonal conditions. The changes shown above can occur over a 0.5 to 1 m elevation range. [Based on B. Smith[A], 1989]

A balanced wet management regime using water retention structures, water-tolerant pasture species and controlled stocking can have several benefits, including

Figure 50. Fires in backswamps destroy surface organic matter and can lead to long term scalding. (Photo: David McIver)

- greater flood tolerance of pastures
- faster vegetation recovery following shallow flooding
- seasonal productivity boosts
- increased livestock carrying capacity in drought
- improved surface organic matter cover and slower rates of drying out soil surface.
- reduced surface acid accumulation, export and scalding
- reclamation of acid-scalded land.

The productivity and water quality benefits of wetter management can be easily undermined by the loss of surface organic matter. Over-drainage, overstocking and fire can destroy surface organic matter. Stock and fire management are critical issues in backswamps and need to be considered in any management strategy. See 'Coastal backswamps – restoring their values' at the guidelines website for further information.

COMPARING BACKSWAMP PASTURE SPECIES

There are many different native pasture species with varying productivity and seasonal growth characteristics. Their responses to environmental factors such as waterlogging, temperature and salinity also vary. It is important to match the species to the hydrology of the site.

Table 2. A comparison of key characteristics of two backswamp pasture species.

Characteristic	**Common couch *(Cynodon dactylon)***	**Water couch *(Paspalum distichum)***
Waterlogging tolerance	Prefers better drained soils, though it can survive flooding.	Thrives in waterlogged conditions (~0-0.4 m depth).
Salinity tolerance	Good tolerance, but reduced growth.	Excellent salinity tolerance. Successfully grown in salt seeps.
Growth season / optimum temperature	More frost tolerant than water couch. Optimum temperature ~35 C°.	Summer growing. Frost sensitive, though stolons remain green in winter, especially if growing in water.
Productivity	Dry matter yields of >1000 kg/ha per month in summer have been reported.	Dry matter yields of 1200-2000 kg/ha per month in summer have been reported.
Response to grazing	Can withstand very close grazing.	More productive if not overgrazed.
Palatability	Very palatable if kept short. Crude protein from ~8% to 14% in young grass.	Very palatable. Crude protein from ~14% to 19% in vegetative stage.

Figure 51. 'Black' deoxygenated water draining from areas of ASS into brown river water after flooding. Large 'black' water events can deoxygenate entire estuaries and cause the death of many aquatic organisms. (Photos: Mitch Tulau)

BENEFIT: ENHANCED WETLANDS

Water retention structures can help retain natural rainfall and inflows of river water for wetland maintenance and environmental purposes. If you plan to do this it is important to understand the hydrology of the site and obtain expert guidance.

BENEFIT: REDUCED FIRE RISK

Fire can have a devastating effect on backswamps through loss of surface organic matter. Many ASS backswamps have been degraded through peat fires. Burning is best avoided (Figure 50). Maintaining a wetter backswamp through water retention or floodgate opening and river inflows can be a useful fire control measure.

BENEFIT: LESS EXPORT OF 'BLACK' WATER

Some floodplain drainage systems, particularly those in ASS backswamps, can export large volumes of deoxygenated 'black' water to the estuary after flooding. The creation of this water on the floodplain is due mainly to organic matter breakdown after flooding. This water typically has a dark colour and often has a very unpleasant smell (Figure 51). It has high dissolved organic carbon from rotting vegetation, high iron levels and can deoxygenate large volumes of estuarine water, causing fish kills and other adverse environmental effects. While organic matter breakdown after flooding in floodplain wetlands is part of the carbon cycling process, drainage has affected it in several ways.

Drainage hastens and prolongs the transport of this water to the estuary, particularly in the flood recession phase when the river's capacity to dilute this water is reduced. Drainage has encouraged the establishment of flood-intolerant pasture species in backswamps which are more prone to die and decompose after flooding. Drainage has also increased surface concentrations of iron and sulfur from ASS. During

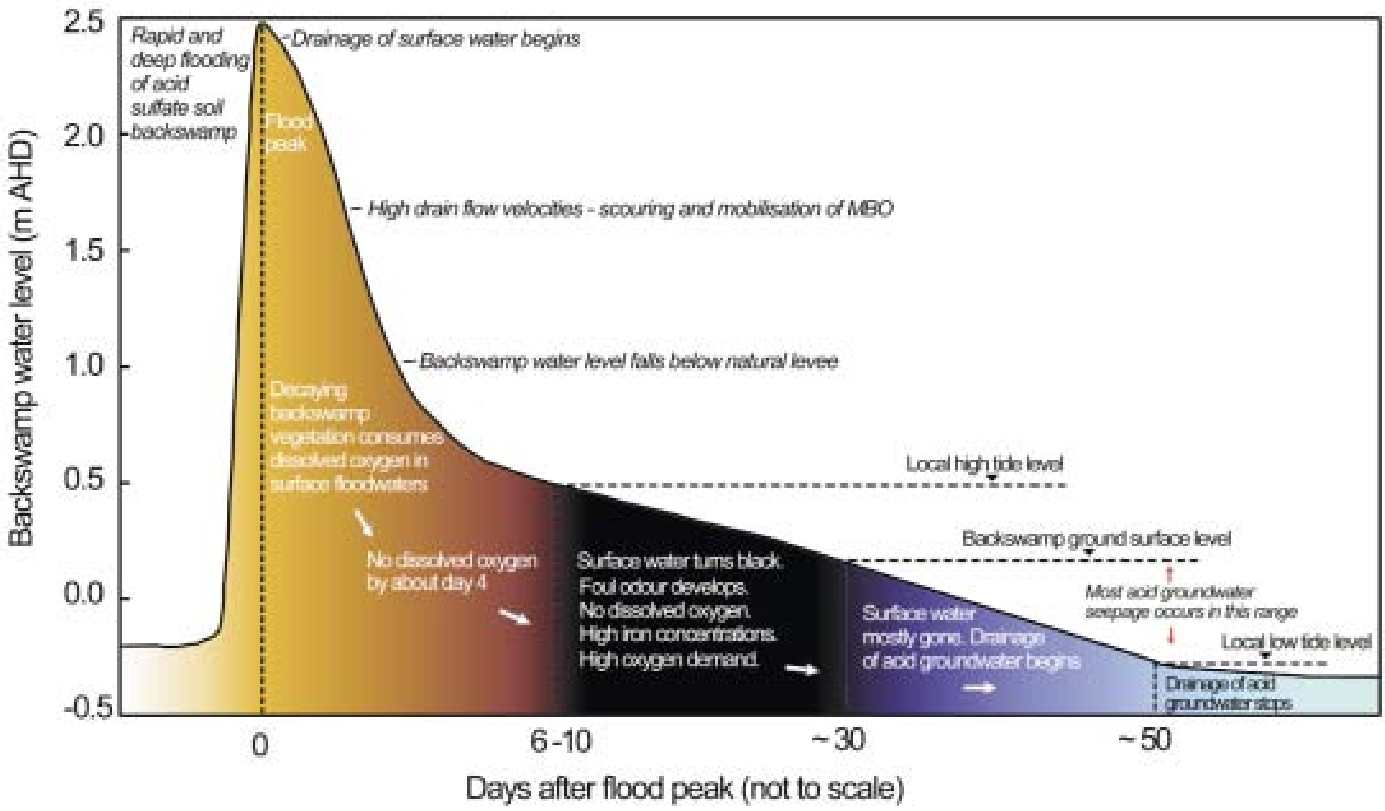


Figure 52: This diagram summarises the general sequence of changes that can occur in drainage water quality from an acid sulfate soil backswamp after deep flooding. It is based on observations made in flooded acid sulfate soil backswamps on the Clarence River floodplain. The precise timing of changes and the actual elevations (ie backswamp surface level and local low tide) will vary between sites, but the general processes still apply. The duration of the acid groundwater seepage phase will be strongly influenced by follow up rainfall.

flooding this can lead to the formation of new pyrite in near surface soils. Importantly, the extra iron and sulfur also affects the chemical processes occurring in backswamp floodwaters and surface sediments in a way that enhances the formation of 'black' water.

Research on the Clarence following severe flooding in 2001 showed the deoxygenation that occurred in the estuary was related to over-drainage of ASS backswamps. Figure 52 is based on this research and summarises some of the general changes in water quality that can occur after deep flooding in an ASS backswamp.

Slowing the drainage rate and retaining the last 0.5 m or so of surface floodwaters in backswamps is likely to greatly reduce the impact of 'black' water. This could be achieved using retention structures. However, this may be too deep for many current land management practices. Encouraging wet-tolerant native pasture species that are more resistant to decomposition following flooding, will also help.

BENEFIT: REDUCING IMPACTS OF *MELALEUCA QUINQUENERVIA*

If you are managing an ASS backswamp in which *M. quinquenervia* encroachment has occurred, then retaining water and encouraging a wetter regime may help limit some of the impacts that can result from such encroachment. Retaining surface water is likely to

- reduce *M. quinquenervia's* reliance on groundwater and the concentration of groundwater acidity
- minimise extra sulfide oxidation
- reduce the risk of fire
- help slow down encroachment.

5.6 Risks of retaining water in drains

The three main risks associated with retaining water in drains are

- impeded fish passage
- reformation and oxidation of surface sulfides
- accumulation of acidity in surface soils.

RISK: IMPEDED FISH PASSAGE

Any retention structure will impede fish passage. Such structures should be used *only* where there is significant benefit, in either reducing chronic acid export or in maintaining / restoring wetland ecological integrity. This will require some balanced consideration of the site context and its resource values and highlights the importance of a thorough initial site assessment to determine what style of management the drainage system is best suited to.

However, 'fishflaps' (essentially reverse facing floodgates) have been designed for weirs and penstocks and can increase fish passage options. Where a retention structure is being considered, the relevant state Fisheries authority should be consulted.

RISK: RE-FORMATION AND OXIDATION OF SURFACE SULFIDES

Sulfide minerals can be reformed near the surface in wet-managed ASS backswamps. The extent to which these minerals form depends on the concentrations of iron and sulfur in the surface sediments and the degree of anaerobic microbial activity.

Formation of these minerals can consume acidity. However, during dry periods they can oxidise and re-release acidity and metals on the soil surface. Increasing the amount of surface organic matter through wise vegetation management can slow the drying processes and subsequent oxidation, and provide organic acids to bind the metals and render them less toxic.

RISK: ACCUMULATION OF ACIDITY IN SURFACE SOILS

Retaining groundwater in areas with shallow ASS has potential to enhance the accumulation of acidic salts in surface soils. This may occur if there are increased evaporative losses from the shallow watertable and a reduction in drainage of acidity from the site. The risk is greatest when there is no vegetation and the soil surface is bare and scalded.

Maintaining surface vegetation cover and a good accumulation of organic matter is an effective means of minimising this risk. Keeping the water level above the ground surface is also effective.

5.7 Infilling and shallowing drains

Infilling, shallowing and reshaping drains can be an extremely effective way of reducing acid export and many of the other negative impacts of over drainage, particularly in ASS backswamps. Infilling and shallowing drains can be part of an integrated strategy involving laser levelling and improved surface drainage efficiency. This strategy is being used increasingly in sugarcane areas (p. 34).

Infilling and shallowing drains may also be used as a means of partial restoration of former wetland hydrology in a grazed backswamp. It is important to seek expert advice and appropriate consents before filling in or shallowing drains.

6. BRINGING IT ALL TOGETHER

Once you have determined your management objectives, assessed the key features of your drainage system and have a clear understanding of the benefits and risks of different options, this information should be used to guide on-ground actions.

Figure 53: Opening up floodgates using a horizontal winch system on a drain in the Clarence River. Floodgate opening devices and opening strategies should be tailored to suit management objectives and the characteristics of individual drainage systems. (Photo: Alan Cibilic)

6.1 Drainage system redesign

Drainage systems can be redesigned to integrate all of the principles outlined in these guidelines. The main aspects of redesign are illustrated in the diagram of a 'model' floodplain drainage system (Figure 54) and would ideally include features such as

- frequent active floodgate management with devices tailored to each system
- strategic use of retention structures to reduce acid export - only where required
- drain infilling and shallowing in ASS backswamps
- tidal flow and fish passage reinstated to natural and modified creeks
- restoration of fish habitat
- separation of wet and dry production systems
- dryland agricultural activities confined to higher areas
- wet backswamp grazing with seasonal, controlled stocking
- wet-tolerant pasture species encouraged in backswamps
- communication, agreement and cohesion amongst all stakeholders
- drain management plans with adaptive, flexible decision making processes
- adherence to industry best management practices guidelines (BMPs)
- drain maintenance plans
- no drain pumping in high permeability ASS backswamps *OR* neutralisation of pump out water
- monitoring changes and access to tidal / salinity information.

These represent ideal features and some will be easier to implement than others.

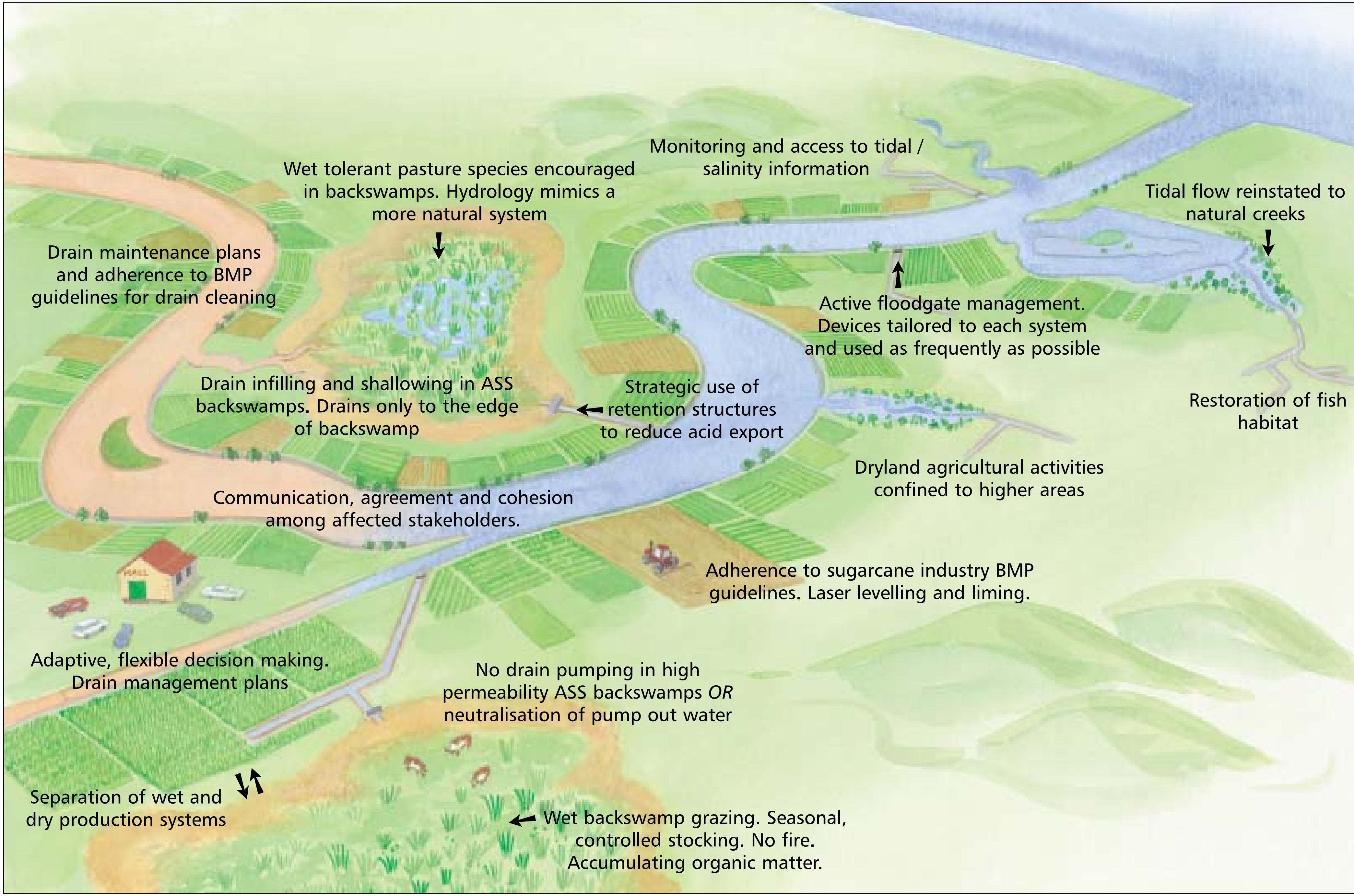


Figure 54: Floodplain diagram 4 – Features of a model floodplain drainage system

6.2 Working together to achieve change

There needs to be agreement, cooperation and open dialogue amongst all affected landholders in any drainage system. Getting agreement between all the stakeholders in a drainage system and working together cooperatively to achieve positive change on

Figure 55: Inspecting a tidal floodgate on a drain in the Clarence River. A cooperative attitude between all stakeholders and a willingness to learn and exchange information are important features of all successful projects. (Photo: Rob Lloyd)

ACHIEVING CHANGE: CASE STUDY - TUCKEAN SWAMP

The Tuckean Swamp is a low-lying ASS backswamp on the north coast of NSW which has been extensively drained for agriculture and has chronic acid drainage water problems. There are many diverse stakeholders including farmers, commercial fisheries, State agencies and local government authorities. Achieving on ground change in the Tuckean drainage system has been a 'slow and steady' process.

In 1996 the Tuckean Swamp Land and Water Management Plan identified acid sulfate soils (ASS) as the major social, economic and environmental issue. The management plan took three years to complete and included a number of technical reports. Landholders however, felt that excessive planning periods risked losing community confidence. They also questioned the disproportionate costs of the planning process in comparison to the implementation funds. This resulted in a difficult environment for on-ground management and landholders needed to gain trust in what was perceived as a top down initiative from government.

Since 1998 the Tuckean Landcare Group Inc. has undertaken a series of State and Federal funded on-ground works and trials to manage acid sulfate soils (ASS). These works have included 'acid containment' through drainage reshaping, in-drain weirs, controlled tidal flushing and grazing management with some very encouraging results.

While these works were being undertaken it became apparent that each stakeholder group had a unique, and on-going, role in addressing the ASS problem. This means that landholders, researchers and government recognise that individually they cannot address the challenges of acid sulfate soil (ASS) management. The lack of input from one of these stakeholder groups limits the usefulness of a project. An inclusive approach has provided a balanced and clear pathway through the many social and political issues of this flood prone coastal environment. As a result, it has been a positive education process for landholders, government officers and researchers alike.

The Tuckean experience demonstrates the need for long term commitment from all parties. It is often unrealistic to expect that problems will be addressed within the limited timeframe of individual government funding initiatives; or through one initial on-ground program by some farmers; or without on-going research to increase understanding and monitor outcomes.

the ground is by no means a simple task. This is often a long process where patience and an open mind are essential ingredients. It can involve many meetings and sometimes a slow building of trust, willingness and understanding. People must *want* to achieve change and be *willing* to overcome obstacles that may arise.

ACHIEVING CHANGE: CASE STUDY - EMPIRE VALE DRAIN

Empire Vale drain on the Richmond River in northern NSW is an example of a successful floodgate opening project. The drain is a partly a modified creek system and was identified as having good potential for tidal flushing. Decaying aquatic vegetation and algae blooms resulted in low dissolved oxygen and episodic fish kills. Discussions between landholders, industry, local government and state agencies in the late 1990s revealed that everyone wanted to improve water quality in the drain. Floodgate opening was proposed as a solution.

The site is located in the lower estuary and often has high salinity. Land elevations are mostly well above local high tide levels and the main adjacent land use is sugar cane. Talks with landholders identified concerns about overtopping and salt seepage. Low points in the drain network were identified using local knowledge and were confirmed by a benchmarking survey using tidal water (see p. 17). Secondary floodgates were installed in one isolated low area to prevent overtopping or tidal intrusion.

Sluice gates with a worm drive mechanism (see p. 20) were installed in 2000. This design was chosen due to the capacity to regulate and fine tune exchange volumes and control maximum water heights in the drain. Trial openings were conducted and a flexible, adaptive management plan developed in consultation with all stakeholders. Conditions under which the gates were to be closed were identified. Monitoring during opening trials showed very limited lateral salt seepage.

Fabricating and installing the gates and safety platforms cost about $15000, with a similar amount being spent by the local government authority on staff time for coordinating and monitoring. Funds for works and monitoring were provided by local government and state agencies.

The result is a drain that is open to tidal exchange with estuarine water about 70% of the time. Water quality, particularly dissolved oxygen, is greatly improved and accumulation of algae and aquatic vegetation is no longer an issue. The tidal range in the drain is about 30 cm and the high elevations of most adjacent land means that the sluicegates can be opened for prolonged periods.

The project was a valuable learning experience which helped build greater trust and goodwill between all stakeholder groups. Important ingredients in the success of this project were landholder willingness, extensive on-ground communication with affected landholders to address their issues of concern, and active support from industry, local government and state agencies.

Figure 56. Installing sluice gates on the Empire Vale drainage system. Selecting drain system management methods should be based on clear objectives and a sound understanding of the key features of the drainage system (see p. 14). The concerns of all stakeholders need to be considered. (Photo: Jon Woodworth)

6.3 Developing a management plan

Achieving balanced outcomes for all stakeholders, resource users and the environment will require changes to drainage system management. Management plans are useful tools for guiding the process of change. They generally include the following components.

- **Management objectives**: Establish objectives which are achievable within the current constraints and review these as understanding grows and constraints change.
- **Drainage system assessment**: Develop an understanding of your drainage system features by answering the questions in section 4.2.
- **Action strategy**: Choose an appropriate strategy to meet your management objectives. This may involve various combinations of floodgate opening, water retention or drain infilling and shallowing. It is important to use devices and methods that accord with both the objectives and characteristics of the drainage system.
- **Risk management strategy**: All the benefits and risks of any strategy need to be considered in context of the site characteristics. Developing ways of managing any potential risks is obviously important. Seeking expert help may be necessary and visiting other sites where changes have already been implemented can be very useful.
- **Review progress:** Monitor and evaluate progress and review and revise the plan regularly.

Developing a management plan requires involvement and communication amongst all stakeholders. A management plan may be a simple agreement or a more complex and formal document, depending on the needs of the stakeholders. It is important to have realistic expectations and recognise that in some situations trade-offs may be necessary. The table below provides some examples of the kind of situations in which trade-offs may occur, but is by no means exhaustive.

Table 3. Some examples of potential trade-offs between different management actions.

Situation and *example action*	Outcome	Trade-off
Chronic acid drain with *periodic floodgate opening*	• Improved fish passage. • Some in-drain dilution / neutralisation.	• Still significant seasonal acid export.
Chronic acid drain with *acid containment using an in-drain water retention structure*	• Significantly reduced acid export from groundwater seepage. • Flexible water level control.	• Barrier to fish passage. • MBO accumulation behind structure. • Increased potential for trapping and loss of juvenile fish recruits. • Slower drainage of residual water.
Chronic acid drain with *drain infilling / shallowing in ASS backswamp*	• Major reduction in acid export. • Less flexibility in water level control. • Less MBO accumulation in drain	• Wetter system. • Less suitable for dryland agriculture.
Low elevation ASS backswamp with *water retention / shallow ponding*	• Increase in wet tolerant pasture species. • Improved drought refuge productivity. • Reduced acid export. • Enhanced biodiversity.	• Reformation of sulfides near surface - risk of acid formation on surface after drought. • Productivity more seasonally variable. • Seasonal risk of increased mosquito populations.
Non-acid drain with *prolonged open floodgates*	• Improved in-drain water quality. • Improved fish passage and access to habitat. • Reduced aquatic weeds. • Reduced mosquito risk.	• Drain water more saline – need to provide alternative stock water. • Need to assess the risk of salt overtopping / seepage and undertake preventative measures if needed.

7. GLOSSARY

anoxic - oxygen deficiency or absence of oxygen.

anaerobic microbial activity - breakdown of organic matter by microbes and bacteria occurring in the absence of air or free oxygen.

acid sulfate soil - a soil which contains sulfides or an acid soil horizon affected by oxidation of sulfides. The exposure of the sulfides to oxygen by drainage or excavation leads to the generation of sulfuric acid. The term acid sulfate soil generally includes both actual and potential acid sulfate soils. Actual and potential acid sulfate soils are often found in the same soil profile, with actual acid sulfate soils generally overlying potential acid sulfate soil.

acid scald - bare soil surface without vegetation due to severe acidity from acid sulfate soils.

AHD - Australian height datum. 0 AHD approximates mean sea level.

black water - very dark coloured anoxic water draining from floodplain backswamps after flooding. This water is derived from the decay of organic matter and typically has a foul odour, high iron levels, no oxygen and a high capacity to strip further oxygen away from any other waters it may come into contact with.

groundwater gradient - the change in hydraulic head (water level) per unit distance. This is the driving force for water flow through soils.

hydraulic conductivity – the rate at which water flows through soil.

MBO - monosulfidic black ooze. Anoxic, black, organic rich, gel like sludge that is rich in highly reactive iron monosulfides. It often forms on the base of drains in acid sulfate soil areas.

oxidation - a chemical reaction generally involving oxygen. Specifically a loss of electrons occurs from one compound to another, ie oxidation of sulfides or decay of organic matter.

potential acid sulfate soils - soils which contain iron sulfides which have not been exposed to air or oxidised. However, they pose a considerable environmental risk and can become very acidic when oxidised.

redox conditions - refers to environmental conditions generally denoting the presence (oxidising) or absence (reducing) of oxygen.

sulfides - mineral compounds containing sulfur and a metal, often iron. Oxidation of iron sulfides (mainly pyrite) is the primary source of acidity in acid sulfate soils.

8. FURTHER INFORMATION

WEBSITE:

A website with a printable version of these guidelines plus related research and extension material* is located at:

- www.agric.nsw.gov.au/reader/floodgate-guidelines
- *For floodgate modification designs see - 'Proceedings of the Floodgate design and modification workshop – Ballina, NSW.' NSW Fisheries, Ballina NSW Australia. Ed: S. Walsh.
- *'Coastal backswamps – restoring their values.' NSW Agriculture, Land and Water Australia, Wollongbar NSW Australia. Author: B. Smith.
- *'Water quality monitoring in acid sulfate soil areas.' ASSMAC, Wollongbar NSW Australia. Authors: C. Collins and S. Henderson.
- *'Hydraulic conductivity – a simple field test for shallow coastal acid sulfate soils.' NSW Agriculture Wollongbar NSW Australia. Authors: S. Johnston and P. Slavich.

RELATED PUBLICATIONS:

- 'Acid sulfate soil scalds: how they occur and best management practices for their revegetation.' NSW Agriculture and ASSMAC, Wollongbar NSW Australia. Authors: M. Rosicky, L. Sullivan and P. Slavich.
- 'Acid sulfate soils: Keys to success.' ASSMAC, Wollongbar NSW Australia. Authors: A. Woodhead, A Jenkins and M. Wood.
- 'Acid sulfate soils remediation guidelines'. NSW Department of Land and Water Conservation (unpub.). Author: M. Tulau.
- 'Acid sulfate soil manual.' ASSMAC and Planning NSW, Wollongbar NSW Australia. Authors: Y. Stone, C. Ahern and B. Blunden.
- 'An introduction to acid sulfate soils.' ASSMAC, Wollongbar NSW Australia. Authors: J. Sammut and R. Lines-Kelly.
- 'Drain and floodgate maintenance procedures.' Clarence River County Council, Grafton NSW Australia. Author: B. Smith.
- 'NSW Sugar Industry best practice guidelines for acid sulfate soils.' Author: NSW Sugar Milling Cooperative.
- 'Review of land and water management impacts upon fisheries and agriculture resources in the lower Macleay – Working Party Report. NSW Agriculture, Wollongbar NSW Australia. Author: B. Smith[A].

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- Department of Infrastructure, Planning and Natural Resources (NSW): www.dipnr.nsw.gov.au
- Wetland Care Australia: www.wetlandcare.com.au
- Clarence River County Council (Clarence Floodplain Project): www.crcc.nsw.gov.au
- Land and Water Australia: www.lwa.gov.au
- Hastings Council: www.hastings.nsw.gov.au
- Kempsey Council: www.kempsey.nsw.gov.au
- Tweed Shire Council: www.tweed.nsw.gov.au
- Shoalhaven City Council: www.shoalhaven.nsw.gov.au
- NSW Sugar Milling Cooperative: www.nswsugar.com.au
- Natural Resources and Mines (Qld): www.nrm.qld.gov.au
- Department of Sustainability and Environment (Vic): www.dse.vic.gov.au
- Water and Rivers Commission (W.A.): www.wrc.wa.gov.au
- Department of Infrastructure, Planning and Environment (N.T.): www.ipe.nt.gov.au
- National strategy for the management of coastal acid sulfate soils: www.affa.gov.au/docs/operating_environment/armcanz/pubsinfo/ass/ass.html

Australian Government
Fisheries Research and Development Corporation
Land and Water Australia
Sugar Research and Development Corporation

Acid Soil ACTION

NSW Fisheries

NSW Agriculture

Clarence River County Council
Floodplain Management

wetlandcare australia

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