


Saltwater Wetlands Rehabilitation Manual

Department of **Environment & Climate Change** NSW

Cover photos (main image, clockwise):
Black-winged stilt (Tony Karacsonyi, DECC);
Bruguiera gymnorhiza, River mangrove, Sarcocornia (Adam Gosling, WetlandCare Australia)

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Contents

CD Contents

Preface

Saltwater wetlands are important features of the NSW coastal zone. They provide an array of social, economic and environmental services. Although the degradation and loss of coastal wetlands has occurred in the past, awareness of their ecological significance has created greater interest in the preservation of existing wetlands, rehabilitation of degraded wetlands and construction of new wetlands.

This manual aims to increase knowledge and understanding of saltwater wetlands and to be a key resource in the field of rehabilitation and management. This manual focuses on the rehabilitation of wetlands influenced by brackish or saline waters. These wetland types are home to swamp forests, saltmarshes, mangrove forests and seagrass beds.

A general overview of saltwater wetland environments, their rehabilitation and the use of this manual is provided in Part 1. Part 2 provides specific advice for planning and implementing saltwater wetland rehabilitation projects. Part 3 of the manual is on the accompanying CD and provides information about saltwater wetland characteristics and processes.

Contributors

The production of this manual was a collaborative effort between the Department of Environment and Climate Change and the Department of Commerce (Manly Hydraulics Laboratory). Contributors included Kerryn Stephens, Dayle Green, Dr David Rissik, Phil Anderson, Dr Pia Laegdsgaard, Dr Brian Wallace, Dr Ian Turner, Peter Nelson, Dr Julie Phillips and Ann Finnigan.

The symbols in chapter 11 are used courtesy of the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Centre for Environmental Science.

(Adam Gosling, WetlandCare Australia)

Part 1
Overview

1 Introduction

1.1 Background

Wetland habitats of NSW have been severely degraded and depleted since the arrival of Europeans in Australia over 200 years ago, helped by the fact that in excess of 80% of the population of NSW live near coastal waterways and their accompanying wetlands. It is estimated that over 60% of the State's coastal wetlands have been lost or severely degraded (Bowen *et al.* 1995). In some areas up to 70% of wetlands have been destroyed (Merrin and Chafer 2000). In addition, the distribution of specific wetland types such as saltmarsh has been severely reduced (for example, by 80% in the Sydney region, Stricker 1995).

> *Wetlands have not had such a good image in the past. For centuries they were mistakenly seen as wastelands, places of little value that were better exploited for urban or rural expansion.*
>
> *As the understanding of how wetlands operate has improved, the perceptions about wetlands have changed and today they are recognised as valuable natural and community assets.*
>
> *Across Australia it is estimated that around 50% of the wetlands have been destroyed since European settlement. This has served to deprive many individual landholders, and the broader community, of the many services and benefits that wetlands provide.*
>
> *Source:* Bennett *et al.* (2001)

Physical changes to coastal wetlands have resulted from poor catchment management practices, land reclamation, agricultural drainage works, urbanisation, and construction of navigation channels, ports and canals. Recent awareness of the ecological significance of wetlands has created greater interest in the preservation of existing wetlands, rehabilitation of degraded wetlands and construction of new wetlands. The destruction or degradation of coastal wetlands is a common issue that has been raised in many of the estuary management plans that have been developed in NSW over the last 15 years or so.

Clyde River estuary and wetlands (DECC)

Hunter River estuary and wetlands (DECC)

1.2 Aim of this document

In recent years there has been a significant increase in the amount of information available in Australia regarding the design, implementation, use and management of constructed and rehabilitated wetlands. For inland and freshwater environments, this has been addressed by *The Constructed Wetlands Manual* (DLWC 1998). The aim of that manual is to provide readers with sufficient information to plan, design, construct and operate a freshwater wetland. It provides comprehensive information on many aspects of constructed freshwater wetlands, with an emphasis on the use of natural wetland processes to treat and manage urban runoff or polluted discharges.

While *The Constructed Wetlands Manual* (DLWC 1998) is useful in providing guidelines and general information on wetland rehabilitation, it does not specifically address saltwater wetlands, which lie within or adjacent to estuarine or coastal environments and are either permanently or occasionally inundated by brackish or saline waters.

The aim of this *Saltwater Wetlands Rehabilitation Manual* is to provide technical information and guidance to assist with the rehabilitation of degraded saltwater wetlands, that is, restoration to a functional condition. Saltwater wetlands have complex hydraulic, physical, chemical, biological and ecological interactions which are quite different from those of freshwater wetlands and which need to be understood and addressed before rehabilitation is undertaken. Furthermore, there are significantly different issues for excavation and construction works in saltwater wetlands, due to the physical (low strength, saturated conditions) and chemical (potentially low pH, highly saline and high organic content) nature of soils in these areas.

The construction of new or compensatory wetlands is not specifically addressed here, though many of the principles and techniques discussed in this manual are applicable. The advice in this manual regarding construction techniques generally relates to construction within existing saltwater wetlands for purposes such as water treatment or habitat enhancement.

1.3 Objectives

The objectives of the manual are:

- to provide land managers and community groups with sufficiently detailed information to design, implement, manage and monitor a saltwater wetland rehabilitation project
- to provide a logical and robust process for wetland rehabilitation, capable of accommodating developing technologies, information, concepts and ideas
- to provide sufficiently detailed information to convey the complexity of saltwater wetlands ecosystems to assist with planning and management of rehabilitation projects.

1.4 Document style and scope

The manual has been prepared for a target audience including:

- technical staff in local government (engineers, planners and landscape architects)
- technical staff in government agencies
- consultancy firms and construction companies
- potential operators, managers and owners of rehabilitated saltwater wetlands (private landholders, agencies, local councils, community groups and schools)
- community groups.

Particular features of the manual include:

- a scientific approach to projects with an emphasis on planning and setting objectives
- encouragement of optimal design through community involvement, multidisciplinary project teams and other techniques
- an outline of an optimal sequence and relationship of tasks during the various project phases from planning through to implementation, operation, maintenance and monitoring
- information on the best available techniques, methodologies and tools for achieving the objectives of the rehabilitation process
- the inclusion of detailed background information on saltwater wetland flora, fauna and physical processes to assist with planning and decision making.

The issues relating to saltwater wetlands are often complex. Where possible, the manual includes simple guidelines to address some of the tasks involved in wetland rehabilitation. As far as possible, the manual has been written in plain English with technical jargon **bolded** and described in a glossary of terms.

A comprehensive literature review has been undertaken during preparation of this manual. A bibliography is included to ensure an authoritative document, and to allow the reader to follow up more detailed information if required.

Information relating to general principles and processes of rehabilitation is applicable to all readers interested in saltwater wetland environments. Information relating to soils, tidal processes, flora and fauna is relevant to NSW and adjacent areas with similar climates, coastal processes and vegetation characteristics. Information relating to legal and policy issues is confined to the Commonwealth and NSW legislative processes and, while correct at the time of publication, may change.

1.5 Restoration or rehabilitation?

The terms 'restoration' and 'rehabilitation' appear to have similar meanings and are often used interchangeably. But within the field of ecology there are subtle differences dependent on the expectations or outcomes that are desired.

The goal of restoration is typically to return a degraded ecosystem to its natural or original state by removing the cause of degradation. Rehabilitation, on the other hand, seeks to improve or recover natural functions and processes without necessarily achieving the pre-disturbance condition. Rehabilitation therefore aims to improve wetland health and function to whatever degree is considered feasible.

The term 'restoration' is widely used in overseas literature in relation to wetland recovery projects. However, in Australia, 'rehabilitation' appears to be more commonly used, perhaps because it is considered a more practical and achievable endpoint. This manual uses the term 'rehabilitation', in acknowledgment of the fact that full restoration to natural conditions is often not possible, given the many stresses that may be acting upon a wetland.

1.6 Description of saltwater wetland types

Estuaries are semi-enclosed bodies of water with a permanent or intermittent connection to the ocean that are characterised by brackish or saline water derived from the mixing of marine and fresh waters. In NSW, estuaries may comprise a number of interrelated wetland habitats, including swamp forest, saltmarshes, mangroves, seagrass beds, reedbeds, shallow sand and mud flats, rocky shores and reefs, and deeper waters.

This manual focuses on the rehabilitation of wetlands whose inundation regime and vegetation characteristics are influenced by brackish or saline waters. These wetland types are home to swamp forests, saltmarshes, mangrove forests and seagrass beds.

Swamp forests

Swamp forests occur around the margins of many estuaries, forming a buffer between dryland communities and the estuaries. The structure and species composition can vary considerably with physical factors, but many consist principally of swamp oak (*Casuarina glauca*), paperbark (*Melaleuca* spp.) or swamp mahogany (*Eucalyptus robusta*), with an understorey characterised by vines, shrubs and a groundcover of forbs, sedges, grasses and leaf litter.

Saltmarshes

Saltmarshes occur at the upper levels of the **intertidal** zone. They are not subject to daily tidal inundation but may be flooded by larger tides. In NSW, saltmarshes are characterised by herbaceous species such as samphire (*Sarcocornia quinqueflora*), saltwater couch (*Sporobolus virginicus*) and rushes (for example, *Juncus kraussii*).

Mangrove forests

Mangroves grow along the shorelines of many NSW estuaries in areas subject to regular tidal inundation. The two most common species are grey mangrove (*Avicennia marina*) and river mangrove (*Aegiceras corniculatum*).

Mangroves (Adam Gosling, WetlandCare Australia)

Seagrass beds

Seagrasses grow in the **subtidal** zones of estuaries. The most common species are eelgrass (*Zostera* spp.), paddleweed (*Halophila* spp.), strapweed (*Posidonia australis*) and sea tassel (*Ruppia* spp.). Seagrass meadows may be **monospecific** or consist of a number of species.

1.7 The importance of saltwater wetlands

Saltwater wetlands are significant features of the coastal zone with many different social, economic and environmental values. A range of services derived from saltwater wetlands are shown in Table 1.1 (overleaf).

Swamp forest communities are found on the coastal floodplains of NSW. Swamp forests are generally associated with clay-loams and sandy loam soils, where the groundwater is saline or sub-saline, on waterlogged or periodically inundated flats, drainage lines, lake margins and estuarine fringes associated with coastal floodplains. The community is important in terms of habitat value, **riparian** protection, flood control and water quality improvement.

Both mangroves and saltmarsh occupy a unique transitional position between purely aquatic and purely terrestrial environments. They have a number of important structural functions, including flood and erosion control, buffering storm surges, and improving water quality by filtering pollutants and excess **nutrients**. In addition, mangrove forests are important habitats for fish, molluscs, crabs, bats and birds, and the trees provide large amounts of organic matter as a food source for the estuary. Saltmarshes support a rich and diverse community of **invertebrates**, provide roosting sites for many species of birds, and provide habitat for juvenile fish when inundated (Morrisey 1995, NSW Fisheries 1999).

Seagrass meadows are important for sustaining recreational and commercial fisheries, by maintaining sediment stability and water quality in estuaries and providing food and shelter for fish, particularly during their juvenile life stages (Bell and Pollard 1989).

Rehabilitation projects usually aim to protect or restore some of these values. A key goal of wetland rehabilitation is to maintain an ecologically healthy, functioning system that maintains its structure over time and is able to recover from stress.

The key threats to the biological health and integrity of saltwater wetlands relate mainly to various human activities that occur in the coastal zone or within coastal river catchments, including:

- drainage
- dredging and stream channelisation
- human-induced climate change and sea level rise
- deposition of landfill
- structural works (levees, floodgates, dams, weirs and road culverts)
- urban development, including stormwater runoff
- air and water pollutants
- introduction of non-native and invasive species
- agricultural activities, including grazing by livestock and runoff
- river regulation and water extraction
- recreation, including boating and four-wheel driving.

Saltmarshes are particularly susceptible to disturbances from both natural and anthropogenic sources. Four-wheel drive vehicles, grazing and trampling by livestock, flooding, fires, drainage works and floodgates can all easily destroy saltmarshes.

Seagrass beds may be directly affected by dredging and reclamation; artificial opening of coastal lagoons; structures such as breakwaters, jetties, ramps and pontoons; boating; oyster leases; and diffuse and point-source pollution (Smith *et al.* 1997).

As a result of the large losses of saltwater wetlands in NSW, remaining wetlands have been protected through a variety of legislation and policy (see Chapter 12). For example, a number of saltwater wetland communities have been listed under the *Threatened Species Conservation Act 1995* (TSC Act) as endangered ecological communities. These include coastal saltmarsh and swamp oak floodplain forest in the NSW North Coast, Sydney Basin and South-East Corner bioregions.

Table 1.1 Services provided by saltwater wetlands

(Relative magnitude (per unit area) of ecosystem services derived from different types of wetland ecosystems: Millennium Ecosystem Assessment 2005).

Services	Comments and examples
PROVISIONING	
Food	Production of fish, algae and invertebrates
Fresh water	Storage and retention of water; provision of water for irrigation and drinking
Fibre, timber, fuel	Production of timber, fuelwood, peat, fodder, aggregates
Biochemical products	Extraction of materials from **biota**
Genetic materials	Medicine; genes for resistance to plant pathogens; ornamental species
REGULATION	
Climate regulation	Regulation of greenhouse gases, temperature, precipitation and other climatic processes; chemical composition of the atmosphere
Biological regulation	Resistance of species invasions; regulating interactions between different trophic levels; preserving functional diversity and interactions
Hydrological regimes	Groundwater recharge and discharge; storage of water for agriculture or industry
Pollution control and detoxification	Retention, recovery and removal of excess nutrients and pollutants
Erosion protection	Retention of soils
Natural hazards	Flood control; storm protection
CULTURAL	
Spiritual and inspirational	Personal feelings and wellbeing
Recreational	Opportunities for tourism and recreational activities
Aesthetic	Appreciation of natural features
Educational	Opportunities for formal and informal education and training
SUPPORT	
Biodiversity	Habitats for resident or transient species
Soil formation	Sediment retention and accumulation of organic matter
Nutrient cycling	Storage, recycling, processing and acquisition of nutrients

Scale is low ●, medium ●, to high ●; blank cells indicate that the service is not considered applicable to the wetland type. The information in the table represents expert opinion for a global average pattern for wetlands; there will be local and regional differences in relative magnitudes.

	Estuaries and marshes	Mangroves	Lagoons, including salt ponds	Intertidal flats, beaches and dunes	Rock and shell reefs	Seagrass beds
	⬤	⬤	•	●	●	•
	•		•			
	⬤	⬤	●			
	•	•				
	•	•	•			
	●	●	●	•	•	•
	●	⬤	●	•	•	
	•		•			
	⬤	⬤	●		•	•
	●	⬤	•			•
	⬤	⬤	•	•	●	●
	⬤	•	●	⬤	•	•
	⬤	•	•	⬤		
	●	•	●	●		
	•	•	•	•	•	
	●	●	•	⬤	⬤	•
	●	●	•	•		
	●	●	●	•	•	

1.8 How should I undertake the rehabilitation process?

This manual provides a process for the effective rehabilitation of saltwater wetlands which encourages rehabilitation based on accurate assessments of the problems, in a manner which is adaptive and therefore able to be changed in response to changing conditions or additional information. The science of rehabilitating saltwater wetlands is still in its infancy in Australia. While some wetland rehabilitation projects have been successful, several have been unsuccessful, and many have been poorly assessed or not assessed at all.

The scale and location of the project being undertaken will determine the effort required in the various stages of the process, but all stages are important to consider and will assist with effective outcomes. Many saltwater wetland species require specific environmental elements for successful establishment and growth. Tidal influence, elevation and topography are essential components to get right in the overall plan and design. The selection of a suitable site for rehabilitation will depend on local conditions, works required and the species to be encouraged or planted. Some aspects of rehabilitation will be more important in some locations than in others; for example, designing saltmarsh rehabilitation so as to minimise mosquito numbers will be more important in wetlands adjacent to urban areas. Greater success will be achieved if adjacent sites are fully functioning ecosystems rather than highly degraded areas.

A flow chart of the suggested process for undertaking rehabilitation projects in saltwater wetlands is presented in Figure 1.1. The major tasks are outlined below and discussed in greater detail in Chapters 2 to 6.

Project management

Overall management of the project should be thought out and clearly articulated. Project management will include the setting up and support of a working group, steering committee or other project 'driver'. Roles, responsibilities and time frames should always be clearly defined.

Selection of wetland and identification of issues and values

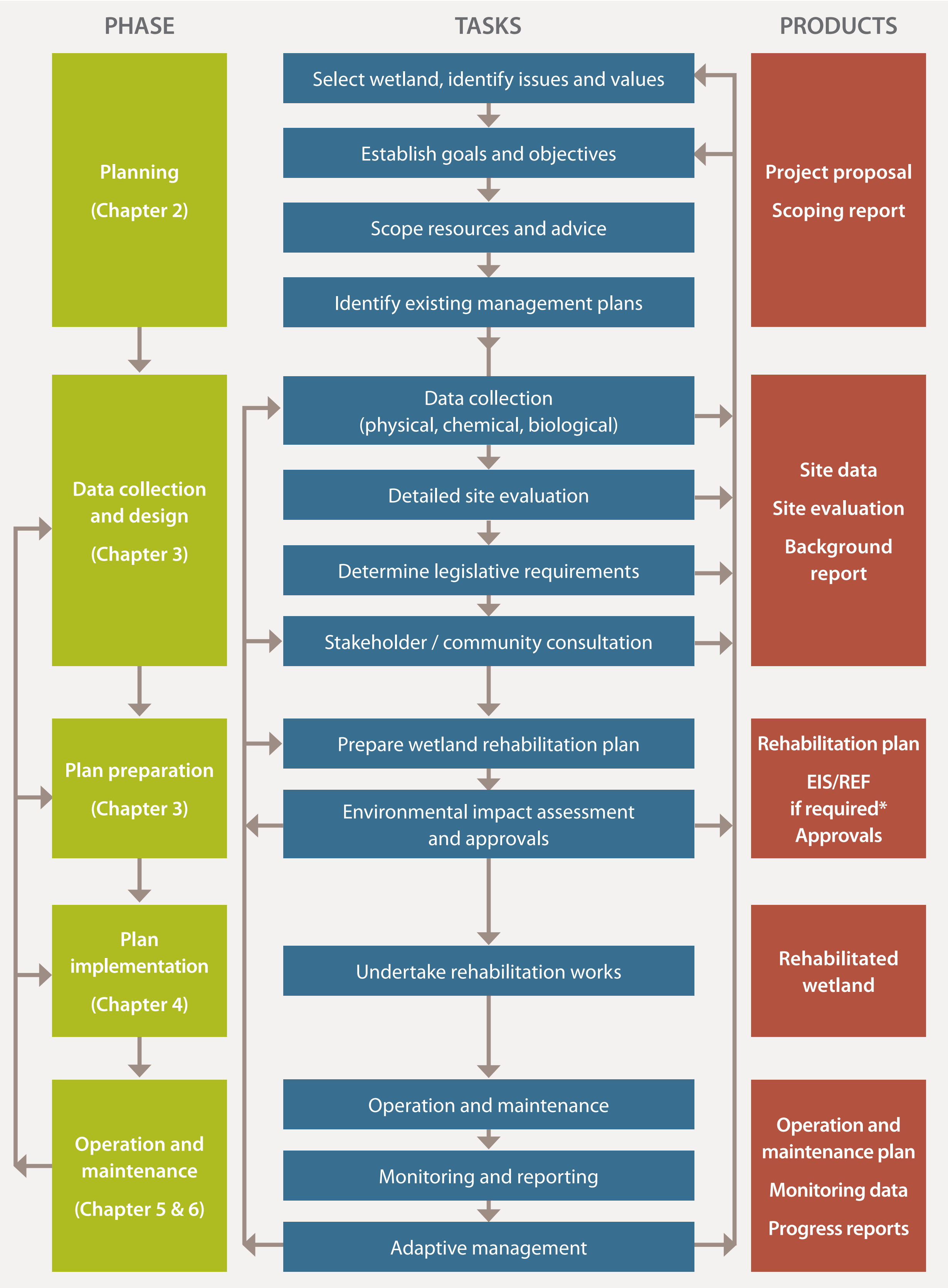
The decision to rehabilitate a wetland is usually made to fulfil a specific objective, which in turn reflects the values that are attributed to wetlands. Values can be diverse and may include scenic quality, recreational opportunities or presence of waterbirds.

Identifying the issues of concern is an important step in the planning process, and can help to focus wetland rehabilitation activities. Issues that are of common concern in NSW saltwater wetlands include water quality, loss or degradation of habitat, weed encroachment, bank erosion, **sedimentation** and changes to fauna populations. It is important to remember that wetlands are generally the receiving waters for the surrounding catchment and thus can be significantly affected by activities within the catchment, as well as those acting directly on the site.

Establishing goals and setting objectives

Regardless of the size of the rehabilitation or constructed wetland project being considered, it is essential that clear, measurable goals and objectives be established. Establishing clear objectives enables you to assess the problem and determine what needs to be done to improve the wetland or to achieve your objectives. Good and focused planning enables identification of materials, labour activities and time frames that will be needed to achieve project goals.

Figure 1.1 Flow chart indicating the management process to achieve effective rehabilitation of saltwater wetlands



*EIS Environmental Impact Statement
REF Review of Environmental Factors

Scoping resources and advice

It is often necessary to solicit advice and help for the planning, undertaking and funding of wetland rehabilitation projects. Advice can generally be sought from a range of specialists, including State agencies, Catchment Management Authorities (CMAs), local councils, non-government organisations and consultants. The amount of advice required depends on the goals and objectives, extent and degradation of the site, and type of wetland.

Integrating with existing management plans

Rehabilitation projects must be fully integrated with other rehabilitation plans in the area and be consistent with the objectives and processes outlined in other management plans relevant to the area such as catchment action plans and estuary management plans. These plans will generally be available through local councils or State agencies.

Data collection

The amount of data collection required will depend on the scale and nature of the project and the amount of information that is already available. The information collected should aim to support a good understanding of the major issues, the natural processes occurring in the wetland and the general biological and hydrological characteristics of the wetland. It will be necessary to identify and understand both the processes currently occurring and those that would be occurring if the wetland were in pristine condition. Where little information is available about a wetland, it may be necessary to begin a data collection program a year or more before preparing a rehabilitation plan.

Detailed site evaluation

A detailed site evaluation is necessary to establish the causes of degradation of the wetland, and the limitations and potential for a range of rehabilitation activities. The site evaluation usually involves several visits to the wetland and analysis of all the available information. The results of the site evaluation should assist in determining the appropriate rehabilitation activities, future data needs and possible monitoring requirements.

Consideration of legislative and legal requirements

After the basic outline of the rehabilitation plan has been prepared, any requirements of legislation or regulatory agencies should be considered, including what level and form of environmental assessment and approval is required.

Liaison and consultation with community and stakeholders

Effective consultation with the various interested parties is essential for the perceived success of the project. This process must begin as early as possible and ensure full involvement of all stakeholders.

Preparation of a wetland rehabilitation plan

Some form of rehabilitation plan should be prepared for each project. While the amount of detail in the plan will vary with the size and complexity of the project, the plan should include broad and specific rehabilitation objectives and specific actions. Actions should be prioritised as far as possible, and time frames, performance indicators, costs, funding sources and other resource requirements should be specified.

Environmental impact assessment and approvals

Obtaining approval to make environmental changes can be a complex and time-consuming process. In NSW the requirement for environmental impact assessment is determined by the *Environmental Planning and Assessment Act 1979* (commonly referred to as the EP&A Act). Wetland rehabilitation activities may require consent from your local council or various State Government departments (and sometimes both). In addition, Commonwealth legislation may sometimes apply.

Undertaking rehabilitation works in accordance with the rehabilitation plan

Implementation of a rehabilitation plan involves the on-site actions required to set up the rehabilitation processes, such as the construction of works and the establishment of plantings.

Operation and routine maintenance of the rehabilitation plan

Plan operation involves all the actions required to ensure continued management of the rehabilitation plan, and normally involves the preparation and implementation of an operation and maintenance plan. While rehabilitated ecosystem functions should be designed to be as self-sustaining as possible, it is likely that at least in the short to medium term, regular operational activities such as inspections, weeding, and maintenance of structures will be required.

Regular monitoring and reporting of agreed success measures

Effective monitoring is critical to the success of a wetland rehabilitation plan. Without proper monitoring the degree of success or failure of a rehabilitation plan cannot be properly judged. The progress and outcomes should be monitored and reported, even if the plan is not being implemented successfully. A well-designed monitoring program with clear objectives and measurable performance criteria will ensure that important information is available at key stages of the plan, and will facilitate informed wetland management decisions in the future.

Adaptive management and fine-tuning of the rehabilitation plan

Owing to the complexity of estuarine systems and the current state of knowledge, management of a saltwater wetland rehabilitation project must be adaptive. That is, management must change if monitoring results indicate that certain objectives have not been achieved. The addition of new knowledge or data or changes in rehabilitation techniques may also necessitate changes to the rehabilitation plan over time (Dialogue Box 1.1).

Dialogue Box 1.1 Adaptive management of Millennium Wetlands

An example of adaptive management can be seen from the Millennium Wetlands at Homebush Bay (near the Sydney 2000 Olympics site). A large area of saltmarsh and mangroves was earmarked for rehabilitation a few years before the Olympics were due to begin. The main objectives at that time were to:

- reduce mosquito breeding
- improve habitat for wading birds
- increase the extent of saltmarsh
- increase the diversity of **benthic** macroinvertebrates.

The main management tool was the use of improved flushing; a number of culverts were built, and two main drainage channels were deepened. The result was vastly improved flushing, draining all water out of the wetland in each tidal cycle. The rapid influx and efflux of the large volume of water reduced mosquito breeding, but eventually resulted in erosion and reduction of use of the area by native birds.

Following this, a decision was made to monitor the movement of water into, out of and within the wetland to determine the effects of changing the flushing regime. The results showed that appropriate changes could be made to the flushing capacity of the system to reduce erosion and increase mudflats and habitat for migratory birds.

1.9 Principles to incorporate in wetland rehabilitation

The following principles offer a useful starting point for wetland rehabilitation. Incorporating these principles into your project design will help provide the foundations of a successful wetland rehabilitation project. (The principles have been adapted from US EPA 2000 and the Ramsar Convention on Wetlands 2002.)

Conserve and protect aquatic resources

The maintenance and conservation of existing wetlands is always preferable and more economical than their subsequent rehabilitation. Existing, relatively intact ecosystems are critical for conserving biodiversity, and provide the biota and other natural materials needed for the recovery of degraded systems. Even in wetlands for which rehabilitation is planned, the first objective should be to prevent further degradation.

Aim for ecological integrity

Rehabilitation should re-establish as far as possible the ecological integrity of degraded habitats, that is, the structure, composition, and natural processes of the biological communities and physical environment. An ecosystem that retains integrity is a resilient and self-sustaining natural system able to withstand or recover from a certain level of stress and change.

Restore natural structure and function

Many wetlands in need of rehabilitation have problems that originate from alteration of their natural form or other physical characteristics. Structure and function are closely linked in wetlands and estuaries. Re-establishing the appropriate natural structure can bring back beneficial functions and is essential to the success of other objectives, such as improving water quality or restoring native biota.

Work within the catchment and broader landscape context

Whenever possible, plan for wetland rehabilitation at the catchment level. Activities throughout the catchment can have adverse effects on the subject wetland. A localised project may not be able to change what goes on in the whole catchment, but it can be designed to better accommodate catchment effects.

Understand the natural potential of the catchment and anticipate future changes

The environment and our communities are both dynamic. Establishing rehabilitation goals for a wetland requires knowledge of the historical range of conditions that existed at the site before degradation and what the future conditions might be. Although it is impossible to precisely plan for the future, many foreseeable physical, ecological and social changes can be factored into rehabilitation design.

Address ongoing causes of degradation

Rehabilitation efforts are likely to fail if the sources of degradation persist. It is essential to identify the causes of the degradation and eliminate or remediate stresses wherever possible. While degradation can be caused by one direct impact, much degradation is caused by the cumulative effect of numerous, indirect impacts.

Develop clear, achievable, measurable goals

Clear goals provide direction for a rehabilitation project and provide the standards for measuring success. Goals should be achievable ecologically, given the natural potential of the area, and socioeconomically, given the available resources and the extent of community support for the project.

Involve the skills and experience of a multidisciplinary team

Rehabilitation can be a complex task that integrates a wide range of disciplines, including ecology, **hydrology**, **geomorphology**, engineering, planning and social science. To the extent that resources allow, the planning and implementation of a rehabilitation project should involve people with experience in the disciplines needed for the particular project.

Involve all relevant stakeholders

Wetland rehabilitation should be an open process that involves the local community and other stakeholders who may be affected by or have an interest in the project. It will be essential to secure the support of any potentially affected neighbours. All stakeholders should be fully involved in wetland rehabilitation from the earliest stage of the project through its implementation to its ongoing management.

Design for self-sustainability

Successful rehabilitation should, as far as possible, be designed for self-maintenance. High-maintenance activities not only add costs to the project, but also make its long-term success dependent on human and financial resources that may not always be available. Where self-sustainability is unlikely, it is important to recognise the need for long-term stewardship and the resources and commitment needed to sustain this stewardship.

Use passive rehabilitation when appropriate

'Time heals all wounds' may apply to some rehabilitation sites. Before actively altering a wetland site, determine whether passive rehabilitation (that is, simply reducing or eliminating the sources of degradation and allowing recovery time) will be enough to allow the site to naturally rehabilitate.

Restore native species and avoid non-native species

Many **introduced species** out-compete natives because they are expert colonisers of disturbed areas and lack natural controls. Invasive, non-native species should not be used in a rehabilitation project, and special attention should be given during the project to avoiding the unintentional introduction of such species at the site.

Use natural fixes and ecological engineering techniques where possible

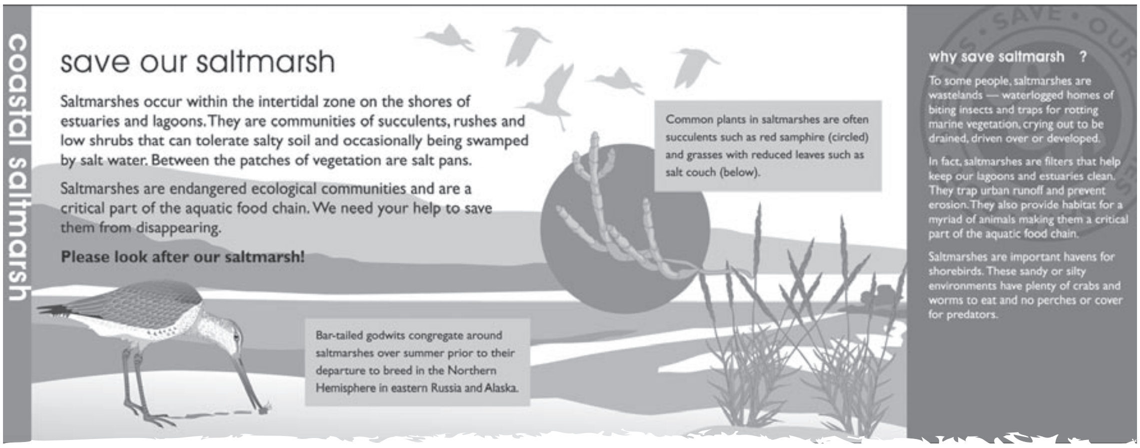
Whenever possible, apply ecological engineering principles and methods in preference to methods requiring hard structures or extensive construction works. Ecological engineering uses living, functioning systems to prevent erosion, control sediment and pollutants, and provide habitat. Examples include the use of constructed wetlands for the treatment of stormwater and the rehabilitation of vegetation on river banks to enhance natural filtering of runoff.

Monitor and adapt where changes are necessary

Monitoring before and during a rehabilitation project is crucial for determining whether goals are being achieved. If they are not, adjustments to the project should be made. It may also be necessary to make changes to the project to accommodate unforeseen circumstances or to take advantage of newly acquired knowledge and resources. This process is known as adaptive management.

Share the results of rehabilitation projects

Successful rehabilitation projects can provide inspiration for continuing stakeholder involvement and for the development of further projects. Information on the results of a rehabilitation project should be widely disseminated in both scientific forums and more accessible sources available to the community and stakeholders. Where possible, wetland rehabilitation should be coupled with measures to raise awareness and influence the behaviours and practices that led to the degradation of the wetland in the first place. Methods to raise awareness of the importance of the rehabilitation site may include information days, media coverage and the use of interpretive signage on site.



Interpretive signage, Koona Bay, Lake Illawarra (DECC; Site Specific Pty Ltd)

(Conservation Volunteers Australia)

Part 2
Project planning and implementation

2 Planning for wetland rehabilitation

The first stage of any wetland rehabilitation project is the planning and design phase. The concepts must be clearly thought out at this stage if the project is to be a success. Good planning, including setting time frames and staging goals, can avoid misunderstandings and the decreasing motivation that may occur if expectations of the working group are not fulfilled within a reasonable time frame. Planning also allows identification of appropriate resources and the timing of activities to achieve objectives. For example, if migratory birds use the wetland as a feeding ground during the Australian summer, it is necessary to recognise this during the planning phase and to conduct any potentially disrupting activities during winter.

2.1 Why rehabilitation?

Reasons for selecting a wetland or part of one for rehabilitation are generally related to the values that stakeholders assign to that wetland. The values that are assigned will in themselves have implications for the management of the wetland (Table 2.1).

Social reasons

When human development occurs near wetlands, there is often a desire to improve the aesthetics of the wetland. Aesthetics can be taken to include scenic quality, amenity related to odours and mosquitoes, and opportunities for recreation, tourism, education, scientific study and social activities.

The protection of **cultural values**, especially those associated with indigenous and European cultural heritage sites and areas, can be a reason for rehabilitation of a saltwater wetland.

Table 2.1 Values and management implications for saltwater wetlands

Value	Management implications
Social	Maintain aesthetics through overall wetland structure Provide appropriate access for recreation and tourism Maintain and commemorate significant sites as far as possible and link them with other management strategies Identify and provide infrastructure and resourcing for development of educational and scientific opportunities with linkages to recreation and commercial opportunities Limit encroachment of rural and residential development (includes managing flood risks) and ensure community activities are compatible with maintaining ecological health Manage odours and mosquitoes
Environmental	Maintain water quality, flora and fauna distributions (including protection of threatened species), hydrological regimes and soil integrity Maintain overall integrity of saltwater wetlands (the importance of this will increase with climate-induced sea level rise and storms)
Economic	Ensure commercial activities are sustainable and compatible with maintaining other wetland values

Mangrove forest, Tweed River estuary (Adam Gosling, WetlandCare Australia)

Environmental reasons

Habitat creation, expansion, enhancement and maintenance within saltwater wetlands can be important for birds, fish, invertebrates, mammals, reptiles and amphibians, including native and migratory species, as well as for overall biodiversity.

Improvement or maintenance of natural resources within a wetland such as water quality, soils and hydrological regimes will in turn benefit surrounding areas.

A plan of management such as an estuary management plan may include as an action the rehabilitation of a saltwater wetland. Such an action would therefore contribute to the overall health and protection of the estuary.

Owing to the combination of values attached to a wetland, the wetland may be considered regionally significant or rare and hence require rehabilitation to maintain those values. Rehabilitation of such wetlands may in turn contribute to regional biodiversity.

Economic reasons

Commercial and economic activities such as extractive industries can result in the need to rehabilitate saltwater wetlands. Alternatively, activities such as ecotourism require degraded wetlands to be rehabilitated for the activity to be viable.

If human activity results in the destruction of a saltwater wetland – for example, through construction of public infrastructure – it may then be appropriate to rehabilitate another wetland or to create new habitat to compensate for the loss of the existing values.

2.2 Identification of issues

The identification of issues will provide direction to rehabilitation activities and assist in prioritising work programs. Issues should be identified in consultation with the full range of stakeholders who have an interest in the site. Some of the issues that may be important for a wetland are described below.

Uncontrolled vehicle access through a wetland (DECC)

Catchment status and activities

As most saltwater wetlands receive runoff from the surrounding catchment, it is important to review the health, processes and activities of the catchment to identify their potential impacts on the wetland. This may include surrounding industry and considering any past and present pollution discharges to the wetland. Encroachment into the wetland by surrounding uses or terrestrial species may also be an issue. Unless catchment effects are addressed, wetland rehabilitation activities could be unsuccessful.

Integration with surrounding management

Management of saltwater wetlands cannot be considered in isolation, but must be integrated with planning policies and management objectives and plans in the surrounding area.

Estuarine and coastal processes

As saltwater wetlands are part of the estuarine or coastal zone, they are affected by estuarine and coastal processes. These processes can include tidal flows and inundation, wave activity and sediment transport by water and wind action. Climate-induced changes will also affect these processes. The effects of these processes need to be considered in the planning of rehabilitation activities.

Climate change processes

Although many aspects of climate change are not easily predicted, it is likely that wetlands will be affected through a number of processes, including sea level rise (see Chapter 7), increased sea temperatures, changes in hydrology, and increases in the frequency and intensity of extreme events such as storms, droughts and floods.

Adaptation strategies need to be considered in the planning of rehabilitation activities. The prevention of additional stress may improve the ability of wetlands to respond to climate change (Bergkamp and Orlando 1999). Reducing pollution, avoiding vegetation removal and protecting wetland biological diversity and integrity will be viable activities to maintain and improve the resiliency of wetland ecosystems so that they continue to provide important services under changed climatic conditions (Kusler and Burkett 1999). Another important adaptation strategy is preventing the fragmentation of existing wetland systems and buffer zones that allow for landward vertical migration of wetlands if sea level rise exceeds the rate of vertical sediment accretion.

Available methods of rehabilitation

Rehabilitation strategies must be compatible with the methods available, otherwise the strategy will not be successful. Review of other rehabilitation projects and scientific literature may be required to determine the most appropriate method to achieve rehabilitation goals.

Beneficiaries

The non-human and human beneficiaries of the rehabilitation activities need to be identified to ensure the activities are appropriate. Conversely, if there are likely to be those who may not benefit from the activities, their concerns should be addressed as early in the process as possible.

Water quality

Identification of the current status of and processes affecting water quality in the wetland will normally be critical to planning and design of a rehabilitation project. Poor water quality can influence the quality of wetland habitat and the chemical processes that occur within wetlands. These in turn may affect the diversity of flora and fauna that can be supported.

Foreshore erosion

Foreshore erosion is a common process in saltwater wetlands. The extent to which this erosion should be managed and the means of doing so must be considered in conjunction with the causes of the erosion. Causes of erosion may include wind-waves, boat wash, removal of riparian vegetation or alterations to natural flow patterns.

Sedimentation

Sedimentation resulting from catchment runoff, input from estuary and coastal sources and reworking processes within the estuary can affect the water flow and volumes within the estuary as well as the distribution of mangroves, saltmarsh and seagrass.

Degradation of habitat, including loss of vegetation and weed encroachment

Swamp forest, mangroves, saltmarsh and seagrass are important habitat types, and their degradation significantly reduces the value of saltwater wetlands. Saltmarshes and swamp forest in particular are vulnerable to weed invasion, which can reduce the habitat value of the wetland for fauna species. The major weed species in saltmarsh include *Juncus acutus*, groundsel bush (*Baccharis halimifolia*), pampas grass (*Cortaderia selloana*) and American pennywort (*Hydrocotyle bonariensis*). The weed species found in swamp forest are numerous and include whiskey grass (*Andropogon virginicus*), madeira vine (*Anredera cordifolia*), crofton weed (*Ageratina adenophora*), camphor laurel (*Cinnamomum camphora*), lantana (*Lantana camara*), small-leaved privet (*Ligustrum sinense*), Japanese honeysuckle (*Lonicera japonica*) and wandering jew (*Tradescantia fluminensis*).

Lantana removal, Tom Thumb Lagoon (Conservation Volunteers Australia)

Changes to faunal diversity

The preservation of faunal diversity has local, regional, national and international implications. Predation by pest fauna such as foxes and cats can reduce the viability of wetlands as faunal refuges.

2.3 Setting goals and objectives

Many wetland rehabilitation projects suffer from poorly stated goals and objectives. Establishment of goals and objectives helps to provide direction to a project and facilitates a clear vision of the desired outcome. The overall success of the project will generally be measured against its goals and objectives by the measurement of performance criteria. It is essential to set clear goals and objectives to ensure that methodologies chosen for the rehabilitation project are not in conflict.

Setting clear goals and objectives help in integrating your project with other plans. How do your goals and objectives fit in with other management actions that are occurring in the area?

Goals are general statements about the desired outcomes of the project. Stating goals allows all people involved to understand in general terms the desired results. In general, goals focus on the values to be restored, enhanced or protected. Goals should be achievable in realistic time frames, or should be staged for longer, more complex projects.

Objectives are specific statements about the desired outcomes of the project. Projects typically have more than one objective, reflecting the multiple functions that individual wetlands perform. Objectives must be unambiguous and measurable and should preferably include time frames. In this way it is possible to test them effectively and make necessary adjustments to management plans. Adjustments may be required if improved knowledge becomes available or because the management actions prove to be ineffective.

Performance criteria are observable or measurable attributes that can be used to determine whether a project meets its intended objectives. Each objective will have at least one performance criterion. It is essential that any measurements be conducted using appropriate methodologies and at appropriate scales that account for natural variability. Information on monitoring is provided in Chapter 6.

Dialogue Box 2.1 Examples of goals, objectives and performance criteria

Project 1

Goal: Increase the quality of wildlife habitat at wetland X.

Objective: To improve habitat value for migratory waterfowl by 2010.

Performance criterion: The abundance of key migratory species using wetland X.

Project 2

Goal: Restore the extent of tidal wetlands of River Y to pre-1970 conditions.

Objective: To increase the area of saltmarsh communities by 50% by 2015.

Performance criterion: Area in hectares of saltmarsh.

Project 3

Goal: To protect and manage the remnant native vegetation of Lake Z.

Objective: To protect riparian vegetation communities by the exclusion of stock within 3 years.

Performance criterion: Area in hectares of vegetation fenced from stock.

The objectives for rehabilitating saltwater wetlands vary, but are often focused on enhancing conditions for native fauna, enhancing visual amenity or expanding the occurrence of rare species. Some of these goals may be mutually exclusive, so it is essential to consider the goals for rehabilitation before initiating works. For example, creating habitat for waders may not necessarily enhance visual amenity or expand the occurrence of a rare plant. Optimising habitat for one faunal group may be detrimental for another, or may create conditions for undesirable species such as mosquitoes.

You may need to ask whether your project aims to provide habitat for a range of species to conserve biodiversity, or to a particular species such as an endangered shorebird. Where the latter applies, the ecology of the target species will be essential knowledge for input to the project design. Typically, the aim of rehabilitation projects should be to provide habitat for a diversity of saltwater wetland plants and animals.

The design of wetland rehabilitation projects must therefore be planned carefully to ensure the right balance between wetland values and to ensure that appropriate measures are implemented for the proposed goal.

2.4 Scoping resources and advice

Once goals and objectives have been set, it is then possible to understand and begin planning the full scope of the project. At this stage the need for specialist advice, funding and other resources can be considered.

Gathering information

Undertaking a review of similar projects either from the literature or from site inspections is an essential task in order to obtain ideas on preferred rehabilitation strategies, technical and practical problems that may be encountered, and time frames over which similar rehabilitation projects have been achieved. The review may also lead to the identification of important contacts, consultants or suppliers that will be useful to the project. The information obtained from this process should be documented in a background or scoping report, along with information obtained during the data collection phase (Chapter 3).

Expert advice is not always free of charge, but the ramifications of not having good advice are large and can be costly. The need for specialist advice should be factored in when scoping the project budget.

Advice can be obtained from a range of sources, including:

- local, State and Commonwealth Government agencies
- special-interest groups including community-based environmental centres
- academic institutions
- libraries and online resources
- specialist consultants in fields such as construction and wetland rehabilitation, hydraulics, hydrology, water quality, and flora and fauna.

Increasingly, information from Commonwealth, State and local authorities is being made available via the Internet. For example, a number of natural resource datasets can be accessed through the *NSW Natural Resource Atlas* (www.nratlas.nsw.gov.au).

The NSW Comprehensive Coastal Assessment toolkit (Department of Planning 2007) provides comprehensive data and information on coastal values and attributes to enable better decision making. The toolkit contains information on environmental, economic, social and cultural heritage issues along the coast. Datasets available include aquatic habitat maps, showing the location and extent of mangroves, saltmarsh and seagrasses; contextual information such as potential aquaculture areas; fish species distribution and biodiversity; and soil and land feasibility maps.

Obtaining funding

Possible sources of funding need to be considered. Rehabilitation projects are eligible for funding under various Commonwealth, State and local programs. In particular, CMAs can often provide advice on available grant programs.

Funding for community-driven projects may be available through the Caring for our Country program. Caring for our Country incorporates the former Natural Heritage Trust and a number of other natural resource management funding programs. Local government, community groups and individuals can apply for grants to carry out actions to target local problems. Your local CMA can provide further information about gaining funding, or you can visit the natural resource management funding website (www.nrm.gov.au).

Funding for works by local councils and other public land managers may be available through the NSW Estuary Management Program, administered by the Department of Environment and Climate Change (DECC; www.environment.nsw.gov.au). The program was established to restore and protect estuaries along the NSW coast. Works funded through the program need to be consistent with a relevant estuary management plan, coastal zone management plan or other strategic plan.

The NSW Department of Primary Industries (DPI) administers the Saltwater Fish Habitat Grant Program to encourage the community to rehabilitate fish habitats so as to achieve long-term improvements to fish numbers and recreational fishing opportunities. Details can be found at www.dpi.nsw.gov.au/fisheries.

The NSW Environmental Trust is an independent statutory body established by the NSW Government to support exceptional environmental projects that do not receive funds from the usual Government sources. One of the objectives of the Trust is to encourage and support restoration and rehabilitation projects. The Trust is administered by DECC (www.environment.nsw.gov.au).

Some stakeholders may be willing to provide 'in-kind' assistance. For instance, an oyster farming association may be willing to provide access to water quality monitoring data that it collects. This can be a good way of encouraging long-term support for the project. Ongoing assistance and financial or technical contributions are more easily achieved if desired outcomes are clearly stated, the nature of the contributions are clearly defined, and all assistance is appropriately acknowledged.

A rehabilitation project will be carried out in various stages from plan preparation to implementation through to operation and monitoring. The latter stages of the project are just as important as the earlier stages. If funding is being sought on a stage by stage basis, it should be remembered that not carrying out subsequent stages of the project may jeopardise the success of the whole project.

2.5 Integrating with existing management plans

Integration with planning policies, management objectives and natural resource management plans applicable to the surrounding area is an important consideration. During the information-gathering process discussed in Section 2.4.1, a search for applicable policies and plans should be made, noting main points from these.

Integrating with broader plans can ensure that activities that will add value to the success of your project will be undertaken simultaneously; for example, if the local council were undertaking a catchment-wide education plan to reduce sediment runoff. This ensures that maximum benefit can be obtained through the rehabilitation process (positive cumulative impact). It also prevents duplication of effort, which saves money and makes the rehabilitation process more efficient.

Local goals should be complementary to or consistent with regional goals. Alignment of objectives with other plans can also be useful when you are attempting to obtain funds. Funding bodies are more likely to invest in well-thought-out, structured, focused actions which provide outcomes of relevance to them.

Consult the Local Environment Plan (LEP) for your local council area, as well as relevant Regional Environment Plans (REP) and other planning policies. Further information on these and other legislation is provided in Chapter 12.

Catchment action plans are natural resource management plans that aim to make improvements to a wide range of natural resource conditions, including coastal and marine waters, rivers and wetlands, soils, coastal lakes and estuaries, threatened species, and native vegetation. The plans are prepared by CMAs and aim to coordinate all environmental work in a region through community partnerships and collaborations. The plans list the most important environmental issues in the catchment and can therefore guide investment and rehabilitation works to where they are most needed.

Dialogue Box 2.2 An example of integrated management

A local community group wanted to rehabilitate a small area of saltmarsh (25 m^2) near their homes. The area consisted of some sparse *Juncus kraussii*, some *Sporobolus virginicus* and a variety of weed species. Because no historical information about the area had been sought and no information about the substrate in which the saltmarsh had established had been gathered, the group was unaware that it was above a large area of reclaimed land.

They were also unaware that an estuary management plan had been prepared for the area, and that a high priority of that plan was the removal of the filled area and re-grading of the edges of the wetland. The plan also included a massive replanting program for that particular area as well as for other small wetlands around the estuary.

When the group became aware of the management plan, they were able to integrate their objectives with those of the plan and work together with local council staff during the replanting and management phases.

3 Data collection and plan preparation

3.1 Data collection

Gathering information about your wetland and the type of management activities you are planning will assist you in reviewing your objectives, assessing how achievable they are, identifying data gaps and planning a future monitoring program.

The amount of detail required will depend on the size and scale of the proposed project, the amount of information that is available about the site, and the complexity of the site. For example, water movement within and about wetlands can be highly complex, and understanding it may require elaborate equipment and sophisticated analyses. While data collection and analysis may be expensive, understanding water movements is often essential to determining appropriate management actions. Ecological and **biogeochemical** interactions are even more complex and time consuming to monitor. It is therefore essential to consult experts and, if necessary, hire consultants to fill in appropriate gaps in information.

Some essential information can be obtained without expert advice and may provide a basis for certain rehabilitation activities. If available, historical records are often very useful in developing an understanding of changes that have occurred to the wetland and its catchment. This can help with the setting or revision of objectives, may provide a pictorial or descriptive vision of what you are trying to achieve, and may help with more specific habitat information such as determining the correct vegetation taxa to be planted.

Early surveys can be invaluable in determining what previously grew on a site. They can be very instructive as to the attributes of the site, such as elevation in relation to **tidal planes**. In the case of extremely modified sites, they may even help determine the type of wetland that grew there originally. Maps or aerial photographs can provide information on the primary sources of water in the catchment, the sources of disturbance and other stresses acting on the wetland, and how these influencing factors have changed over time.

Identify human influences and constructed features such as roads, weirs, drains and impervious areas, such as parking lots. Identify the presence of levee banks and floodgates, and investigate the reason for their construction (for example, for flood mitigation or land reclamation).

Gather all available information on your wetland site or similar wetlands to help develop a hypothetical or conceptual model of the processes taking place within the wetland. Document any sources of uncertainty or any assumptions, and identify the **risk** associated with these assumptions. Some of the specific information requirements that should be considered include:

- current and historical tidal and survey information
- surface and groundwater flows and their possible interactions
- vegetation communities native to the site
- use of the wetland by fauna (which fauna use which habitats)
- soil types and changes in sediment processes
- water quality (within the wetland and entering it from its catchment)
- Aboriginal and European heritage and cultural values.

Further information about some of these wetland characteristics and processes is provided in Part 3.

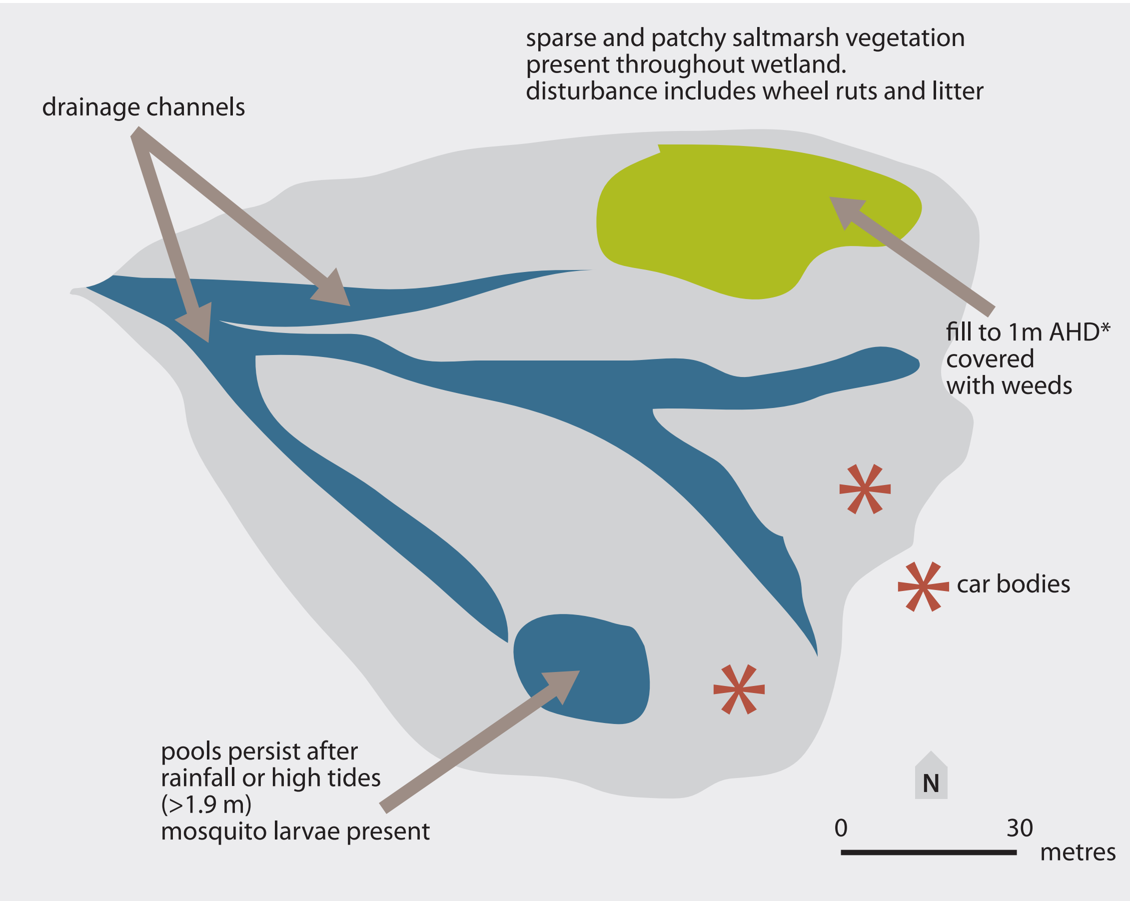
3.2 Detailed site evaluation

The amount of detail in the site evaluation will depend on the scale of the project. Generally, the bigger the project is, the more detail will be required. Small-scale projects may require only the drawing of 'mud-maps' (Figure 3.1), while large-scale projects are likely to benefit from the use of spatial information stored in a **geographic information system** (GIS) (Figure 3.2, overleaf).

Visit the proposed project wetland and other similar wetlands in the vicinity and pay careful attention to what vegetation species are present, where weeds grow, and any areas with erosion problems or exposed **acid sulfate soils** (**ASS**). Make notes on maps or aerial photographs of the site. You may want to use a **Global Positioning System** (**GPS**) receiver to record the location of any significant natural or cultural features. You can then load the GPS data into a GIS if you are using one, or use it to accurately plot the locations of the features on a topographic map.

Depending on the size of the project and the money available, it may be necessary or possible to undertake several data collection activities. In large projects where it may be necessary to model possible changes to tidal inundation, detailed high-quality data may be needed. This may include data on water levels at a few sites, water movement within the wetland, and levels of the wetland bottom and banks. Details on undertaking topographic and bathymetric surveys and on tidal gauging are given in Appendix 1.

Figure 3.1 Sample annotated wetland map



*Australian Height Datum

In other situations it is possible to collect information about the wetland during a few visits to the site and with some careful thought. Components which are often necessary include:

- connectivity to other wetlands
- exact elevations and topography
- water flow rates and timing
- location of different sediment and soil types and wetland plants
- diversity and cover of native and exotic or invasive plants
- diversity of fauna species.

Avocets (Kooragang Wetland Rehabilitation Project)

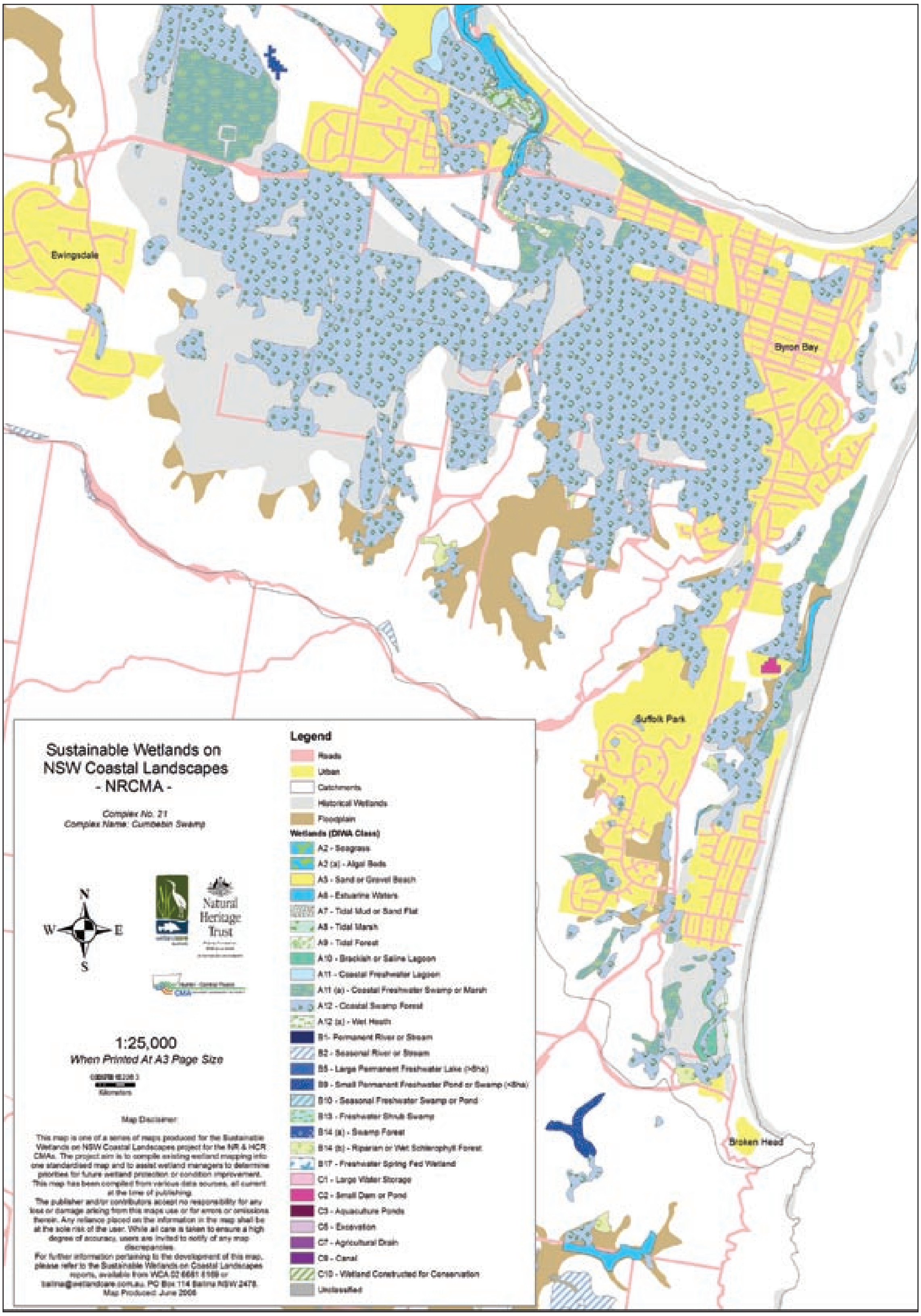
Obtain information on soils at the site either from available information or by site investigation. Information that may be useful includes soil profile descriptions, soil limitations, testing of soil chemistry and soil quality (further information on soils is presented in Chapter 9 and Appendix 5).

While you are on site it is important to draw a rough map of your wetland and to annotate it. An example is presented in Figure 3.1. Also write down the time and dates of ambient weather conditions, flora and fauna observations, and any other relevant observations.

Remember: To monitor the success of your rehabilitation project it is necessary to collect information before you begin. The information you collect in the early stages of your project will be the **baseline** against which you measure future changes at the site.

As part of the site evaluation it is essential to establish the causes of degradation, as this can enable you to design an effective rehabilitation process. If a wetland is degraded because of events occurring in the catchment, it may be better to concentrate your efforts in the catchment before beginning rehabilitation of the wetland itself. Alternatively, you will need to plan your rehabilitation with the knowledge that these influences will continue.

Figure 3.2 Sample GIS wetland map



Source: WetlandCare Australia, 2006

Dialogue Box 3.1 Tools for carrying out a site evaluation

Essential tools

- notebook
- pencil or waterproof pen
- tide tables
- plant and weed identification books
- bird identification books
- camera
- plastic bags
- topographic maps

Desirable tools

- aerial photographs
- GPS receiver

3.3 Determination of legislative requirements

At all levels of government a large amount of diverse planning instruments and policy may be relevant to wetland rehabilitation or protection (see Tables 3.1 to 3.4, overleaf).

Determining the legislative requirements during the early stages of a rehabilitation project will ensure that the relevant authorities have been contacted and the possible time frames for approvals can be built into the rehabilitation plan. Delaying consultation with local councils and government agencies until you are ready to start work may result in significant delays to the project. You may also have to rethink your goals and objectives if you find out that a proposed action is not possible or has to be modified owing to legal requirements.

Further information on the legislation, planning instruments and policy outlined in Tables 3.2 to 3.4 can be found in Chapter 12.

Environmental impact assessment processes

All proposed rehabilitation activities should have an appropriate level of environmental impact assessment. For minor matters this may involve consideration of environmental impacts as part of the issue of a licence or Development Application (DA). For larger projects it may require a detailed **Environmental Impact Statement** (**EIS**) or Review of Environmental Factors (REF). In addition, you may be required to prepare an ASS management plan if there is the potential for ASS to be disturbed, which is often the case along the NSW coast.

Local government has a significant role in determining legislative requirements, as the local council will often be the authority that grants consent for an activity or development under the *Environmental Planning and Assessment Act 1979* (EP&A Act).

Table 3.1 Wetland rehabilitation issues and relevant agencies

Agency	Issue
Local council or DECC	water pollution
Local council or NSW Heritage Office	European heritage
CMA or local council	clearing of native vegetation
DECC	Aboriginal heritage native flora and fauna threatened species and endangered ecological communities activities in coastal areas soils (including ASS)
DPI	aquatic vegetation aquatic threatened species fisheries dredging and reclamation fish passage
Local council or DPI	noxious weeds
Local council or Department of Lands	public land management
Department of Water and Energy	activities in or near rivers and foreshores

Development Application

A Development Application (DA) is required for any development identified in a local government planning instrument as requiring consent. This can vary from council to council, so you will therefore need to read the relevant Local Environmental Plan for your council area.

If the proposed activity does not require consent from a local council, it may still require consent from other government authorities. The relevant authorities are required to assess the impacts of the activity and determine whether there will be any potential problems.

If the works are to be carried out on land owned by the Crown, the local council or someone other than the group undertaking the work, the landowner's consent will be required before a DA can be lodged. In the case of Crown Land, contact the Department of Lands.

Environmental Impact Statement

An EIS or other supporting document may be required as part of the approval process if the impacts are likely to be significant. Certain activities classified as designated development automatically trigger the preparation of an EIS.

Review of Environmental Factors and Statement of Environmental Effects

Where an activity is not a designated development, the local council or the determining government authority may still request a supporting document – usually referred to as a Review of Environmental Factors (REF) or Statement of Environmental Effects – to assist them in assessing the likely environmental impact.

Permits and approvals required

A range of permits or approvals may be required from a range of agencies. Agencies that may need to be consulted are listed in Table 3.1. Legislation, planning instruments and policy that may indirectly affect wetland protection and rehabilitation are listed in Tables 3.2 to 3.4.

General legal issues

A number of other general legal issues need to be considered during the rehabilitation process, particularly if the project is located on public land or if contractors will be employed to carry out works on the site. *The Constructed Wetlands Manual* (DLWC 1998) provides further details of these issues, as outlined below.

Due diligence

At least one of the parties involved in planning, establishing, operating and decommissioning a wetland rehabilitation project must take reasonable care to ensure the safety of people who come in contact with the project.

Nuisance

The operator can be held liable for nuisance if the project substantially and unreasonably interferes with the beneficial use and enjoyment of nearby land.

Damage to adjoining property

The operator can be held liable for all damage caused by the escape of any inherently dangerous thing brought to the wetland by the operator. This can include pollution, flora and fauna, and water (for example, saltwater intrusion onto neighbouring properties).

Contractual obligations

The operator can be held liable for damage suffered by other parties to any agreement expressed or implied in relation to the various phases of the project.

Occupational health and safety

Occupational health and safety obligations are imposed on employers, employees and certain manufacturers and suppliers involved with the project by the *Occupational Health and Safety Act 2000*.

Table 3.2 Commonwealth and New South Wales legislation

Legislation	Principal agency	Purpose	Implications for wetlands
COMMONWEALTH LEGISLATION			
Environment Protection and Biodiversity Conservation Act 1999	Department of Environment and Heritage	Protects the environment, particularly matters of national environmental significance, and provides mechanisms for protection of biodiversity	Activities within Ramsar wetlands or wetlands which provide habitat for migratory waders under international agreements require environmental assessment under the Act. Also applies to Commonwealth marine areas
Australian Heritage Council Act 2003	Australian Heritage Council	Provides for the constitution of the Australian Heritage Council and its responsibilities in providing heritage advice	Allows for listing of wetland sites on the Register of the National Estate
NEW SOUTH WALES LEGISLATION			
Environmental Planning and Assessment Act 1979	Department of Planning	Establishes the process and requirements for assessment of development and activity applications	Requires environmental impact assessment before a development or activity can proceed Allows for creation of policies, including SEPP 14 and the Coastal Policy, that protect coastal wetlands
Local Government Act 1993	Local councils Department of Local Government	Allows local government to undertake a range of functions and responsibilities	Sets requirements for drainage, removal of obstructions Outlines requirements for State of the Environment reporting
Coastal Protection Act 1979	Department of Environment and Climate Change (DECC)	Provides a framework for coastal management and defines the coastal zone	Development activities within the coastal zone that are below the mean high-water mark, excluding any estuary, lake or artificial harbour, require concurrence from the Minister for the Environment and Climate Change

Legislation	Principal agency	Purpose	Implications for wetlands
Contaminated Land Management Act 1997	DECC	Provides a process for investigating and remediating land where contamination presents a significant risk of harm to human health or the environment	Where site contamination is considered to pose a significant risk, DECC has powers to direct the investigation or remediation of polluted land and water
Crown Lands Act 1989	Department of Lands	Provides a regime for the ownership and management of Crown Land	Conservation or restoration works in wetlands and foreshore areas on Crown Land require land assessment and approval
Fisheries Management Act 1994	Department of Primary Industries (DPI)	Establishes responsibility for management and protection of marine, estuarine and freshwater fish and aquatic habitats	Protects threatened aquatic species and habitats Requires permits for fish habitat destruction and any works involving disturbance of wetland sediment Provides for development of habitat protection plans, creation of aquatic reserves and habitat rehabilitation (for example, fishways)
Heritage Act 1977	NSW Heritage Office	Provides for the constitution of the Heritage Council of NSW and the establishment of the State Heritage Register and heritage agreements	Permit is required for damage to or removal of heritage items
Marine Parks Act 1997	DECC	Provides for the declaration of marine parks for the conservation of marine biology and marine habitats. It also regulates the activities that may be undertaken within a marine park	Where a wetland forms part of a Marine Park, any Development Application is subject to the EP&A Act, and consultation with the Marine Parks Authority is required

(continued overleaf)

Legislation	Principal agency	Purpose	Implications for wetlands
National Parks and Wildlife Act 1974	DECC	Provides a framework for managing National Parks and reserves and provides mechanisms to conserve and manage cultural and natural heritage across NSW	Permits are required for the taking of native fauna and flora and for disturbance of Aboriginal objects Allows for off-reserve conservation of wetland areas through wildlife refuges and voluntary conservation agreements
Native Vegetation Act 2003	Catchment management authorities (CMAs)	Controls the management of native vegetation in rural areas Protects sensitive areas from tree removal and provides for penalties for illegal clearing	May apply to clearing and rehabilitation projects on private land, depending on circumstances Permit is required to remove trees within 20 m of a prescribed stream or other protected lands
Noxious Weeds Act 1993	DPI Local councils	Provides for the management and monitoring of noxious weeds on public and private lands	Specifies landholder responsibilities to control noxious weeds. Outlines requirements for herbicides and their use
Protection of the Environment Operations Act 1997	Local councils DECC	Protects the quality of the environment through controls on air, water and noise pollution	Restoration activities such as dredging, landfill and aquaculture may require a licence
Threatened Species Conservation Act 1995	DECC	Establishes a process for classifying and protecting endangered species and critical habitats Allows for development of species recovery plans	A licence is required if an activity is likely to significantly affect threatened species, populations or ecological communities, or their habitats Endangered ecological communities include coastal saltmarsh and swamp oak forest
Water Management Act 2000	Department of Water and Energy	Provides for the integrated and sustainable management of the State's waters Provides for the carrying out of works along rivers and foreshores	Allows for preparation of water management plans that may affect wetlands and estuaries Requires approval for works within 40 m of a river, lake or foreshore

Bollards used to protect swamp oak forest at Coila Lake (DECC)

Table 3.3 NSW planning instruments

Planning instrument	Principal agency	Purpose	Implications for wetlands
Local Environment Plans	Local councils	Controls land use by identifying permissible and prohibited activities	Maps identify zoning of wetland areas and land use tables determine permissible uses in wetland areas
Regional Environment Plans (REPs)	Department of Planning	Applies land use controls across regional areas to issues of regional significance	Some REPs relate specifically to coastal and wetland issues
STATE ENVIRONMENTAL PLANNING POLICIES (SEPPS)			
SEPP 14 Coastal Wetlands	Department of Planning	Provides for the protection of coastal wetlands in NSW	EIS is required for works within an SEPP 14 wetland A rehabilitation plan is required for any restoration works

(continued overleaf)

Planning instrument	Principal agency	Purpose	Implications for wetlands
SEPP 19 Bushland in Urban Areas	Department of Planning	Provides protection of natural bushland in listed local government areas	Development consent must be obtained before bushland is disturbed
SEPP 26 Littoral Rainforest	Department of Planning	Controls development activities within or adjacent to littoral rainforest communities	EIS is required for works within wetlands affected by SEPP 26
SEPP 44 Koala Habitat	Department of Planning	Provides for the protection of koala habitat in listed local government areas	Swamp mahogany, a koala habitat species, is commonly associated with wetlands. Councils must investigate core koala habitat before granting development consent
SEPP 71 Coastal Protection	Department of Planning	Ensures that development within the coastal zone is appropriate and consistent with the principles of ecologically sustainable development	Guides development assessment in sensitive coastal areas, including SEPP 14 wetlands, coastal lakes, Ramsar wetlands, marine parks and aquatic reserves

Table 3.4 Commonwealth and New South Wales policies

Policy	Principal agency	Purpose	Implications for wetlands
COMMONWEALTH GOVERNMENT POLICIES			
Commonwealth Coastal Policy	Department of Environment and Heritage	To promote ecologically sustainable use of Australia's coastal zone	Guides government decision making in coastal areas managed by the Commonwealth. Provides guiding principles for all levels of government to encourage sustainable use of coastal resources
Wetlands Policy of the Commonwealth	Department of Environment and Heritage	To ensure that the activities of the Commonwealth Government promote the conservation, ecologically sustainable use and enhancement of wetland functions	Guides government decision making in relation to wetlands on Commonwealth land. Provides guiding principles for all levels of government to encourage sustainable use and management of wetlands

Policy	Principal agency	Purpose	Implications for wetlands
NEW SOUTH WALES GOVERNMENT POLICIES			
NSW Coastal Policy	NSW Government	Provides a framework to balance and coordinate management of the physical, ecological, cultural and economic attributes of the NSW coastal zone	Applies to lands within the coastal zone
NSW Estuary Management Policy	DECC	To achieve integrated, balanced, responsible and ecologically sustainable use of the State's estuaries	Estuaries and wetlands can be protected through the preparation of estuary or coastal zone management plans with funding available through the Estuary Management Program
NSW Fisheries Policy and Guidelines	DPI	To achieve consistent management of aquatic resources in NSW	Guides conservation and management actions in all marine and estuarine environments
NSW Weirs Policy	DECC	To halt and, where possible, reduce and remediate the environmental impact of weirs	Discourages construction of new weirs or structures in wetland areas. Impacts of existing structures will be reviewed
NSW Wetlands Management Policy	NSW Government	To halt and, where possible, reverse the loss of wetlands in NSW, and to encourage activities that will restore the natural functions and values of wetlands	Guides government decision making in relation to the management of all types of wetlands in NSW

3.4 Stakeholder and community consultation

Strategies for consultation

Many people may have an interest in the management of a particular wetland area, including the local council, Landcare groups, adjacent landowners, recreational users and the residents who live near the wetland. Taking into account many different values and opinions can be a challenge when you are designing a rehabilitation project. However, an effective program of consultation can help to ensure that the community takes an active role in the conservation of its local area and can therefore contribute to the continued success of the project.

Community and stakeholder input is likely to be required during both the plan establishment and plan operation phases. Any required ongoing activities such as maintenance, monitoring and adaptive management are more likely to succeed if stakeholders have been involved in the plan and support its outcomes.

Community involvement is particularly relevant to cultural heritage. Aboriginal community participation can be initiated by contact with the relevant local Aboriginal Land Council at the early stages of the project. Many local councils will have an Aboriginal liaison officer, who may be able to assist in identifying additional Aboriginal community contacts. If archaeological surveys, excavations and assessments are required, a heritage officer will usually represent the Aboriginal Land Council. Relevant information is available from the DECC Aboriginal Heritage Information Management System and the NSW Aboriginal Land Council.

Local historical societies and similar groups can provide information on the European cultural and heritage values of the project site. Some local councils have a heritage officer. Museums and the Heritage Office of NSW may also be able to provide information.

The methods that you can use to engage with the community will vary with the size of the project and its aims. Some of the more common methods include:

- steering committees
- use of a project facilitator
- using local champions (community leaders)
- questionnaires and surveys
- printed brochures and newsletters
- media releases to local newspapers and to radio and TV stations
- public meetings and workshops that identify issues and objectives
- community monitoring programs
- project launch and field days
- involvement in hands-on activities such as site clean up, planting and weeding, landscaping and fencing, monitoring, operation and maintenance activities.

The Constructed Wetlands Manual (DLWC 1998) outlines seven key steps to achieving community involvement in wetland projects, as shown in Dialogue Box 3.2.

Dialogue Box 3.2 Steps to achieving community consultation and involvement

1. Identify your project objectives and determine the best level of community involvement.
2. Canvass the community to determine the interest level of groups and individuals, and identify their potential roles.
3. Discuss the community's values, expectations and required resources with key decision makers of the project.
4. Define community involvement objectives.
5. Determine the best mix of community involvement techniques to achieve your community involvement objectives.
6. Prepare a community involvement plan.
7. Implement the plan and form an agreement with community groups and individuals outlining their roles and responsibilities.

Source: DLWC 1998 (adapted from America's Clean Water Foundation 1991).

Principles for effective consultation

For consultation to be effective it must be undertaken as soon as possible to allow full participation of all interested parties in the planning process. A common complaint about community consultation is that community members feel that their opinion is not valued or that it is sought when it is too late or too difficult to make changes.

For consultation to be meaningful, useful and effective, Carson and Gelber (2001) provide the following principles. Each consultative situation should be:

Timely: Consultation must occur early in the project, when participants have the best chance of influencing outcomes. Give people enough time to consider implications and express their views.

Inclusive: Select participants in a way that is not open to manipulation and that includes a cross-section of the population. Random selection offers the best chance of achieving this.

Community focused: Ask participants what they consider is appropriate in their role as citizens, not what they want personally or what is in their self-interest.

Interactive and deliberate: Encourage debate and allow consideration of the big picture so people can become engaged. Avoid reducing questions to simplistic responses.

Effective: Although decision making can strive for consensus, complete agreement does not necessarily need to be the outcome. Be clear on how decisions will be made so that participants know and understand the impact of their involvement. Make sure all participants have time to understand material they are unlikely to be familiar with.

Meaningful: The potential for any recommendations that emerge from the consultative process to be adopted is important. If they are not, provide a public explanation. Faith in the consultative process by both the organisers and the participants is important.

Well-facilitated: An independent, skilled and flexible facilitator with no vested interest in the project will give the process credibility and allow participants some control of the agenda.

Open, fair and subject to evaluation: The consultation method should be appropriate to the target group. Formulate evaluation questions in advance. Decide how the success of the consultation will be measured and provide feedback to the community afterwards.

Cost effective: Consider how many and which types of community members should be consulted on a given issue. Some questions will require broader consultation, others more targeted consultation. Costs will vary, but the process must be properly resourced.

Flexible: A variety of consultation mechanisms exist. Consider which one best suits the circumstances. Try a variety of mechanisms over time. Think about how to reach all your users, including those with special needs (for example, language, disability, age). Different communities and different questions will produce better responses with different forms of consultation. Mix qualitative and quantitative research methods.

3.5 Preparing a wetland rehabilitation plan

A wetland rehabilitation plan will normally be required. The level of detail in the plan will depend on the size and nature of the activities being undertaken and the relevant approval processes. Some plans will need to be detailed; for example, rehabilitation work within an *SEPP 14* wetland will require a formal wetland rehabilitation plan to be prepared and lodged as part of the approval process. Having a documented plan including a project timeline and budget will assist with obtaining funding and stakeholder support, and ensure that all participants have consistent and realistic expectations. It also assists in monitoring the progress of your project.

The minimum components of a rehabilitation plan should include:

- goals and objectives
- an outline of the issues and the proposed management actions
- a timeline for various phases of the project
- identification of the project team (how and when each person will contribute)
- the project budget, including funding sources and major expenditure associated with each phase of the project.

The plan does not have to provide fine details about specific implementation activities such as seed harvesting and weed removal techniques, but if it does not, it should provide a reference to a document with that information.

A monitoring program should be designed to determine the success of the plan over a long period of time. This could form a part of the rehabilitation plan, or it can be developed as a separate document for projects where a detailed level of monitoring is being proposed.

3.6 Methods and techniques available

A wetland rehabilitation plan can involve both structural and non-structural measures. New techniques are being developed and tried constantly, and a number of successful methods have been documented.

Examples of structural measures:

- restoration of previously blocked meanders and natural flow paths to allow for natural regeneration of affected areas
- modification of artificial barriers such as floodgates and road crossings to enable the return of natural flows
- alteration of contours and bank batters to enhance natural colonisation
- construction or improvement of ditches, runnels or channels to improve water flow
- construction of bunds to prevent or alter water flow
- filling of areas to above the tidal limit to create an estuarine–terrestrial transition zone
- removal of degrading processes or materials such as solid waste, sediment from landfill, liquid effluent or toxic waste
- diversion of stormwater away from saltwater wetlands
- fencing to control movement of animals and visitors away from sensitive areas
- construction of boardwalks, bird hides and other interpretation facilities.

Boardwalk on foreshores of Merimbula Lake (DECC)

Examples of non-structural measures:

- control and removal of competitive introduced species to allow for regeneration of native species
- revegetation where natural regeneration processes are interrupted
- education programs
- rubbish and litter removal.

Litter removal Hunter River estuary (Kooragang Wetlands Rehabilitation Project)

The design and implementation of rehabilitation strategies are intimately linked, and feedback from implementation to subsequent design or redesign is often necessary. Accordingly, some details relevant to design of strategies are presented in Chapter 4.

4 Plan implementation

4.1 Introduction

As discussed in Chapter 3, implementation of a wetland rehabilitation plan may involve both structural and non-structural works. This chapter addresses various types of works and issues related to their implementation.

Many aspects of construction in wetland environments are already covered in *The Constructed Wetlands Manual* (DLWC 1998). For example, the introduction and sections on contract administration and construction management in Chapter 22 apply equally to saltwater wetlands. This section avoids repeating topics covered in *The Constructed Wetlands Manual* and focuses on areas more specific to saltwater wetlands.

Saltwater wetlands are rarely constructed from scratch. Projects generally comprise the rehabilitation of existing wetlands which have suffered a degree of degradation. Degradation may range from draining of part of a saltmarsh or moderate siltation of a mangrove area to extensive bunding and filling of an entire wetland with waste.

Most construction activities in a saltwater wetland will have to be carried out within or just outside the intertidal zone and will often have to fit in with the tidal cycle. This creates special problems for working in and around wetlands on account of the soft sediments, the potential for disturbance of ASS and the constant inundation that may occur in some habitats. Saltwater wetlands usually contain fine-grained sediments which, once disturbed, can be very difficult to handle and require long timescales to stabilise their sediment structure and pore water pressure.

It is usually important to preserve most vegetation in the wetland, so construction activities must avoid damaging vegetation. These habitats are particularly susceptible to indirect impacts such as the generation of **turbidity** or bed compaction. Trampling by people through saltwater wetlands can also have a deleterious effect on plants and animals. If the area is to be used recreationally or educationally, then the installation of boardwalks may need to be planned into the design.

When you are considering restoration in estuarine areas, it is important to assess the use of boats in the area. Damage by boat anchor chains, propellers and boat wash can have a deleterious effect on the success of a rehabilitation effort. Likewise the use of areas for moorings and informal boat storage may also affect habitats. Make efforts wherever possible to minimise damage from these sources.

Mooring within mangrove pneumatophores, Minnamurra River (DECC)

4.2 Major construction considerations in saltwater wetlands

Access

Consider access to the site to minimise the potential for disturbance during both the construction and maintenance phases.

Environmental loadings

Most artificial estuarine constructions, such as weirs, spillways, culverts and floodgates, may be subjected to both environmental forces, such as waves, currents and fluctuating water levels, and specific forces, such as vessel impacts.

Construction of saltmarsh at Scott Park, Rockdale (DECC)

Saltmarsh created at Scott Park, Rockdale (DECC)

Site layout

Saltwater wetlands create a difficult environment for survey work, as they invariably have unstable soil, which poses problems for establishing survey marks, and restricted line of sight due to vegetation. Carry out survey work as early as possible, preferably before or during the design phase, to allow design decisions to be based on hard numbers rather than guesswork. Engage a registered surveyor to set up a survey control system. Where property boundaries are involved, a registered surveyor is essential.

Information on survey control is presented in Appendix 1.

Foundation design

Foundation design for estuarine and coastal structures requires reasonable estimates of the expected loading conditions in order to determine the foundation soil engineering properties and to understand the interaction between structure and soil. Geotechnical investigations are conducted to gather information about the soil layers beneath the construction.

Environmental impacts of construction

Environmental issues have to be considered for all construction in coastal wetlands. Threatened and endangered species of fish, birds, mammals and reptiles merit special consideration and accommodation during the reconnaissance, planning, implementation and monitoring phases of projects. Construction activities that involve dredging are most detrimental. Many crustaceans (such as shrimp and blue crabs) burrow and overwinter in channels and are likely to be encountered during maintenance dredging. **Sessile** invertebrates (such as oysters, mussels and clams) can be buried and killed by dredging. When dredging is planned, estimate the dredging volumes and determine how the dredged material will be transported and disposed of. Consider beneficial uses of the material.

Estuarine and coastal projects generally require regulatory approval from local, State and sometimes Commonwealth agencies. Fulfilling the regulatory requirements may affect the construction design, the method of construction, the transportation of materials to the site and even the choice of construction materials. Therefore, you must clearly understand the provisions likely to appear in various permits and approvals so that the design will meet all approval criteria. Failure to consider these important aspects will result in delays, added expenses or even an unviable project.

Maintenance of completed construction

Maintenance requirements for each construction element have to be taken into account, especially for elements that are expected to suffer some damage over their **design life**.

Land-based constructions may have adequate access for maintenance with land-based equipment. Monitoring and periodic inspections of intertidal or submerged constructions may be required to determine when maintenance should be performed.

At some project sites it may be necessary to consider the potential consequences of vandalism and theft of materials. If vandalism and theft are potential threats, materials must be chosen that cannot be easily cut, carried away, dismantled or damaged. For example, sand-filled geotextile bags can be cut and small concrete blocks can be stolen.

Construction of saltmarsh as part of the Kooragang Wetland Rehabilitation Project (Kooragang Wetland Rehabilitation Project)

Saltmarsh created as part of the Kooragang Wetland Rehabilitation Project (Kooragang Wetland Rehabilitation Project)

Construction in a saline environment

Construction in saline environments is often exposed to continual cyclic wave loading, impact loading from waves or vessels, and occasionally accelerations due to seismic activity. Construction also needs to resist abrasion, chemical attack and corrosion, marine **biodegradation**, wet–dry cycles, freeze–thaw cycles and temperature extremes.

The construction materials used may vary depending on adaptability, cost and availability. Material strength, flexibility, durability and resistance to cyclic, impact and seismic loads are important to resisting tension, compression and flexure stresses. Information on construction materials in saline environments is presented in Appendix 3.

Depending on the type of project, construction may require land-based plant, floating plant or a combination of both.

4.3 Implementing structural works

Earthwork may be required to increase the size of channels, to lower or raise bottom levels, to remove unsuitable material or to construct bunds to prevent water flow (Table 4.1, overleaf). Before any earthworks are carried out, engage a specialist to determine the most effective construction methods and materials in terms of both production and minimisation of environmental impact. Production efficiency will depend on selecting machinery that can handle the sediment after it has been disturbed and that suits the weight-bearing capacity of the site. The soil properties critical to soil handling and trafficability of equipment can be estimated by field or laboratory tests (Appendix 5).

Both hydraulic and mechanical methods can be used. Hydraulic methods pump the soil as a slurry. Mechanical methods involve excavating and moving discreet blocks of soil.

Channel construction

Drainage systems in estuarine wetlands are typically constructed to a **dendritic** or branching pattern comprising, in descending order of size, channels, ditches and runnels. Ditches are constructed as lateral drains to channels, and runnels as lateral drains to ditches or channels.

Channels

Channels should have a depth sufficient to ensure that they remain inundated throughout the tidal cycle. As a general rule they should be at least twice as wide as they are deep, and battered sufficiently to prevent slumping of their banks, which causes sediments to build up in the channels. The actual slope will depend on the properties of the sediment, but as a general rule the slope should be no steeper than 1 in 3 (vertical to horizontal). Channel excavation is well suited to being performed by a small barge floated into position. Don't place excavated sediments along the side of the channel as this may lead to the formation of stagnant pools.

Ditches

Ditches are smaller in section than channels, and their bed level may be above low tide level. Excavation methods are similar to those for channels, but if bed levels are above low tide, only small barges can be used, and barges will be left stranded on the bottom at low tide. Alternatively, the ditch can be over-dredged and allowed to fill in somewhat during construction.

Table 4.1 Mechanisms in earthwork construction phases

Methods for . . . excavation	removal and transport	deposition
Cutting or ripping with knife, blade or plough	Mechanical: by loader scraper, truck or conveyor belt	Simple dumping from transporter or discharge of slurry from pipeline into disposal area
Scooping or digging with a bucket, shovel or clamshell	Water-based: by barge	Partial compaction by wheels or tracks
Scouring (erosion) with a moving water or air stream	Hydraulic: pumping a slurry of soil particles or clumps of material in a pipeline	Full specification compaction by mechanical rolling in layers or by vibration
Equipment for . . . excavation	**removal and transport**	**deposition**
Dozers, loader-scrapers	Loader-scrapers, wheeled trucks	Mechanical or hydraulic
Backhoes, shovels, bucket ladders, draglines, clamshells	Conveyor belts	
Dredges: direct suction, cutter suction, bucket wheel suction	Barges, slurry pipelines	
Factors affecting suitability of . . . excavation	**removal and transport**	**deposition**
Soil trafficability	Bulking, pumpability, abrasiveness	Sticking of clayey soils
Soil characteristics (presence of ASS, hydraulic conductivity, etc.)		Turbidity for underwater disposal
Availability of water for pumping		Degree of compaction required

Runnels

Runnels are very shallow spoon-shaped channels that connect pools in saltmarsh to open waters of the estuary. Their width is generally three times the depth, and they follow natural drainage lines along a low gradient. The aim of creating runnels is to increase the tidal flushing into areas where water tends to pond and stagnate. Runnels are generally constructed by hand-trenching to minimise disturbance to vegetation and during a period of **neap tides** to maximise the time available for construction. Runnels are generally 600 to 900 mm wide and 150 to 300 mm deep. The depth of the runnels is adjusted so that water is drained from the lowest pool on the ebb tide (Dale *et al.* 1996, Hulsman *et al.* 1989).

Take care to ensure that no large isolated pools occur within the runnels at low tide. Don't place excavated material along the side of the runnel as it may lead to the formation of stagnant pools. Once the runnel system is constructed, sediment transport induced by the tidal flow should result in the formation of a natural channel system. Incorporation of runnels into a saltwater wetland can assist in alleviating mosquito problems by allowing improved drainage and greater fish passage; this is further discussed in Section 4.8.

Pay particular attention to ensuring that the drainage system remains free of sedimentation and blockages, which can reduce tidal flushing. To ensure that channels remain free-flowing, it is important to consider the layout of the system that is to be constructed. Pay detailed attention to sharp bends, stream intersections or other places where low velocities can cause sedimentation. Mimicking the dendritic drainage patterns that occur in natural systems will minimise the likelihood of blockages.

Runnells are best suited to sites with simple, clear water movement patterns and where the length of runnels is relatively short, so that flushing reaches well into the wetland (Dale 2005). Pay attention to soil type before you construct runnels so as not to disturb shallow ASS and not to facilitate erosion of susceptible soil types.

Hydraulic structures

Locate hydraulic structures with care so as not to concentrate flows and thus cause localised erosion and consequent sediment deposition further downstream.

If hydraulic structures are to be used to control the tidal flushing of saltmarsh rehabilitation areas, it may be necessary to install screens to prevent mangrove seeds entering and establishing within the area.

Culverts

Culverts, which carry a stream under or through an embankment or fill, can be used to reconnect side channels, ponds, billabongs or cut-off channel meanders within wetlands that have become isolated from the main channel or water body. Take into account the movement or migration of fish species when planning culverts.

Floodgates

Floodgates are one-way hinged flap gates that are a common feature of coastal floodplain drainage systems, particularly on the North Coast of NSW. Floodgates prevent saline tidal water and river floodwaters from inundating low-lying land. They also allow ebb tide drainage to the local low tide level. Unfortunately, floodgates have many unintended side effects, such as reducing water quality, blocking fish and prawn movement, and accumulating substances that can reduce downstream water quality.

Guidelines are available from the DPI outlining principles and strategies which can be used to improve the environmental performance of coastal floodplain drainage systems while retaining their benefits for agriculture (Johnston *et al.* 2003 available at www.dpi.nsw.gov.au/agriculture/resources/soils/ass/general/balance).

Spillways

Spillways used as overflow or emergency channels provide a safe discharge from the wetland during storms that exceed the design specifications. A common design condition of an emergency spillway is the 50- to 100-year storm event. In wetland design, the emergency spillway should be placed to limit the extended detention of stormwater to a maximum of 1 m or the level calculated as a result of a 50- to 100-year **design storm**, whichever is less.

Riser and barrel

Riser and barrel structures are often used to control flow from a wetland. The riser is a vertical pipe or inlet structure joined to a horizontal pipe (or barrel) that conveys flow under an embankment to an outlet point.

Floodgate at Macleay River (DECC)

Pipe being floated over a wetland during the 1966 construction of the Taloumbi Radial drains, that now drain into Lake Wooloweyah (Clarence Valley Council)

Weirs

Weirs are used to control and regulate wetland inflow, outflow and water level. The permanent pool in a wetland system is defined by the water level determined by the lowest outlet point of the weir. In the case of a wetland controlled by a weir, the permanent pool can make up a large proportion of the total detention storage of a wetland compared to one controlled by a riser.

Drop board weirs and culverts

Drop board weirs and culverts can be used to control tidal flushing of a wetland. Water enters the wetland, then boards are placed in the weir or culvert to keep the water in. Structures such as this have been used to improve wader bird habitat and for the management of ASS.

Level spreaders

Level spreaders are structures that are designed to distribute concentrated flow uniformly over a large area. Level spreaders come in many forms, depending on the peak rate of inflow, the duration of use, and the site conditions. Level spreader inflow pipes are commonly used in constructed wetlands.

Excavation equipment and techniques for soft ground

When disturbed, the bed materials of saltwater wetlands readily turn to mud. The ability of a machine to stay on top of soft ground is affected by its ground pressure (weight per unit area of ground contact), shear (the load on the edge of the track or tire) and total weight. Shear is most important when a soft soil is protected by a harder crust. Total weight affects deep mud, which may creep or flow from beneath a machine. Problems working in mud can be reduced by proper selection of equipment. Crawlers are better than wheels; tracks should be the longest and widest available; tires should be big, soft and cleated; mechanical equipment should be the smallest that will do the job. Some wheel tractors can be fitted with temporary metal and rubber tracks which enable them to work in soft soils.

Temporary roads

Temporary roads can be constructed to provide access to soft areas. Geotextile fabric may be spread over soft surfaces to increase their load bearing capacity. A corduroy road comprising logs or half logs laid across the route touching each other can be built to support heavy equipment on very soft ground. Plank roads comprising planks on sleepers are more expensive but are easier to lay and provide a smoother surface.

Platforms, pontoons or mats

Platforms, pontoons or mats are timber supports used by machinery such as draglines or revolving shovels working on soft ground. They spread the weight of machines over a large area and act as temporary bridges over ditches and holes. They are usually trucked as near to the job as possible and then dragged or carried by a loader or shovel. Platforms can be used to move a shovel across soft ground: the shovel transfers them from behind it to in front of it as it moves from platform to platform.

The space between platforms will vary with the nature of the ground. In very soft conditions they should be placed in contact and chained together or even laid in two layers. On ordinary soft or suspicious ground, the widest spacing should be that which will allow the shovel to reach the next platform before its centre of gravity reaches the edge of the current one so that the shovel will not tip forward so much that the track will push the next platform instead of climbing it.

Draglines

Draglines are often the most efficient machines in soft conditions. Their long reach allows them to keep well back from the holes they are digging and to pile spoil far enough away to reduce slumping back into the pit or against the shovel. The sliding action of the bucket during digging and hoisting reduces problems with suction.

Hydraulic full-revolving backhoes

Hydraulic full-revolving backhoes are comparable to draglines but can dig much harder material and to greater depths, and have more precise control in both digging and dumping. They are better at getting themselves out of trouble and working without a platform. However, their reach is much shorter in proportion to weight and bucket size: in wetland work, long reach is highly desirable and weight increases problems, costs and risks.

Clam shells

Clam shells have almost as much reach as a dragline and can work without dragging debris such as roots, stumps and boulders up against themselves or platforms. However, they have the disadvantage of pulling the bucket straight up, which in sticky mud requires overcoming suction greater than the weight of the bucket and load.

Bulldozers

Bulldozers are not suited to wet excavations since they cannot work on artificial supports. However, they can skim shallow layers of mud off hard surfaces and dig cautiously in muds compact enough to give them some traction. In skimming work it is usually best to start at one side of the mud area and make a pass removing the mud cleanly.

During wet digging, large quantities of water will be retrieved along with the solid material. In some situations the water running back into the excavation may be minimised by compartment digging. In this case a ridge is left between the hole and the water until excavation is finished, and the ridge is then dug out to allow the water to flow in. Compartments may be large or small. This technique permits water-free digging for the bulk of the excavation but can't be used if the whole excavation area is under water.

If groundwater flows into the excavation rapidly enough to be a nuisance, digging can be carried out in two or more compartments. The whole area is first dug in layers until it gets wet. Digging is then concentrated in one area until most of the water flows into the hole. An adjoining area, separated by a ridge, is then dug deeper, and the ridge is cut. The water will now flow into the deeper hole, leaving the first one nearly dry and ready to be deepened in its turn. This alternation of digging locations can be continued to the bottom of the cut.

Permanent access roads should not be built over unstable mud unless absolutely necessary. Mud (particularly if rich in organic matter) will be gradually compressed and displaced by the weight of the road, causing it to sink unevenly. Mud must therefore be removed down to a firm bottom and replaced with clean fill if possible. If it is too deep or otherwise too difficult to remove, measures such as the use of geotextile fabric must be taken to stabilise it.

Prepare a plan for the event that bogged machinery must be rescued. Time to rescue machinery may be limited by an approaching high tide. The strongest measures should be applied early, as every failed attempt is likely to make the job more difficult. A minor rescue job can become a major job by continuing to spin wheels too long. Generally, the most effective device for extricating bogged machinery is a winch. A power winch with a long cable can reach a long way from firm ground or can multiply its power by using pulleys and ground anchors. Loaders and shovels have a greater chance of self rescue. Crawler machines do not bog down as easily as wheeled vehicles, but when they do are more difficult to rescue.

Dredging

Dredging is a form of channel modification, used to deepen, widen or lengthen as well as to clean. Dredging involves the scooping or suction of underwater materials including, but not limited to, rocks, bottom sediments, debris, sand, refuse, and plant or animal matter from the bottom of a water body. Dredging systems are available as land-based and water-based plants and are divided into hydraulic and mechanical systems. Dredging plants comes in all sizes, but the operation depth depends mainly on pumping power to bring up the slurry.

Dredging is often too expensive to be practical because the dredged material must be disposed of somewhere and the stream will usually fill up again with sediment in a few years.

Mechanical dredging

Mechanical dredging is generally done with a barge-mounted crane using a clam bucket or dragline bucket. The material is excavated and placed in a barge. A towboat or tugboat moves the barge to the disposal area. In estuaries, the barge is generally moved to the shore and the mud is unloaded with a crane using a clam bucket. The mud is placed in trucks and hauled to a disposal site. For coastal dredge disposal the barge is towed to an approved area that is generally far out in the ocean and the mud is bottom-dumped from the barge. The barge can also be unloaded by pumping to a spoil area.

Hydraulic dredging

Hydraulic dredging systems are usually mounted on a floating barge. A boom, called a ladder, is lowered into the mud. On the end of the is a cutter head, which rotates and excavates the material. A large pump in the hull of the dredge sucks the excavated material from inside the cutter head through a pipe. The slurry in the pipeline contains about 20% mud and 80% water. Excavated material is placed in a barge or pumped through pipes to other destinations.

Bunding

A bund is a raised earthen barrier used to separate an area and control the water level within a wetland or protect the inflow or outflow of adjacent areas. During construction within wetlands, dispersal of silt can be prevented by bunding to protect the water quality. Temporary bunds may be required to protect an area of germinating vegetation, at least until the plants can withstand currents and waves.

Bunding is also used to improve the efficiency of wetland stormwater drainage. Installation of a permanent bund must be approved in advance and monitored after setting up, because of its ecological impacts on high-value protected marine wetland areas such as loss of tidal habitats, reduced tidal prism, altered water quality and salinity, reduced fish passage and altered weed management within the wetland.

4.4 Implementing non-structural works

Natural regeneration

Rehabilitation efforts will have the most success in areas that require little effort to promote natural recovery. This reduces the effort and costs associated with long-term maintenance, which can be intensive and expensive.

Examples include saltmarsh areas adjacent to urbanised areas, which can be damaged by cars and trail bikes. Natural regeneration of such areas will be assisted by the blocking of access using fences or bollards.

Cows in particular will seek out mangrove seeds and seedlings. Their consumption of seeds and leaves and their trampling of the root systems can undo rehabilitation work. If cattle are present, fencing is imperative to prevent damage. Sheep and goats may also be a problem.

Although in some areas wetland can appear to regenerate rapidly, at Kooragang Wetlands on the Hunter River the regeneration of saltmarsh areas following the exclusion of stock took approximately 5 years to return to natural condition. Other areas may take even longer (Section 6.1.4).

Establishment of *Wilsonia* sp. in wheel ruts after vehicle exclusion, Coila Lake (Eurobodalla Shire Council)

Replanting

Natural recovery of saltwater wetlands may not always be possible, particularly where the site is separated from natural wetlands: species may not be able to cross over to recolonise it. In such cases, it may be necessary to lend a helping hand in the form of replanting.

It is essential to ensure that the area to be replanted is compatible with the requirements of the species to be planted, or it may not be successful. For this reason it is necessary to understand as much as possible about the local topographical range of the species being planted if a specific area of each community is to be rehabilitated.

Each form of flora to be established has its specific planting strategies. It is important to consider the habitat suitable for each of these. Normally, a permit is required to collect plants or seed. Information on replanting swamp forest, mangrove, saltmarsh and seagrass habitats is presented in Appendix 2.

Volunteers assisting with replanting (Kooragang Island Rehabilitation Project)

4.5 Reinstating tidal inundation

Most areas suitable for establishment of mangrove and saltmarsh wetlands were formerly tidal areas which have had tidal inundation eliminated or reduced by reduction of the tidal range or alteration of the topography. Tidal flooding in NSW estuaries has typically been reduced by construction of weirs and floodgates, levees, culverts, bunds and roads. On the NSW coast over 4000 of these structures have been identified (Williams and Watford 1997).

Often where the tide has been excluded from areas, the ecology has been completely altered, changing to either freshwater or terrestrial communities. Where these areas are to be reconnected, the existing vegetation must be dealt with. For example, a sheltered tidal embayment is to be reconnected to a large estuary after being cut off for some decades. Freshwater species with low salt tolerance have taken over. Should the vegetation be removed before the salt water is reintroduced, or can the expected die-off and redistribution of the plant material and organic substrate be tolerated? Biomass largely made up of pasture can be reduced by mowing, but removal of freshwater reeds could require extensive excavation at considerable cost.

Where saltmarsh rehabilitation is to be achieved through the removal of restriction to tidal flows, upland grasses will usually be present. If so, these should be left in place, as after they quickly succumb to the salt water, the dead root systems will hold the soil together until the saltmarsh becomes established, and the leaves will help to trap and hold saltmarsh plant seeds floating on the tide.

Where land needs reshaping to restore tidal inundation, it is important to understand that changes of only a few centimetres in elevation can strongly influence the type of wetland that will establish. Zonation of plants requires a specific combination of land gradients (to ensure inundation) and soil salinity. This may be particularly difficult to achieve. Tidal inundation is particularly important. Mangroves will establish where tidal inundation is regular. However, if saltmarsh is to be encouraged, elevation and maintaining soil salinity are crucial in excluding mangroves from the saltmarsh flats.

In addition, soil salinity and hydraulic conductivity are major factors determining seed germination and the ability of plants to mature, so the right balance of tide and fresh water is essential (discussed further in Chapters 8 and 9).

4.6 Timing rehabilitation activities

It is important to consider timing of works if the goal of the project is to attract birds. This is particularly true if adjacent habitats are functioning as bird roosts and the aim is to expand habitat availability. Continual disturbance of waders feeding on intertidal flats may severely limit their food intake, particularly smaller waders and especially during February to April, when the birds are rapidly building up fat reserves before their return migration: heavy losses may occur during migration if the birds have insufficient fat reserves. The birds also have high energy requirements from October to February, when they are moulting their flight feathers and replacing them, so a reduced food intake during this period may also have serious effects on their preparation for migration (Smith 1991).

Timing of structural works may also be important, particularly where the undertaking of tasks at low water levels requires planning ahead to ensure that low tide coincides with suitable working times. In some areas it may also be best to work outside local wet seasons.

It is also advantageous to time works even if visual amenity is the only goal for the site. Vegetation will appear sooner and grow better if works are timed to be completed when nearby areas are flowering or setting seed.

4.7 Minimising disturbance during construction

All construction work should be planned and implemented to minimise effects on both the short-term and long-term health of the wetland and to improve its amenity, including water quality. To achieve this, a number of factors must be considered:

- Construction work can readily result in the blanketing of adjacent areas with sediment. In some cases the sediment can be toxic. In others, it can stifle flora and fauna growth.
- Mangroves can die if sediment covers pneumatophores.
- Disturbance of ASS should be minimised or avoided.
- It is important to monitor the rate of sedimentation to ensure that it is not excessive.
- A number of erosion and sediment control measures can be used to reduce sedimentation of adjacent areas, such as silt curtains and sedimentation basins.

Erosion and sediment control measures are discussed in Chapter 24 of *The Constructed Wetlands Manual*. Another document that presents a thorough treatment of this topic is *Managing Urban Stormwater – Soils and Construction* (Landcom 2004), also known as the *Blue Book*.

Wetland plants play an important role in reducing erosion within a wetland, including protecting newly constructed banks and channels. Root growth can bind the soil, vegetation can reduce water flow velocity, and **evapotranspiration** by plants can reduces soil saturation, which in turn helps to prevent bank collapse. In addition, the stems of plants can armour the soil surface to reduce soil erosion.

Disposal of excavated sediment from mangrove areas may be difficult. Don't place it where it may trap water and lead to the formation of stagnant pools. If it is not feasible to remove sediment from the area, place it carefully at the base of nearby mangrove plants without damaging the pneumatophores or scatter it widely so as to avoid pooling. Acidic sediments would require neutralisation before placing near vegetation.

Vegetation may be disposed of by burial and long-term decay, shredding or chipping and removal from the site, or a combination of these methods.

4.8 Rehabilitation and construction to control mosquitoes

When planning wetland creation or rehabilitation, avoid areas that may enhance breeding of mosquitoes. In estuarine habitats, *Ochlerotatus vigilax* (previously known as *Aedes vigilax*) and *Ochlerotatus camptorhynchus* (previously *Aedes camptorhynchus*) are the major pest mosquitoes, and both are vectors of viruses affecting humans (Russell 1994). In southern coastal areas of NSW, *O. camptorhynchus* is the major pest (Webb and Russell 2006). *Ochlerotatus vigilax* may disperse far from its larval habitat, and its connections with Ross River virus and dog heartworm have made it a focus for control efforts in coastal urban areas (Turner and Streever 1997). Other species of mosquito associated with estuarine areas include *Ochlerotatus alternans* (previously *Aedes alternans*), *Culex sitiens* and *Anopheles annulipes*.

Knowledge of egg laying sites favoured by mosquitoes may help improve mosquito control and guide wetland rehabilitation practices to avoid creating or exacerbating a mosquito problem. Mosquitoes are typically found in the ephemeral pools of saltmarshes and at the back of mangroves, rather than within the mangroves, where there is regular tidal exchange. In disturbed areas, stagnant pools create ideal mosquito breeding habitat. Poor drainage will promote mosquitoes, so there should be no restriction to tidal flushing. This will not only reduce the risk of mosquito infestation, but also assist in establishing saltmarsh plants.

As discussed in Section 4.3.1, runnels can assist with drainage of low-lying areas and prevent mosquito breeding by flushing larvae out into the more hazardous open water. Runnels also allow greater fish passage into the area, increasing predation of mosquito larvae.

Information on other methods for mosquito control is found in Section 5.5.6.

Dialogue Box 4.1 A case study of runnelling for mosquito control

Runnelling was carried out at Coomera Island on the Gold Coast in 1985. A half-hectare portion of saltmarsh was experimentally runnelled after more than 3 years of field and aerial survey research, to see whether a small alteration to the saltmarsh would be enough to reduce the larval population of the mosquito *Ochlerotatus vigilax*.

The runnels were manually dug with smooth sides to no more than 300 mm deep and 900 mm wide. This design mimicked the existing natural saltmarsh channels.

The project has been monitored for nearly 20 years. After 3 months there were very few mosquito larvae in the runnelled site (an average of 0.6 larvae per 240 mL dip compared with the surrounding saltmarsh (16 larvae per 240 mL dip).

Minor environmental changes related to runnelling have been identified at Coomera Island:

- increased wetness near runnels (because tides flood the area more often)
- slightly lowered salinity near runnels (because of flushing)
- increased numbers of some crabs (mainly in the upper saltmarsh).

However, runnelling was not found to affect:

- the acidity of soils or groundwater
- **water table** depth or groundwater salinity
- the size or density of the dominant grass, succulents or mangrove pneumatophores.

Compared with other methods of modifying saltmarshes for mosquito control (for example, open marsh water management and drain ditching), runnelling has been shown to have the least impact on saltmarshes. Runnels significantly reduce the numbers of mosquito larvae but do not significantly affect the saltmarsh or its processes (Dale *et al.* 1996, Dale *et al.* 2002, Dale 2005).

A note of caution: Consider runnelling only where drainage systems are likely to remain free of blockages, shallow ASS will not be disturbed and the soil type will not result in erosion.

4.9 Hazardous materials considerations

A hazardous substance can be defined as any substance that, because of its quantity, concentration, acute or chronic toxic effects, carcinogenicity, teratogenicity, mutagenicity, corrosiveness, flammability, explosiveness, radioactivity, or physical, chemical or infectious characteristics, may pose a hazard to human health or the environment when improperly treated, stored, disposed of or otherwise managed.

Laws apply to the use, storage and transport of certain hazardous materials (for example, dangerous goods and pesticides). Managing the generation, treatment, storage and disposal of hazardous materials, including household and industrial hazardous waste, is essential for wetland protection. Hazardous materials cannot be dumped in wetlands. Make sure you are aware of any requirements before using hazardous materials.

Hazardous materials can occur in wetland sediments and vegetation as a result of the long-term accumulation of heavy metals or toxic compounds. Thus, dredged materials which contain hazardous levels of toxic materials must be disposed of in accordance with the Waste *Avoidance and Resource Recovery Strategy* (Resource NSW 2003), and never in wetlands.

The DECC's Hazmat register (www.environment.nsw.gov.au/hazmat/index.htm) list providers that offer resources, equipment, products and advice on how to minimise the environmental effects of hazardous materials incidents.

For further relevant information about chemicals, visit the National Chemical Information Gateway (www.environment.gov.au/erin/index.html).

The soil within a wetland will act as a sink for many heavy metals, which can be released back into the water if pH is reduced or salinity is increased (Hart 1982). Heavy metal concentrations above **background levels** can cause adverse impacts on aquatic flora and fauna and, by association, people.

4.10 Acid sulfate soil management

Potential ASS contain iron sulfides (mainly pyrite), which can generate large amounts of sulfuric acid when exposed to air. NSW has about 600 000 hectares of ASS along its coastline (Naylor *et al.* 1998). The occurrence of ASS is related to low elevation and so is common in estuarine wetlands, estuary foreshores and the beds of estuaries. These soils formed naturally over the last 10 000 years, and are safe unless dug up or drained. Large-scale drainage of coastal flood plains for flood mitigation, urban expansion and agriculture has exposed large areas of ASS. Acid **leachate**, plus the aluminium, iron and heavy metals it releases from soils, can cause significant environmental and economic problems. Further information on the extent, formation and physical properties of ASS is given in Section 9.9.

ASS risk maps covering the entire NSW coastline are available from DECC. The Department of Planning has encouraged coastal local councils to develop local environmental plans for developments in ASS areas.

It is likely that an ASS management plan will be required for saltwater wetland projects.

Information resources on acid sulfate soils

The ASS risk maps are a series of 1:25 000 maps which identify the potential distribution of ASS along the NSW coastline. These maps also indicate the likely depth of ASS, the probability of ASS occurrence and the types of work that might disturb them. Guidelines to assist with the interpretation of the maps (Naylor *et al.* 1998) can be downloaded from the DECC website.

The *Acid Sulfate Soils Manual* (Stone *et al.* 1998) is a detailed reference manual on ASS assessment and management. The manual includes sections on planning, assessment and management, laboratory methods, drainage, groundwater, drain clearing and industry guidelines. The manual is currently under revision. The *Acid Sulfate Soils Remediation Guidelines for Coastal Floodplains in New South Wales* (Tulau, 2008) provides a framework for designing ASS remediation projects. The guidelines provide information on the design, implementation, management and monitoring of ASS remediation projects.

Principles for managing acid sulfate soils

In managing ASS the primary objective is to prevent or minimise the potential impacts, both on-site and off-site. The NSW *Acid Sulfate Soils Manual* (Stone *et al.* 1998) provides general management strategies for dealing with ASS including:

- prevent oxidation of iron sulfides:
  - avoid ASS
  - place iron sulphide sediments under water
  - collect and treat acid leachate (where the iron sulphide content of soil is very low)
- neutralising acid soil and leachate, generally through the addition of large quantities of lime
- separation of acid sulphate material (applicable to wet dredging operations where the acid sulphate fines can be separated by sluicing or hydrocycloning techniques).

With the exception of avoiding ASS disturbance, each strategy has its strengths and drawbacks. The limitations of ASS remediation strategies are discussed in the *Acid Sulfate Soils Remediation Guidelines for Coastal Floodplains in New South Wales* (Tulau, 2008).

Regeneration of swamp oak forest at Coila Lake after vehicle exclusion (Eurobodalla Shire Council)

Wader roost constructed at Stockton Sandspit (Kooragang Wetland Rehabilitation Project)

Floodgate Yarrahapinni, Macleay River (DECC)

5 Operation and maintenance

5.1 The need for management

Saltwater wetlands that have been constructed or rehabilitated are susceptible to a number of external and internal pressures and require medium- to long-term management to ensure that project objectives are achieved. Ongoing management is necessary to deal with damage due to physical, chemical and biological processes and the ongoing effects of human activities such as agricultural and industrial pursuits adjacent to or within wetlands systems.

A prime objective of the management of saltwater wetland rehabilitation is the protection or enhancement of ecosystem health. Accordingly, operational procedures will normally focus on this objective.

The type and intensity of management should depend on the scale of the activity, and should be considered before the initial rehabilitation or construction process begins.

As indicated in *The Constructed Wetlands Manual* (DLWC 1998), it is sometimes necessary to prioritise management activities and then to allocate resources accordingly for their implementation. The priority list for constructed freshwater wetlands is also suitable for saltwater wetlands:

1. Safety – Give the highest priority to public safety.
2. Stability – Maintain and repair structures to prevent their failure.
3. Plants – Maintain plants to prevent their loss and consequent reduction in the ecological health of the wetland.
4. All other management activities – essential for the health and performance of the wetland.

5.2 Elements of management

The main elements of management can be categorised as:

- operation
- maintenance
- monitoring and inspection
- emergency management.

The successful operation of a saltwater wetland rehabilitation plan will require the effective implementation of each one of these elements. Implementation is not a linear process, but rather a circular process with continual feedback from one element to another.

The operation, maintenance and monitoring of constructed wetlands is comprehensively covered in *The Constructed Wetlands Manual* (DLWC 1998). Much of that material is directly applicable to saltwater wetlands, and should be consulted in conjunction with this manual.

Examples of each of the elements of management:

- Operation – controlling flows into and out of the saltwater wetland.
- Maintenance – repairing damage to structures built as part of the rehabilitation plan; controlling weeds and pests.
- Monitoring – data collection in relation to water levels, water quality and habitat.
- Inspection – inspecting structures for damage and to assess whether they are working as planned.
- Emergency management – repair to controlling structures, general geomorphology and plantings following coastal storms or floods.

The information in this chapter is provided as a guide or a possible approach to maintenance. The amount of detail required in individual projects will depend on their nature and size, and can be adjusted to suit your purposes. A small-scale project may require only a single-page operational plan, while a larger-scale project may require more detail. It is essential that plans be tailored to the people undertaking the work.

5.3 Operation and maintenance plan

An operation and maintenance plan provides an adaptive management framework and should be tailored to suit the main objectives of the rehabilitation project.

Management activities should seek to maintain sustainable coverage of native vegetation. The operation and maintenance plan should allow for gradual changes in the relative coverage of these species, rather than seek to prevent such changes.

Elements of the operation and maintenance plan include:

- a description of the saltwater wetland, its values and the management strategies or structures that have been established
- a list of specific management objectives related to the values
- a list of management activities or tasks
- a timetable for activities and resource availability
- a description of monitoring activities
- an inspection checklist
- a list of contacts for approvals and advice
- an emergency management plan.

Details of each of these elements are presented in Appendix 4.

5.4 Implementing the operation and maintenance plan

The implementation of the operation and maintenance plan can be considered in terms of the phases presented in *The Constructed Wetlands Manual* (DLWC 1998) with some adaptation; that is, commissioning, operation, decommissioning and refitting.

Commissioning phase

The commissioning phase is generally taken as the time from the end of the construction or installation phase to when plantings and surface and groundwater flow regimes have become established.

Access requirements should be reviewed in the commissioning phase to ensure that access is adequate for maintenance activities.

Careful monitoring and inspection are necessary during the commissioning phase to ensure that any control structures are operating appropriately, any erosion or sedimentation is acceptable or can be rectified, and water levels are maintained within an acceptable range to prevent the new plantings from drying out or becoming drowned.

At this time the newly rehabilitated saltwater wetland can be particularly vulnerable to outside influences such as catchment runoff, flooding, storm and wave attack, and disturbance by humans and other animals. It is therefore important that regular (possibly weekly) inspections be undertaken. If necessary, public access may need to be restricted until plantings are successfully established.

Operation phase

The operation phase covers the design life of the rehabilitated saltwater wetland, which could be up to 50 years. During this phase, all management activities applicable to operation, maintenance, monitoring, inspection and emergency management would be implemented. These management activities seek to ensure that the saltwater wetland is performing adequately to attain the management objectives. Ongoing monitoring and inspections are necessary to ensure that performance is acceptable and to identify where changes to the operation and maintenance activities may be necessary.

Several years after the start of the operational phase it will be appropriate to review the original management objectives. As estuarine and coastal systems are dynamic environments, it is possible that the values of the saltwater wetland will change or the initial management activities will no longer be entirely appropriate to protect and enhance those values. As a result of this review, some change to the operation and maintenance plan may be necessary.

Decommissioning and refitting phase

The decommissioning and refitting phase comes after the end of the design life of the rehabilitated saltwater wetland. While in most cases we should hope that the wetland would last indefinitely, some situations, such as growth in adjacent residential and commercial areas, can make a saltwater wetland unviable or at least affect the operation of wetland processes.

Common reasons that may result in the need to refit a saltwater wetland, particularly within a very urbanised environment, are the accumulation of sediment from the catchment and reworked sediment within the wetland and the alteration to stormwater runoff due to changes in the catchment. Changes in runoff can bring additional loads of pollutants to the wetland and change the flow regime.

Major refits to the wetland could include the removal of accumulated sediment, alteration to flow control structures and the re-establishment of plantings. Sediment must be removed in such a way as to minimise damage to existing vegetation communities, and be disposed of appropriately. Flow control structures should be altered only after an assessment of the likely changes to the flow regime. This would normally require seeking specialist advice and reviewing the results of any monitoring of water levels and flows.

In the refit of the wetland it may be appropriate to set new management objectives.

A possible cause for the decommissioning of a saltwater wetland could be the growth in adjacent urban development, which may increase catchment pollutant loads to such an extent that the wetland cannot operate satisfactorily. To avoid this situation, take all opportunities during the planning process to minimise encroachments on the wetlands.

Information on a range of general operation and maintenance considerations is included in Appendix 4.

5.5 Maintenance considerations

Storms and floods

High flows and wave activity can result in erosion and sedimentation. In addition, litter and other debris can be deposited in the wetland. Inspect your wetland as soon as possible after storm and flood events to note any damage or deposition of sediment and litter and rectify it.

Storms and floods may damage saltwater wetland vegetation through sedimentation or erosion. Small events are unlikely to cause significant damage. However, if larger events do cause damage, seek specialist advice to determine the most suitable form of remediation.

Invasive plant species

Several invasive species have the potential to completely overrun saltwater wetlands. Of particular note are common cordgrass (*Spartina anglica*) and spiny rush (*Juncus acutus*). The invasive common cordgrass was introduced into Tasmania and Victoria specifically for reclamation of land and stabilisation of mudflats. In Tasmania, it has completely taken over the Tamar Estuary (Adam 1981). Yet despite attempts to establish it in NSW it has not become a problem here (Adam and Hutchings 1987). It can have several detrimental effects on natural environments in Australia, including invading mudflats that are rich in invertebrates and producing dense monospecific stands that replace more diverse plant communities. Birds have been observed to avoid it (Simpson 1995, Hedge and Kriwoken 2000), and species richness and total abundance of fauna are greater in areas dominated by native plants than in those dominated by *S. anglica* (Hedge and Kriwoken 2000).

Juncus acutus removal (Kooragang Wetland Rehabilitation Project)

Spiny rush was introduced from the Mediterranean, and has become widespread throughout estuaries and on saline pasturelands in south-eastern Australia (Milford and Simons 2002). It has been so successful that it has been listed as a noxious weed in Australia (NAWC 2003). It occupies the same niche as the native rush, *Juncus kraussii*, but is tougher and more resilient and easily out-competes the native species.

The introduction of *J. acutus* into saltmarshes has altered their structure and complexity. Once *J. acutus* becomes established, its sharp, tough, cylindrical leaves form dense, impenetrable thickets, displacing the native rush. Many gastropods and other invertebrates are believed to depend on *J. kraussii* for completion of their life cycle, which the harsher habit of *J. acutus* precludes. Therefore, the ecosystem may be severely affected by the invasion of *J. acutus*. Removal of this species has become a focus for management in some areas, but it is proving particularly difficult to eradicate. Paul and Young (2006) have trialled a number of methods for its control, including physical removal, application of glyphosate and application of salt. More information is required on the general biology and physiology of this species in order to formulate effective methods for its permanent eradication.

Weeds

Although seagrasses and mangroves in NSW have remained substantially uncontaminated by weeds, a number of weed species have become established in saltmarsh and swamp forest.

Annual beardgrass (*Polypogon monspeliensis*) favours damp, disturbed sites often close to water, and coast barbgrasses (*Parapholis incurva* and *Monerma cylindrica*) are found in saline soils subject to flooding. Other common introduced species include buck's horn plantain (*Plantago coronopus*), rock sea lavender (*Limonium binervosum*), annual beardgrass and salt daisy (*Aster squamatus*). All these species have been introduced from the Northern Hemisphere, and most can out-compete native species. Generally, however, invasive annual species are not as detrimental as invasive perennials that may invade during periods of low salinity and become a permanent feature of the wetland (for example, *Typha orientalis*).

Groundsel bush (*Baccharis halimifolia*) is an increasing problem in North Coast marshes owing to its masses of windborne seeds. Alligator weed (*Alternanthera philoxeroides*) and bitou bush (*Chrysanthemoides monilifera*), though generally more a problem in other habitat types, show a level of salt tolerance and are found on brackish saltmarsh margins. Other exotic species found in the saltmarsh margins and swamp forest are pennywort (*Hydrocotyle bonariensis*) and coastal morning glory (*Ipomoea cairica*). Salt daisy is found throughout the upper marsh. Common weed species in swamp forest also include lantana (*Lantana camara*) and wandering jew (*Tradescantia fluminensis*).

Macroalgal mats

In shallow estuaries and coastal lagoons, species of the opportunistic green algal genera *Cladophora*, *Enteromorpha*, *Ulva* and *Chaetomorpha* and of the red algal genus *Gracilaria* grow luxuriantly and form extensive mats which, under certain conditions, can detach and float in the water column. For example, *Enteromorpha intestinalis* formed mats along the shoreline of shallow semi-enclosed bays in Lake Macquarie, first appearing in the late winter and early spring and later developing into dense mats which detached and floated in the lake (Wood 1959). In the same lake, *Enteromorpha prolifera* and an unidentified *Enteromorpha* sp., at first **epiphytic** on seagrasses, formed free-floating mats in the shallows.

Floating mats of these nuisance species are becoming more common in estuarine systems around the world, a phenomenon due largely to **eutrophication**. In eutrophic estuaries, large free-floating banks of opportunistic green algae, sometimes exceeding 0.5 m in thickness, grow in response to the increased nutrient loading. Following the opening of coastal lakes, the sudden drop in water level can strand the macroalgae in dense mats that eventually dry out and decompose.

Dense mats of macroalgae exposed as water levels drop in Lake Wollumboola after the lake's opening to the sea (DECC)

Litter and debris

If gross pollutant traps have been installed to trap litter and other debris, they will require regular inspection and cleaning, especially after storms. If traps are not installed or prove to be ineffective, litter and other debris can accumulate in the saltwater wetland. Some of the accumulated litter and debris may leave the wetland on the ebb tide, while additional material can enter on the flood tide.

Litter and accumulated debris within a wetland (DECC)

Certain facilities such as walkways may result in increased litter in their vicinity due to the number of people visiting them. It is important to determine the sources of litter and then implement a reduction plan, which could involve structural measures such as installation of gross pollutant traps or non-structural means such as an education program.

Control of cattle, pests and mosquitoes

Cattle can trample and graze plants in saltwater wetlands. They can be excluded by appropriate fencing and off-stream watering points.

Damage caused by uncontrolled cattle access to an estuary bank (Adam Gosling, WetlandCare Australia)

Pests

Pests may include rats, birds, flies and mosquitoes. Birds and rats can damage saltwater wetland vegetation, especially new plantings. Regular inspections are necessary after new plantings. In extreme situations culling may be necessary.

The larvae of a moth (*Enoplidia* sp., Oecophoridae) periodically cause widespread damage to mangroves in the Hunter estuary and possibly elsewhere. The species is undescribed, and control measures have not been investigated. Although damage is substantial, the larvae do not appear to cause permanent damage to mature stands. However, the degree of damage evident in mature stands would cause severe setbacks to seedling establishment projects, and control methods such as spraying would have to be carried out to prevent substantial loss of the new plants.

More recently, the Sydney Olympic Park Authority has commissioned a study by the University of Western Sydney of a severe attack by a moth. The attack started in late 2003 and has been repeated over the last 3 years. As a consequence or as a coincidence, a significantly low number of **propagules** have been produced by the mangroves in the greater Sydney area. The moth was identified as a species of *Ptyomaxia* (Phycitinae). The species is believed to be close to *Ptyomaxia metasarca*, which has been described from Brisbane (S. Paul, Sydney Olympic Park Authority, personal communication, 11 January 2006).

Mangrove dieback as a result of insect grazing (DECC)

Insects such as Cecidomyiidae flies can cause galls or lumps on mangrove leaves. Ten different types of cecidomyiid-caused galls have been recorded from *A. marina* in Queensland (Burrows 2003).

Insects can be a symptom of stress, and may not actually be the cause. Where insect damage is of concern, look more broadly for causes of mangrove stress.

Mosquitoes

Mosquitoes are common in saltwater wetlands and can cause health problems. Stagnant areas tend to become mosquito breeding zones. The objective of mosquito control is to maintain the population below threshold levels for disease transmission and nuisance.

Mosquito control is achieved by physical, biological or chemical means. Physical control by habitat modification can be achieved by preventing ponding, as the larvae are generally easily washed out with flowing water. Information on the use of runnels is provided in Sections 4.3.1 and 4.8. Biological control is achieved by predators, including larvae and adult insects, bacterial and fungal **pathogens**, and growth regulators. Chemical control is achieved by spraying with larvicides and insecticides. This can have immediate results, but is often indiscriminate and can lead to the development of resistance. Chemical spraying is not appropriate where the site has conservation or habitat value.

Educating the local community on the ecology and the risk levels allows a more informed and environmentally sustainable approach. There is a need to balance the perceived threat with the actual public health risk and the needs of the environment. Effective mosquito control requires liaison between land use planners, mosquito managers and the local community. An example of a coordinated regional response to mosquito populations and arbovirus activity in NSW is the *Living with Mosquitoes* program developed by five local councils and stakeholders in the Lower Hunter and Mid North Coast regions.

Mosquito populations in wetlands can be managed by integrated control measures such as:

- the reduction or minimisation of areas suitable for mosquito breeding
- the maintenance of vegetation communities in a form which does not provide extensive mosquito breeding habitat
- the development of a diverse and balanced aquatic community
- the encouragement or implementation of biological control (such as the presence of native insectivorous fish species)
- the use of pesticides in a judicious manner and only when necessary.

Within tidal wetlands the scope for introducing fish as a mosquito control mechanism is obviously limited, but if the wetland area is effectively flushed, then predators such as native fish should be able to enter the area freely. However, if self-contained pools of water are a part of the wetland rehabilitation design (for example, to provide a range of diverse habitat types for birds), it may be possible to stock native fish to control mosquitoes.

Many small native fish are widely distributed in natural waters and are considered effective for the control of insect pests. If investigating fish stocking as a control mechanism, use only local native fish, as the introduction of non-locals may have detrimental effects if they expand their distribution. Native fish are easy to locate, are suited to local conditions, and are unlikely to cause ecological disturbance. Most small native fish are hardy and will reproduce quickly in most permanent water bodies such as ponds in created wetland habitats. They can be obtained from some aquarium shops or from registered fish hatcheries. It is important to select species that occur within similar habitats and locations to those that are being recreated. Fish stocking may require a permit from the DPI.

The use of pesticides for mosquito control is limited by the availability of appropriate products and concern for effects on non-target species and environmental contamination. The number of chemicals considered environmentally acceptable for use in diverse ecosystems is diminishing. The organophosphate pesticide temephos is widely used in freshwater wetlands, where it kills mosquito larvae on contact, but it is not suitable for saline wetlands because it has detrimental effects on the development of some crustaceans.

Two agents are available for the control of mosquito larvae (University of Sydney and Westmead Hospital, Department of Medical Entomology 1998):

- *Bacillus thuringiensis israelensis* is considered to be a temporary control measure owing to the relatively narrow window of opportunity for it to be effectively applied. This commercially produced bacterium kills larvae when ingested. It must be applied within the first few days of the mosquito's aquatic life cycle as it does not affect mature larvae.
- Methoprene is an insect hormone analogue and a growth retardant relatively specific to mosquitoes which prevents the larvae from developing to adulthood. The product must be applied to larval populations as it does not affect pupae. Larvae will continue to develop after the application but will eventually die in the pupal stage, and no adults will be produced. However, because it does not directly kill the larvae, its effectiveness is often difficult to evaluate in the field.

These products are believed to target aspects of mosquito biology without having undue effects on non-target species and the environment in general.

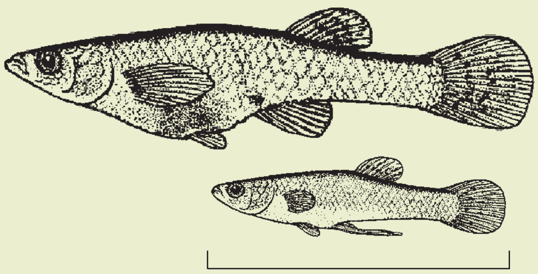
Dialogue Box 5.1 A note on the use of mosquito fish

The mosquito fish *Gambusia holbrooki* is a small, live-bearing fish native to Central America and has been used widely in mosquito control. First introduced to eastern Australian waters in 1929, by 1945 it was widespread. The introduction of exotic fishes adversely affects native systems and fauna through competition for food and space and the introduction of exotic disease and parasites.

Mosquito fish not only cause reductions in native fish populations, but may also reduce populations of invertebrates such as aquatic insects, crustaceans and molluscs. There is also evidence that mosquito fish prey upon eggs and tadpoles of the green and golden bell frog (*Litoria aurea*) (Morgan and Buttermer 1996).

The actual impact that these fish have on mosquitoes is minimal, as mosquito larvae form only a small portion of their diet. Consider native alternatives if fish are to be a means of biological control of mosquito larvae in any constructed ponds or areas of standing water.

Predation by *Gambusia holbrooki* has been listed as a key threatening process under the TSC Act.



Mosquito fish (*Gambusia holbrooki*): Top, female; bottom, male (adapted from Department of Primary Industries (Victoria), 2003)

Sediment and toxic materials

You may need to monitor sediment accumulation in the saltwater wetland if sedimentation from the surrounding catchment is accelerated by anthropogenic influences. Sedimentation may be a particular problem after storms and floods. Accumulated sediment may need to be removed to maintain water depths and flow conditions.

Accumulation of heavy metals and other toxic compounds in saltwater wetland sediments and vegetation can lead to **bioaccumulation** in the ecosystem and redistribution by wetland food chains, with implications for faunal and human health.

Sediments must be disposed of in accordance with current legislation. This will usually require contaminant testing of the sediment, and disposal may require consent from DECC.

Vandalism

Vandalism can reduce the environmental and aesthetic qualities of the rehabilitated wetland. Activities can include damage to control structures, other facilities, plantings and established vegetation; dumping of litter, sediment, chemicals and other material into the wetland; and disturbance of wetland fauna.

Education programs are recommended to advise of the values and sensitivities of saltwater wetlands. If the vandalism is recurrent or extreme, monitoring or the involvement of local council rangers or the police may be required.

Neighbouring activities and usage

Operation and maintenance activities need to allow for neighbouring activities and usage. Monitor any odours and mosquito problems generated by the wetland, and put appropriate measures in place.

Consider also the potential effects of the neighbouring areas on the saltwater wetland in ongoing management. The effects can range from minor short-term impacts such as the isolated deposition of litter to major long-term impacts such as the loss of sustainability of the wetland due to the growth of urban development. The wetland operator must always be aware of neighbouring activities and usage and be prepared to respond to changes in them.

It is important to anticipate and then prevent damaging impacts on the wetland. Activities to particularly watch out for include any that will generate sediment or hydrocarbons. These include construction work, commercial and residential developments, and activities that redirect stormwater, as well as waves generated by boats, and oil or toxic spills.

6 Monitoring and reporting

6.1 Monitoring

Introduction to monitoring

The current management of Australia's estuarine areas is often confounded by an absence of adequate scientific information. Environmental monitoring within estuaries is poor, so the consequences of pressures on the environment are not well understood or documented.

> *Monitoring is defined as the intermittent recording of the condition of a feature of interest to detect or measure compliance with a predetermined standard.*
>
> *Source:* Hellawell (1991)

Monitoring is a very important component of successful management and rehabilitation of wetland environments. Monitoring may be used to determine when a wetland is moving away from its desired state, to measure the success of management actions, and to detect the effects of disturbances to the wetland (Legg and Nagy 2006).

Since monitoring addresses the extent of change within the environment, which is naturally variable, monitoring studies require a degree of scientific rigour. This does not mean that an effective monitoring program is necessarily complex or expensive, just thorough and well designed with clear objectives. Inadequate or inappropriate sampling design and lack of clear objectives in past monitoring programs has led to a failure to deliver useful information when required (Finlayson and Mitchell 1999, Grayson *et al.* 1999, Chapman and Underwood 2000). If rehabilitation, restoration and creation of saltwater wetlands are to succeed, then monitoring is key.

This manual provides only a brief summary of the parameters and techniques that can be used in monitoring a saltwater wetland. A number of useful guidelines provide more specific information on sample design, methods of measurement and statistical analysis for rivers and wetlands (Dialogue Box 6.1). While not all relate specifically to saltwater wetlands, many of the methods and principles are transferable.

We strongly recommend that you seek professional assistance in the design of monitoring programs and in the collection and analysis of monitoring data.

Dialogue Box 6.1 Useful references for wetland monitoring

ANZECC, ARMCANZ (2000) *Australian Guidelines for Water Quality Monitoring and Reporting*. Available from www.mincos.gov.au

McGloin E, Botting S. (2005) *Establishment of a monitoring and evaluation framework for the Hunter–Central Rivers Catchment Management Authority.* NSW Department of Natural Resources, Hunter Region.

Rutherford I D, Jerie K, Marsh N. (2000) *A Rehabilitation Manual for Australian Streams, Volume 1*. Cooperative Research Centre for Catchment Hydrology, Monash University, Victoria. Available from www.rivers.gov.au

Tucker P. (2004). *Your Wetland: Monitoring Manual – Data Collection*. River Murray Catchment Water Management Board, Berri, and Australian Landscape Trust, Renmark. Available from www.rivermurray.sa.gov.au

Ward T, Butler E, Hill B. (1998) *Environmental Indicators for National State of the Environment Reporting – Estuaries and the Sea. Australia: State of the Environment (Environmental Indicator Reports)*, Department of the Environment, Canberra.

Available from www.deh.gov.au/soe

Sampling design

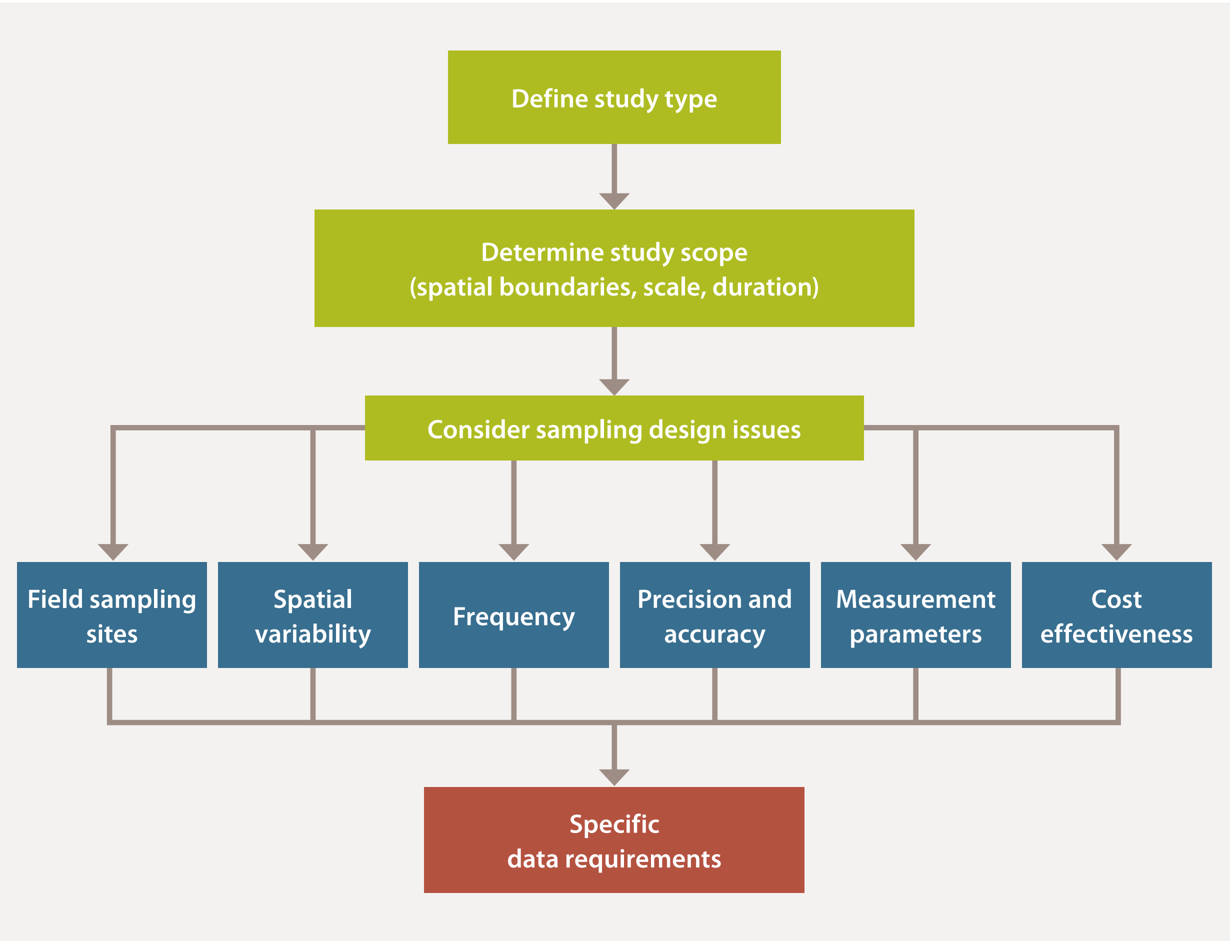
The design of the monitoring program should be based on the stated goals and objectives of the rehabilitation project (Section 2.3). The identification of clear objectives and measurable performance criteria will form the starting point for your monitoring program.

The ultimate design of your monitoring program will depend on many factors, including:

- time and budget available
- whether specialist consultants will be required
- how large and complex your wetland is
- how extensive the proposed changes or rehabilitation actions will be.

Figure 6.1 presents a framework to consider when you are designing a monitoring program. It highlights some of the decisions that you need to make when determining what, where and how you will collect data. Dialogue Box 6.2 provides a more comprehensive checklist of things to consider before you embark on a program of data collection.

Figure 6.1 Framework for designing a monitoring study



Source: ANZECC and ARMCANZ (2000)

Baseline and operational monitoring

Some degree of monitoring is necessary before any rehabilitation or disturbance of the project site occurs. Begin this during the data collection phase of your project (Chapter 3). Baseline monitoring is necessary to provide a basic understanding of how your wetland is functioning and what its current condition is. Baseline data provides information against which future changes can be detected and quantified.

Baseline monitoring should cover as long a period as possible, but as a minimum, you will need at least two sampling events before the proposed rehabilitation begins (ANZECC and ARMCANZ 2000). It is preferable for baseline sampling to cover at least two different seasons (summer vs. winter, or autumn vs. spring) to take into account seasonal differences in, for example, water temperatures, aquatic organisms, vegetative conditions and waterbird activity.

Operational monitoring is used to assess the effectiveness of operation and maintenance activities. Operational monitoring may include regular checking and clearing of any litter and debris traps or checking for soil erosion. Many aspects of operational monitoring can be carried out through inspections of the wetland (Section 6.1.7).

Dialogue Box 6.2 Checklist for designing a monitoring study

1. Has the study type been made explicit and been agreed on?
2. Have the spatial boundaries of the study been defined?
3. Has the scale of the study been agreed on?
4. Has the duration of the study been defined?
5. Have the potential sources of variability been identified?
6. Are there sufficient sampling sites to accommodate variability?
7. Are the sites accessible and safe?
8. Can sites be accurately identified?
9. Has spatial variation in sites been considered, and have options to minimise it been considered?
10. What is the proposed frequency of sampling?
11. Have decisions been made about the smallest differences or changes that need to be detected?
12. Is replication adequate to obtain the desired level of precision in the data?
13. Have the measurement parameters been chosen?
    (a) Are they relevant?
    (b) Do they have explanatory power?
    (c) Can they be used to detect changes and trends?
    (d) Can they be measured in a reliable, reproducible and cost-effective way?
    (e) Are the parameters appropriate for the time and spatial scales of the study?
14. Has the cost-effectiveness of the study design been examined?
15. Have the data requirements been summarised?

Source: ANZECC and ARMCANZ (2000)

Reference and control sites

The design of the monitoring program should include sampling at reference and control sites. These sites are used to characterise the before and after condition of the wetland.

Reference sites are places that have not been subject to degradation. They approximate the condition that is being aimed for at the restored wetland.

Control sites are places that are in similar condition to the unrestored wetland and where no rehabilitation work will take place.

For a wetland to be considered rehabilitated it should change to become similar to the reference sites and different from the control sites.

It is preferable to have at least two reference and two control sites so that any differences can confidently be attributed to the rehabilitation actions rather than to natural variability. Control and reference sites should be located so that they will experience the same natural processes (tides, wind, floods etc.) or stresses as the wetland to be restored, and should be free of any human impacts that are not present at the rehabilitation site.

Depending on the size of the project site it may be possible to find suitable reference or control sites within the same wetland. For example, one side of a tidal channel may be in good condition (and can therefore represent the reference condition), while the opposite side of the channel is the site to be restored. Alternatively, there may be a section of the wetland that may not be able to be rehabilitated (for example, owing to the continuing presence of a structure), and this may then act as a control site against which to compare the rehabilitated part of the wetland.

Parameters to measure

Parameters measured as part of a monitoring program can be physical, chemical, biological or social. There are two main types of data that can be collected by monitoring programs: quantitative and qualitative.

Quantitative data

Quantitative data refers to data collected in an exacting and measurable manner. As the name implies, the emphasis of this method is to rigorously quantify the data so that an exact measure of change can be estimated. The assumption is that anybody repeating the study or using the same instruments and methods would get comparable results. Monitoring of parameters such as water or soil chemistry usually involves quantitative methods.

Qualitative data

Qualitative data refers to data that is collected in a less exacting, more subjective manner. The data collected by these methods is indicative, meaning it will indicate a change but not by a precise degree. The use of photo monitoring points or survey results from recreational users would be considered a qualitative method of data collection.

The parameters that need to be measured must relate to the objectives and performance criteria selected for the project. It is important to ensure that information collected on wetland performance can be and is related to wetland operation. This will then enable subsequent review of operational procedures. Once you have defined a possible list of parameters to monitor, ask these simple questions as you consider each one:

- *What am I monitoring?* Be specific, for example, percentage vegetation cover, not just vegetation.
- *Why am I monitoring this?* How does it relate to the project objectives?

- *How am I going to monitor this?* Is the method qualitative or quantitative? Is there a better method?
- *What will this tell me?* Is the data going to provide a clear indication of change?

Some of the common parameters that may be included in wetland monitoring programs are listed in Table 6.1 (overleaf; adapted from Laegdsgaard 2003). Again, the parameters you choose will depend on the specific objectives to be achieved at your site. For example, monitoring changes in elevation through surveying is unnecessary if your project is weeding and revegetation, but it will be critical where channel works or tidal alterations are proposed.

Photo monitoring

One of the easiest ways to document changes in a wetland is to establish permanent photo points that can be revisited on a regular basis. The following guidelines will ensure that you get the best results from a photo monitoring program (modified from Tucker 2004):

- Try to use a relatively high vantage point (for example, fallen log or step ladder) so you can continue the photograph series if vegetation begins to grow.
- To provide perspective, include the sky line in each photograph, and make use of features such as fallen logs, dead trees or rocks.
- Consider using a range pole at a set distance from where you are standing to provide your photograph with a measure of relative height.
- Ensure that you are able to locate the photo point at a later date by accurately recording the site location (using GPS, a sketch map or other detailed description).
- Consider using permanent posts (star pickets or wooden survey pegs) to mark the location if there are no other significant features to use for reference.
- Use a compass to record the bearing (direction) of each photograph to ensure that the same frame is taken repeatedly each time you return.
- Take a copy of the previous series of photographs into the field with you to assist with reproducing the exact view (amount of sky, location of prominent features and amount of zoom used).

Inspections

Inspections are required to check that all components within the wetland are operating appropriately, to check for any damage, and to check for any unanticipated changes. Make inspections on a predetermined regular basis and following specific events, such as storms and floods, large spring tides or large community functions on adjacent land.

An inspection checklist should list the inspections required, listing:

- the component to be inspected
- the required frequency of inspection
- the date of inspection
- the result of the inspection
- the action taken
- additional follow-up required.

The checklist can be kept as a record of operation and maintenance activities and used as a basis for quality assurance to verify that activities are being undertaken in accordance with the operation and maintenance plan.

Table 6.1 Parameters that could be included in wetland monitoring programs

Information sought	Measurements	Methods
Changes in elevation of the study site	Land levels	Surveying of transects
Changes to water level	Water levels	Water level recorder
Changes to area of inundation	Area inundated	Land survey
Concentrations of nutrients available for plant growth	Total nitrogen and phosphorus in water and sediments	Laboratory analysis
Changes in organic content of sediments	Percentage total organic content of sediments	Laboratory analysis
Salinity of the environment with respect to plant zonation	Soil salinity	Field measurements of soil pore water
Temperature range of the water	Water temperature	Field measurements with a water quality instrument
Salinity range of the water	Water salinity	As above
Dissolved oxygen range of the water	Dissolved oxygen	As above
Amount of waterborne sediment arriving at the site	Turbidity	As above
Change in vegetation cover over time	Percentage cover of vegetation	Field measurements using quadrats or transects
Change in vegetation composition over time	Species composition of vegetation	As above
Mangrove incursion	Recording mangrove seeds and seedlings	Field measurements of number and height of seedlings Air photo monitoring
Changes in the diversity and abundance of molluscs	Density and species composition of molluscs	Field measurements in 1 m^2 quadrats
Changes in the diversity and abundance of crabs	Abundance of crab holes	Field measurements in 1 m^2 quadrats
Changes in the diversity and abundance of insects and spiders	Density and species composition of insects and spiders	Sweep netting Laboratory sorting and identification of insects and spiders

Information sought	Measurements	Methods
Changes in the benthic invertebrate fauna over time	Composition of benthic invertebrate fauna	Core samples (in conjunction with total organic carbon samples) Laboratory sorting and identification
Use of the wetland by fish	Composition of fish fauna	Fish traps, dip-netting or seine netting Field or laboratory sorting and identification
Use of the wetland by waterbirds	Composition of waterbirds and waders	Observations of numbers and composition of waterbirds (early morning or dusk)
Use of the wetland by surrounding residents	Visitation	Survey of local residents Visitor counts

Field measurements of plant distribution using small quadrats (Koorangang Wetland Rehabilitation Project)

Collection of fish from a seine net (Koorangang Wetland Rehabilitation Project)

How long and how often should we monitor?

Monitoring can be a very intensive task that is often underestimated in preliminary project plans and budgets. Insufficient monitoring and poorly designed monitoring programs make it impossible to gauge the true impact of management actions. Ideally, the more information that can be gathered over a given time frame, the better the data set will be and the easier it will be to establish clear patterns in the data. Monitoring needs to occur more frequently in the early stages of a rehabilitation project while rapid changes are occurring (perhaps monthly or bi-monthly), while seasonal or biannual sampling will usually be sufficient after a few years.

Since it is easier to measure structure than function, it is necessary to have clear links between the two. In this way, measurements of structure can be used to provide useful information on function. Monitoring must continue even after the wetland structure looks right to ensure that proper functioning of the wetland has also been restored. Examples from rehabilitation projects at Homebush Bay show that this is not always the case (discussed in greater detail in Section 6.4).

Full wetland functionality may not return for many years, or may never return. Long-term documentation of saltmarsh recovery in North Carolina (USA) showed that although vegetation may quickly compare to reference sites, it can take 15–25 years for benthic fauna to become similar in composition and abundance to that at reference sites. Soil attributes were the slowest to match reference sites and were still dissimilar after 26 years (Craft *et al.* 1999). Other studies have confirmed that soil attributes are the slowest to recover after rehabilitation works (Table 6.2).

There is general consensus within the literature that saltmarsh vegetation often recolonises within 4 to 6 years (Table 6.2), but it may not fully resemble the natural reference sites for at least 20 years (Williams and Orr 2002, Warren *et al.* 2002, Morgan and Short 2002).

If left to recover under natural conditions, local saltmarsh species can vary in recovery from a few years up to 10 years depending on the type of impact. *Sarcocornia* sp. saltmarsh at Kooragang Island, near Newcastle, took at least 5 years to recover naturally following cattle exclusion, while experiments by Laegdsgaard (2002) have shown that recovery of this species may be as quick as 2 years on the lowest parts of the shoreline.

Studies of natural saltmarsh recovery in Connecticut (USA) have shown that certain types of benthic fauna such as snails may return relatively early (within 5 years), yet full recovery of other species may take up to 20 years (Warren *et al.* 2002). Similarly, while a typical fish species assemblage may return within 5 years, it can take much longer for the population size to be similar to that at reference sites.

In the context of the above examples, an initial monitoring plan should aim to collect data for at least 5 years after the rehabilitation works have been implemented. At this time the monitoring program can be reviewed, and a less intensive, longer-term sampling program can be designed. Although water quality and vegetation objectives may be achieved within a 5-year time frame, it is likely that faunal populations and soil properties will still be evolving in response to the management actions. A continuing program of monitoring is therefore required if the objectives are to continue to be assessed.

Table 6.2 Observed wetland recovery times

Wetland component	Recovery time	References
Saltmarsh vegetation	4–6 years for initial recovery	Broome *et al.* 1988
(general)	Up to 20 years for full recovery	Frenkel and Morlan 1990 Simenstad and Thom 1996 Boumans *et al.* 2002 Eertman *et al.* 2002 Thom *et al.* 2002 Williams and Orr 2002 Craft and Sacco 2003
Salt couch (*Sporobolus virginicus*)	5–6 years	Laegdsgaard 2002
Samphire (*Sarcocornia quinqueflora*)	4–5 years on upper shore 2 years on lower shore	Laegdsgaard 2002
Benthic fauna	15–25 years (re-creation sites) 9–21 years (natural recovery sites)	Craft *et al.* 1999
	5–15 years	Warren *et al.* 2002 Craft and Sacco 2003
Waterbirds	15 years for saltmarsh specialists	Warren *et al.* 2002
Fish	5–15 years	Warren *et al.* 2002
Soils	> 25 years	Seneca *et al.* 1976 Havens *et al.* 1995 Craft *et al.* 1999 Havens *et al.* 2002 Craft and Sacco 2003

6.2 Data storage, analysis and reporting

The storage, analysis and reporting of monitoring data are all important if meaningful information is to be obtained.

Data storage

Data may be stored in a variety of forms, including hard copies of field and laboratory notes and computer spreadsheets and databases. Organise field sheets and laboratory records in a folder or filing system. Retain the data sheets even when the data has been transferred to computer in the event of computer failures or errors in data entry.

Spreadsheets are an appropriate form of data storage for the manipulation of small data sets, calculation of simple summary statistics, and presentation of data in basic graphical formats.

Data should be stored in databases, which can sort and present data according to specific criteria. This can be useful for generating reports on various parameters and sites over time. Data sets can be exported into statistical packages for detailed analysis and presentation of data. Spatial data, such as that collected using GPS (Section 3.2) should be stored in databases compatible with the GIS to be used.

Data analysis

Data analysis can range from simple observations of trends to very complicated statistical and mapping techniques. Graphical analysis of data can reveal a wealth of information and should always be the first step in any analysis. Graphs are a simple and important way to check by simple observation that the statistical analyses undertaken match what the data is telling you. In many cases it is sufficient to draw conclusions from graphs that depict clear trends, unless a measure of statistical significance is being sought.

There are many statistical methods available to analyse data. Simple statistics are often the best and can be most easily interpreted by a range of people. Often the significance of data can be tested. There are many statistical software programs available to assist with data analysis, so that intimate knowledge of the maths behind the analyses is not required. However, it is important to understand the analyses you are doing and what information they provide about the data to ensure that you are interpreting the results correctly.

Table 6.3 (overleaf) summarises statistical analyses that could be useful in a wetland monitoring program (Laegdsgaard 2003).

Reporting

It is important to include in the design of the rehabilitation plan measures for reporting progress and outcomes, so that others can learn from the experience. This applies even if the project is unsuccessful.

Compile all data gathered and analysed as part of a monitoring program into regular progress reports. These should detail the results of the sampling and the interpretation of the results in relation to each monitoring event and any previous monitoring events. Progress reports would typically be produced each year, with a major report prepared after 3 to 5 years of data collection. By this time it should be possible to draw some conclusions about the recovery of the site with respect to natural variation and seasonality. The major report should include full analyses of the data and interpretation of the results. At this time it should then be possible to evaluate future data collection and any adjustments that may be required to sampling methods or frequency.

People interested in the results of your project may include:

- community and conservation groups
- the scientific community
- the local council
- local businesses
- regional, State and Commonwealth natural resource management agencies.

Table 6.3 Statistical analyses that could be applied in wetland monitoring

Parameter	Appropriate analyses relating to each monitoring event	Appropriate analyses relating to whole data set over time
Changes in any of the individual parameters among sites	Analysis of variance (ANOVA)	Repeated-measures ANOVA
Relationship between water quality parameters or sediment parameters to biotic factors	Correlations and regressions	Correlations and regressions
Differences in faunal or vegetation communities among sites	Numerical classifications Ordination Multivariate analysis of variance (MANOVA)	Numerical classifications Ordination Repeated-measures MANOVA

Consider which format is most appropriate for delivering the project results. Newsletters and brochures are easily digested and understood by the local community and school children, but detailed reports may be of more interest to local council and government agencies. Websites and CDs are increasingly popular and cost-effective methods of providing access to information for a wide range of people.

6.3 Adaptive management

Often when you are implementing a management plan and assessing the performance of outcomes, it becomes clear that certain actions did not achieve their objectives. To accomplish these objectives it may be necessary to review the actions being implemented and to change them somewhat. This process is known as adaptive management. Adaptive management can be achieved by assessing and reviewing the performance of a management plan at a site and its control locations and then altering the plan. It can also be achieved by reviewing a management plan based on experience gained at other sites.

A key part of adaptive management is the monitoring of performance indicators, including regular inspection of how specific wetland components and regulating works are operating or performing, so that any necessary maintenance action or changes to operating strategies can be made.

6.4 Monitoring and reporting as a contribution to research

With the current state of saltwater wetland knowledge, rehabilitation projects should be considered as experiments. Whether the project is ultimately successful in its aims or not, the knowledge gained through a well-thought-out monitoring program will help in improving future rehabilitation projects.

Examples can be seen at the restoration works undertaken by the Sydney Olympic Park Authority at Homebush Bay in Sydney (Barnes and Chapman 2001, Lindegarth *et al.* 1999, Lindegarth and Chapman 2001).

Example 1: Restoring tidal flushing to mangroves

Large areas of mangroves at Newington, on the southern shore of the Parramatta River, have been destroyed or seriously degraded. To increase the ecological health of the remaining mangrove wetlands, the Sydney Olympic Park Authority constructed a channel from the Parramatta River into the wetlands. The aim of the channel was to restore tidal flushing and natural drainage. Previous studies showed that the numbers and types of benthic invertebrates found in naturally flushed and drained mangrove forests in Sydney Harbour were very different from those in forests with reduced tidal flushing such as that at Newington.

To assess changes in the benthic fauna in response to the improved tidal flushing, replicate sites were sampled twice before and four times after the construction of the channel. Samples were also taken from two nearby reference sites. The sampling showed no evidence that the new tidal conditions had restored benthic fauna to what might be expected under more natural conditions. Possible reasons for this may be that:

- there may not have been enough time for change to occur
- the muddy floor of the mangroves (which varies from that at the reference sites) may not be suitable habitat
- the artificial channel may be preventing or restricting the arrival of **planktonic** larvae into the mangroves
- the new regime of tidal flushing may still be different from that at the reference sites and may not be suitable for animals to recolonise or survive in.

The moral of the story

The results illustrate the importance of testing the success or otherwise of management strategies with well-designed biological monitoring. This example highlights the fact that while a wetland may look to be rehabilitated (because tidal flushing is restored), its biological functioning may not have been restored. This may be because wetlands evolve slowly over time and more time is needed, or because some other limiting factor prevents full function from being restored. Without such monitoring it would be difficult to know whether the rehabilitation had truly been successful, and the value of spending large amounts of money on constructing future channels would be unknown. Continuing monitoring and research into reasons for the lack of success will allow the Sydney Olympic Park Authority to make more informed decisions regarding the conservation and maintenance of the Newington mangroves.

Example 2: Providing habitat for Japanese snipe

Another project at Homebush Bay aims to create new habitat for the the Japanese snipe (or Latham's snipe, *Gallinago hardwickii*), a wading bird. The project involves large-scale modification of freshwater levels to create areas along the edge of a marsh where the birds will be able to feed. Benthic fauna in the sediments fringing the marsh are thought to be a food source for the birds. For modifications to be successful it is therefore necessary that the areas drained during the experiment provide sufficient prey for the birds. Monitoring the abundance of animals is required in order to test whether modifications are successful.

Monitoring involved measurement of changes at two sites within the manipulated pond and at one site in a nearby control pond (where water level was not manipulated).

The results of the experiment were contrary to the initial predictions, that is, draining of the wetland area reduced the abundance and diversity of benthic fauna. At the conclusion of the sampling program, very few benthic animals were left that were suitable as food for Japanese snipe. The abundance and diversity of animals at reference sites, however, had increased or remained similar.

The moral of the story

Testing hypotheses about the effects of rehabilitation actions is important and should be planned before the initiation of large-scale projects. Pilot studies may need to be undertaken to assess whether success is likely before large amounts of time and money are invested. When biological monitoring is undertaken, appropriate spatial replication is required in order to take into account natural variability in animal abundances. Otherwise differences between control sites and the project site may be difficult to interpret. As with the mangrove example, monitoring must focus on function as well as structure. In this case, monitoring was able to clearly show that the predicted results did not occur. These results contribute to the current state of knowledge about wetland rehabilitation and will allow future projects to learn from the experience.

References for Parts 1 and 2

Chapter 1

Bell JD, Pollard DA. 1989. Ecology of fish assemblages and fisheries associated with seagrasses. In: Larkum AWD, McComb AJ, Shepherd SA, eds. *Biology of Seagrasses*, 565–597. Elsevier, Amsterdam.

Bennett J, Whitten S, Handley M, Moss W, Phillips B. 2001. *Wetland Management Assistance for Private Landholders*. Environment Australia, Canberra.

Bowen R, Stephens N, Donnelly P. 1995. SEPP 14 — wetland protection and the role of mitigation. *Wetlands (Australia)* 14: 6–12.

DLWC. 1998. *The Constructed Wetlands Manual*, vols 1 and 2. NSW Department of Land and Water Conservation, Sydney.

Environment Australia. 2001. *A Directory of Important Wetlands in Australia*, 3rd edn. Environment Australia, Canberra.

Merrin J, Chafer C. 2000. *Illawarra Wetlands Action Plan*. Illawarra Catchment Management Committee, Wollongong.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Wetland and Water Synthesis*. World Resources Institute, Washington DC.

Morrisey D. 1995. Saltmarshes. In: Underwood AJ, Chapman MG, eds. *Coastal and Marine Ecology of Temperate Australia*, 205–220. UNSW Press, Sydney.

NSW Fisheries. 1999. *Policy and Guidelines Aquatic Habitat Management and Fish Conservation* (Smith AK, Pollard DA, eds). NSW Fisheries, Port Stephens.

Ramsar Convention on Wetlands. 2002. *Principles and Guidelines for Wetland Restoration* (resolution VIII.16). http://www.ramsar.org/key_guide_restoration_e.htm. Accessed 9 July, 2007.

Smith AK, Holliday JE, Pollard DA. 1997. Management of seagrass habitats in NSW estuaries. *Wetlands (Australia)* 16(2): 48–55.

Stricker J. 1995. Reviving wetlands. *Wetlands (Australia)* 14: 20–25.

US EPA. 2000. *Principles for the Ecological Restoration of Aquatic Resources*. EPA841-F-00-003. Office of Water (4501F), United States Environmental Protection Agency, Washington DC.

Chapter 2

Bergkamp G, Orlando B. 1999. *Wetlands and Climate Change — Exploring collaboration between the Convention on Wetlands (Ramsar, Iran, 1971) and the UN Framework Convention on Climate Change*. IUCN Background Paper for Ramsar Convention on Wetlands. IUCN, Gland, Switzerland.

Kusler J, Burkett V. 1999. Climate change in wetland areas. Part I: Potential wetland impacts and interactions. *Acclimations* May–June 1999. Newsletter of the US National Assessment of the Potential Consequences of Climate Variability and Change.

Department of Planning 2007 *Protecting our Coast: The Comprehensive Coastal Assessment Toolkit*. State of NSW through the Department of Planning, Sydney.

Chapter 3

Carson L, Gelber K. 2001. *Ideas for Community Consultation. A Discussion on Principles and Procedures for Making Consultation Work.* Prepared for NSW Department of Urban Affairs and Planning, February 2001. DUAP, Sydney.

DLWC. 1998. *The Constructed Wetlands Manual*, vols 1 and 2. NSW Department of Land and Water Conservation, Sydney.

Wetland Care Australia. 2006. *Sustainable Wetlands on NSW Coastal Landscapes*. Report prepared for Northern Rivers and Hunter Central Rivers Catchment Management Authorities, Wetland Care Australia, Ballina.

Chapter 4

Dale P. 2005. Longterm impacts of runnelling on an intertidal saltmarsh. *Arbovirus Res in Aust* 9: 80–85.

Dale PER, Chandica AL, Evans M. 1996. Using image subtraction and classification to evaluate change in subtropical intertidal wetlands. *International Journal of Remote Sensing* 17: 703–719.

Dale MB, Dale PER, Li C, Biswas G. 2002. Assessing impacts of small perturbations using a model-based approach. *Ecological Modelling* 156: 185–199.

DLWC. 1998. *The Constructed Wetlands Manual*, vols 1 and 2. NSW Department of Land and Water Conservation, Sydney.

Johnston S, Kroon F, Slavich P, Cibilic A, Bruce A. 2003. *Restoring the Balance: Guidelines for Managing Floodgates and Drainage Systems on Coastal Floodplains.* NSW Agriculture, Wollongbar, NSW. Available at www.dpi.nsw.gov.au/reader/floodgate-guidelines.

Hart BT. 1982. *Australian Water Quality Criteria for Heavy Metals Water.* Technical Paper, Studies Centre, Chisholm Institute of Technology, Australian Water Resources Council. Australian Government Publishing Service, Canberra.

Hulsman K, Dale P, Kay B. 1989. The runnelling method of habitat modification: an environment focussed tool for saltmarsh management. *Journal of the American Mosquito Control Association* 5: 226–234.

Landcom. 2004. *Managing Urban Stormwater — Soils and Construction*, 4th edn. Landcom, Parramatta.

Naylor SD, Chapman GA, Atkinson G, Murphy CL, Tulau MJ, Flewin TC, Milford HB, Morand DT. 1998. *Guidelines for the Use of Acid Sulfate Soil Risk Maps*, 2nd edn. Department of Land and Water Conservation, Sydney.

Resource NSW. 2003. *NSW Waste Avoidance and Resource Recovery Strategy*. Resource NSW, Parramatta.

Russell RC. 1994. Mosquito-borne arboviruses in Australia: the current scene and implications of climate change for human health. *International Journal for Parasitology* 28: 955–969.

Smith P. 1991. *The Biology and Management of Waders (suborder Charadrii) in NSW*. NSW National Parks and Wildlife Service, Sydney.

Stone Y, Ahern CR, Blunden B. 1998. *Acid Sulfate Soils Manual*. ASSMAC, NSW Agriculture, Wollongbar, NSW.

Tulau MJ. 2008. *Acid Sulfate Soils Remediation Guidelines for Coastal Floodplains in New South Wales*. NSW Department of Environment and Climate Change, Sydney.

Turner PA, Streever WJ. 1997. The relationship between the density of *Aedes vigilax* (Diptera, Culicidae) eggshells and environmental factors on Kooragang Island, New South Wales, Australia. *Journal of the American Mosquito Control Association* 13(4): 361–367.

Webb CE, Russell RC. 2006. Mosquito management and legislation in NSW. In: *Wetland Legislations: Where and How to Apply Them*. Wetland Education and Training Program, 21–22 September 2006, Sydney Olympic Park.

Williams R, Watford FA. 1997. Identification of structures restricting tidal flow in New South Wales. *Wetlands Ecology and Management* 5: 87–97.

Chapter 5

Adam P. 1981. Australian saltmarshes. *Wetlands (Australia)* 1: 8–10.

Adam P, Hutchings P. 1987. The saltmarshes and mangroves of Jervis Bay. *Wetlands (Australia)* 6(2): 58–64.

Burrows DW. 2003. The role of insect leaf herbivory on the mangroves *Avicennia marina* and *Rhizophora stylosa*. PhD dissertation, School of Tropical Biology, James Cook University, Townsville, Queensland.

DLWC. 1998. *The Constructed Wetlands Manual*, vols 1 and 2. NSW Department of Land and Water Conservation, Sydney.

DPI (Victoria). 2003. *An Illustrated Checklist of Freshwater Fishes of Victoria*. Fisheries Note FN0019. Department of Primary Industries, Melbourne.

Hedge P, Kriwoken LK. 2000. Evidence for effects of *Spartina anglica* invasion on benthic macrofauna in Little Swanport estuary, Tasmania. *Austral Ecology* 25: 150–159.

Milford HB, Simons N. 2002. *The Salinity Soil Data Card. Supplement 1 to the 3rd edition of the Soil Data Entry Handbook*. NSW Department of Land and Water Conservation, Sydney.

Morgan LA, Buttermer WA. 1996. Predation by the non-native fish *Gambusia holbrooki* on small *Litoria aurea* and *L. dentata* tadpoles. *Australian Journal of Zoology* 30: 143–149.

NAWC. 2003. *Noxious weeds list for Australian States and Territories*. National Australian Weeds Committee, Canberra.

Paul S, Young R. 2006. Experimental control of exotic spiny rush, *Juncus acutus*, from Sydney Olympic Park: I. *Juncus* mortality and re-growth. *Wetlands (Australia)* 23(2): 1–12.

Simpson J. 1995. Wading birds of Anderson Inlet and the work of the Victorian Wader Study Group. In: Rash JE, Williamson JS, Taylor JS, eds. *Proceedings of the Australas Conference on Spartina control.* Victorian Government, Melbourne.

University of Sydney and Westmead Hospital, Department of Medical Entomology. 1998. *Mosquito Management for Wetlands – Saline*. http://medent.usyd.edu.au/fact/saltwet.htm. Accessed 9 July 2007.

Wood EJF. 1959. Some aspects of the ecology of Lake Macquarie NSW with regard to an alleged depletion of fish. *Australian Journal of Marine and Freshwater Research* 10: 322–340.

Chapter 6

ANZECC, ARMCANZ. 2000. *Australian Guidelines for Water Quality Monitoring and Reporting*. Australian and New Zealand Environment Conservation Council, Canberra.

Barnes PB, Chapman MG. 2001. *Changes to Benthic Fauna in the Newington Mangroves in Response to Restoration of Tidal Flushing.* Final Report to the Olympic Co-ordination Authority. University of Sydney, Centre for Ecological Impacts of Coastal Cities.

Boumans RMJ, Burdick DM, Dionne M. 2002. Modeling habitat change in saltmarshes after tidal restoration. *Restoration Ecology* 10(3): 543–555.

Broome SW, Seneca ED, Woodhouse WW Jr. 1988. Tidal saltmarsh restoration. *Aquatic Botany* 32: 1–22.

Chapman MG, Underwood AJ. 2000. The need for a practical scientific protocol to measure successful restoration. *Wetlands (Australia)* 19(1): 28–59.

Craft C, Reader J, Sacco JN, Broome SW. 1999. Twenty-five years of ecosystem development of constructed *Spartina alterniflora* (Loisel) marshes. *Ecological Applications* 9(4): 1405–1419.

Craft C, Sacco JN. 2003. Long-term succession of benthic infauna communities on constructed *Spartina alterniflora* marshes. *Marine Ecology Progress Series* 257: 45–58.

Eertman RHM, Kornman BA, Stikvoort E, Verbeek H. 2002. Restoration of the Sieperda tidal marsh in the Scheldt Estuary, The Netherlands. *Restoration Ecology* 10(3): 438–449.

Finlayson CM, Mitchell DS. 1999. Australian wetlands: the monitoring challenge. *Wetlands Ecology and Management* 7: 105–112.

Frenkel RE, Morlan JC. 1990. *Restoration of the Salmon River Saltmarshes: Retrospect and Prospect*. Final Report to the US EPA (Region 10), 143 pp. US EPA, Washington DC.

Grayson JE, Chapman MG, Underwood AJ. 1999. The assessment of restoration of habitat in urban wetlands. *Landscape and Urban Planning* 43: 227–236.

Havens KJ, Varnell LM, Bradshaw JG. 1995. An assessment of ecological conditions in a constructed tidal marsh and two natural reference tidal marshes in coastal Virginia. *Ecological Engineering* 4: 117–141.

Havens KJ, Varnell LM, Watts BD. 2002. Maturation of a constructed tidal marsh relative to two natural reference tidal marshes over 12 years. *Ecological Engineering* 18: 305–315.

Hellawell JM. 1991. Development of a rational for monitoring. In: Goldsmith FB, ed. *Monitoring for Conservation and Ecology*. Chapman and Hall, London.

Laegdsgaard P. 2002. Recovery of small denuded patches of the dominant NSW coastal saltmarsh species (*Sporobolus virginicus* and *Sarcocornia quinqueflora*) and implications for restoration using donor sites. *Ecological Management and Restoration* 3(3): 200–204.

Laegdsgaard P. 2003. *A Guide to Monitoring a Created Wetland at Kooragang Island*. NSW Department of Land and Water Conservation, Sydney.

Legg CL, Nagy L. 2006. Why most conservation monitoring is, but need not be, a waste of time. *Journal of Environmental Management* 78: 194–199.

Lindegarth M, Chapman MG. 2001. Testing hypotheses about management to enhance habitat for feeding birds in a freshwater wetland. *Journal of Environmental Management* 62: 375–388.

Lindegarth M, Barnes PB, Chapman MG. 1999. *Changes to benthic fauna in Wharf Marsh in response to water drainage to provide habitat for the Japanese Snipe* (Gallinago hardwickii). Final report to Olympic Co-ordination Authority. University of Sydney, Centre for Research on Ecological Impacts of Coastal Cities.

McGloin E, Botting S. 2005. *Establishment of a Monitoring and Evaluation Framework for the Hunter–Central Rivers Catchment Management Authority*. NSW Department of Natural Resources, Hunter Region, Newcastle.

Morgan PA, Short FT. 2002. Using functional trajectories to track constructed saltmarsh development in the Great Bay estuary, Maine/New Hampshire, USA. *Restoration Ecology* 10: 461–473.

Rutherford ID, Jerie K, Marsh N. 2000. *A Rehabilitation Manual for Australian Streams*, vol. 1. CRC for Catchment Hydrology, Monash University, Melbourne.

Seneca EDSW, Broome WW, Woodhouse LM, Cammen, Lyon JT. 1976. Establishing *Spartina alterniflora* marsh in North Carolina. *Environmental Conservation* 3: 185–188.

Simenstad CA, Thom RM. 1996. Functional equivalency trajectories of the restored Gog-Le-Hi-Te estuarine wetland. *Ecology Applications* 6: 38–56.

Thom RM, Ziegler R, Borde AM. 2002. Floristic development patterns in a restored Elk River estuarine marsh, Grays Harbour, Washington. *Restoration Ecology* 10: 487–496.

Tucker P. 2004. *Your Wetland: Monitoring Manual — Data Collection*. River Murray Catchment Water Management Board, Berri, and Australian Landscape Trust, Renmark, SA.

Ward T, Butler E, Hill B. 1998. *Environmental Indicators for National State of the Environment reporting — Estuaries and the Sea*. Australia: State of the Environment (Environmental Indicator Reports). Department of the Environment, Canberra.

Warren RS, Fell PE, Rozsa R, Brawley AH, Orsted AC, Olsen ET, Swamy V, Niering WA. 2002. Saltmarsh restoration in Connecticut: 20 Years of science and management. *Restoration Ecology* 10(3): 497–513.

Williams PB, Orr MK. 2002. Physical evolution of restored breached levee saltmarshes in the San Francisco Bay estuary. *Restoration Ecology* 10(3): 527–542.

Glossary

advective: The horizontal movement of water, as in an ocean current.

aeolian: A geomorphic process whereby soil-forming material is transported and deposited by wind.

aerobic: A state where free oxygen (O_2) is available.

anaerobic: A state where no oxygen is available.

AHD: Australian Height Datum; the single reference point to relate all vertical measurements throughout Australia. AHD is based on the Mean Sea Level.

anoxic: A metabolic state where there is no free oxygen, but molecularly bound oxygen is still available.

ANZECC and ARMCANZ: Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand.

ASS: acid sulfate soil.

***Australian Soil Classification* (Isbell 1996):** This classification scheme operates using a hierarchical system and is based on Australian soils data that is significant with regard to land management. The general form of the nomenclature is: Subgroup, Great Group, Suborder, Order; family (for example, Bleached, Eutrophic, Red Chromosol; thick, sandy).

background level: Level of substance commonly found in the local environment.

bathymetry: the measurement of water depth at various places in a body of water.

baseline: A datum used as the basis for calculation or comparison.

benthic: Bottom-dwelling, that is, on a wetland substrate.

bioaccumulation: Process in which substances are accumulated by organisms, for example through consumption of food containing the substance.

biodegradation: Decomposition of biological substances into more elementary compounds by the action of microorganisms.

biofilm: Organic matrix supported by substrates which contains an often diverse and abundant microfauna and microflora.

biogeochemical: The chemical, physical, geological and biological processes and reactions that govern the composition of the natural environment.

biological oxygen demand: The demand for oxygen, measured as the concentration of biodegradable organic matter present in a sample.

biota: The sum total of the living organisms of any designated area.

CAMBA: China–Australia Migratory Birds Agreement (1986).

cation exchange capacity (CEC): A general indicator of soil storage capacity for available, positively charged plant nutrients such as Ca, Mg, K and NH_4. Generally determined by the amount and type of clay and the amount of organic matter.

cultural value: Value determined by sites, places, artefacts or memories that are meaningful to contemporary society or parts of society; for example, sites showing material evidence of past Aboriginal occupation.

DECC: NSW Department of Environment and Climate Change.

dendritic: With the branching shape characteristic of a tree.

design life: The period of time during which an item is expected by its designers to work within its specified parameters.

design storm: A storm with a given amount of rainfall and distribution over a particular drainage area.

detritus: All non-living organic material, including animal waste products and the remains of animals, plants and microorganisms, together with the associated microbial community (bacteria and fungi).

dispersive: Tending to separate and move apart.

dissolved oxygen: The gaseous oxygen (O_2) that is dissolved in water and available for organisms to use.

DPI: NSW Department of Primary Industries.

DWE: NSW Department of Water and Energy.

EIS: Environmental Impact Statement.

emergent: Form of an aquatic plant that is rooted in the sediment and extends its leaves into the air.

epiphytic: Form of a plant that grows on another plant upon which it depends for mechanical support but not for nutrients.

euryhaline: Able to live within of a wide range of salinity.

eutrophication: Enrichment of a water body by nutrients which can lead to excessive algal growth or other water quality problems.

evapotranspiration: The process of transferring moisture from the earth to the atmosphere by the evaporation of water and transpiration from plants.

fluvial: Of, relating to, or inhabiting a river or stream or produced by the action of a river or stream.

geographic information system (GIS): A computer system used for capturing, storing, checking, integrating, manipulating, analysing and displaying data related to positions on the Earth's surface.

geomorphology: The study of landforms and the processes that shape them.

global Positioning System (GPS): A navigation system for determining position on the Earth's surface by comparing radio signals from several satellites.

great Soil Group: A soil classification system developed by Stace *et al.* (1968). It is based on the description of soil properties such as colour, texture, structure, drainage, lime, iron, organic matter and salt accumulation, as well as on theories of soil formation.

hydrogeologist: A geologist who deals with the occurrence, distribution and effects of groundwater.

hydrological cycle: The continuous circulation of water within the Earth's hydrosphere driven by solar radiation. This includes the atmosphere, land, surface water and groundwater. As water moves through the cycle, it changes state between liquid, solid and gas phases.

hydrology: Study of the movement, distribution and quality of water throughout the earth.

intertidal: Those areas of land covered by water at high tide but exposed at low tide. This is the interface between the aquatic and terrestrial environments.

introduced species: Plant or animal species that has been introduced by humans, deliberately or accidentally, to a place where the organism is not native to.

invertebrate: Animal without a backbone.

JAMBA: Japan–Australia Migratory Birds Agreement (1974).

jarosite: A hydrous sulfate of potassium and iron. Jarosite mottles (yellow streaks and mottles around old root channels) are a positive indicator of acid sulfate soils. Jarosite can form as an intermediate mineral during the chemical reaction, which results in sulfuric acid.

king tide: Highest of the spring tides.

leachate: A liquid produced when water percolates or drains through material. It may contain dissolved or particulate material.

microphytobenthos: Community of bottom-dwelling microscopic diatoms and cyanobacteria.

monospecific: Relating to or made up of the one species.

neap tide: Tide with the smallest range in a monthly cycle.

nutrient: Substance that provides nourishment to biota.

oxidation: The combination of oxygen with a substance.

pathogen: Organism capable of causing disease in another organism.

pedologic: Relating to soil formation, soil morphology and soil classification.

permeability: Measure of the degree to which water or air can enter a soil.

photosynthesis: The conversion of carbon dioxide and water to carbohydrates in the presence of chlorophyll by light energy, undertaken by most plants.

piezometer: A small-diameter water well used to the measure the top of groundwater in aquifers.

plankton: Plants (phytoplankton) and animals (zooplankton), usually microscopic, suspended in water systems.

propagule: Seed, bulb or other organ by which a plant propagates itself.

riparian: Pertaining to rivers and streams.

ripening: Whereby a freshly deposited mud is transformed to a dryland soil. Physical ripening essentially involves an irreversible loss of water (drying out).

risk: A statistical concept defined as the expected frequency or probability of undesirable effects resulting from a specified exposure to known or potential hazards.

RoKAMBA: Republic of Korea–Australia Migratory Birds Agreement (2006).

saturated hydraulic conductivity: A measure of how quickly water can move through soil when it is saturated.

sedimentation: The process in which settleable solids are removed from the water column by gravity.

semi-diurnal: Occurring approximately once every 12 h, as the tides.

sessile: Of organisms that are not able to move about. They are usually permanently attached to a solid substrate of some kind, such as a rock.

shrink–swell: A characteristic of soils that tends to make the clays within them expand on contact with water and shrink (and crack) when they dry.

sodicity: A measure of exchangeable sodium in the soil. High levels adversely affect soil stability, plant growth and land use.

spring tides: Tides with the largest range in a monthly cycle.

subtidal: Below the level of low tide.

submergent: An aquatic plant that is rooted in the sediment and grows entirely under the water.

tidal plane: Height of standard tide above a datum, usually Indian Spring Low Water.

total actual acidity: A simple measure of acidity within the soil. Includes free acid and acidity absorbed on the clay and organic matter, and in acid salts.

turbidity: Measure of the clarity of water on a colorimetric scale, generally relating to suspended material in water.

water table: The surface of a body of groundwater at which the pressure is atmospheric.


(Chris Chafer)

Part 3
Characteristics and processes

7 Surface water

7.1 Introduction

Saltwater wetlands are usually semi-enclosed by land but have open, partly obstructed or sporadic access to the open ocean, being inundated by sea water either regularly or sporadically. Rainfall and flows from rivers and streams, including floods, may dilute these saline waters. Thus, biota may be exposed to a wide range of salinities within a given wetland environment according to the prevailing climatic and weather conditions.

The depth, duration and seasonality of flooding of saltwater wetlands are predominantly affected by both short-term lunar and long-term seasonal cycles in the height of the tide. In some areas, meteorological influences may also be important, but these effects are more difficult to predict.

Differences in water salinity and temperature can induce stratification in a wetland system. In addition, evaporation can induce hypersaline conditions, exposing biota to saline levels greater than those experienced in the open ocean.

Changing the tidal area of a wetland by reclamation, dredging, or opening and closing the entrance channels can profoundly change the flushing characteristics and salinity regime of a wetland system. Climate change may also lead to substantial changes in wetland salinity regime along the entire NSW coast. Climate change is likely to result in further sea level rise, increased sea temperatures, changes in hydrology and changes in the frequency and intensity of extreme events, such as storms, droughts, and floods.

Although the hydrology of a wetland is known to significantly influence chemical and physical aspects of the wetland, and thereby also the ecosystem, this is not a simple cause-and-effect relationship, as the flora and fauna can also significantly affect the hydrology of the wetland.

Plant matter and **detritus** that build up in wetlands can affect the water balance by preventing direct evaporation, and by increasing the hydraulic resistance to surface water flows, thereby reducing velocities, and in turn enhancing sedimentation and impeding erosion. Plant matter and detritus perform a filtering role, trapping sediments and thereby also nutrients (particularly phosphorus) associated with these sediments. They also increase the **biological oxygen demand** within the water column and wetland sediments.

High tide in a mangrove forest (Koorangang Wetland Rehabilitation Project)

7.2 Tidal processes

Tidal motion

The movement of water in and out of saltwater wetlands is predominantly influenced by the tides. Freshwater flows are generally small except in times of flood, but water quality may be a significant consideration. Ocean tides fluctuate in regular and predictable cycles primarily as a response to the gravitational effects of the Moon and Sun upon the Earth. Other forcing functions which cannot be predicted also affect ocean levels, such as the passage of high- and low-atmospheric-pressure systems, storm surges, wave set-up and tsunami.

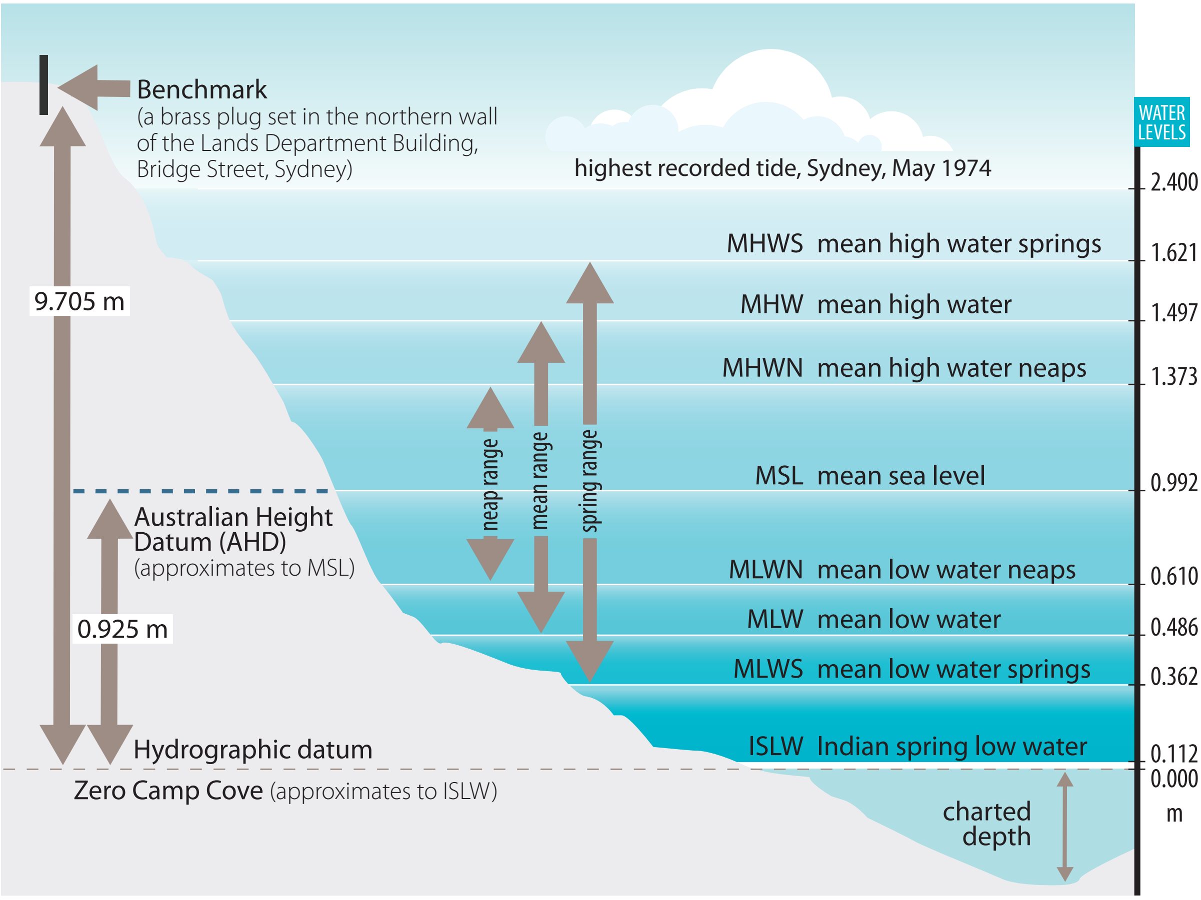
The Moon's orbit around the Earth produces the largest effect, resulting in a regular 29-day cycle. Tidal ranges increase to a maximum (**spring tides**) over 14.5 days and then decrease to a minimum over the next 14.5 days (neap tides). In theory, spring tides occur at both full and new Moon (when the Sun, Moon and Earth are aligned), and neap tides occur with the first and last quarters of the Moon (when the Sun and Moon are at right angles to the Earth). However, in practice, spring tides occur several days after full and new Moon as a result of inertial effects. The relative declination of the Sun and Moon as the Earth orbits the Sun results in the solstice or **king tides** in June and December each year, when the Sun is directly over the Tropics of Cancer and Capricorn respectively.

Tides along the NSW coastline are **semi-diurnal** in nature; that is, high water and low water occur about twice daily (the actual period of a tidal cycle is approximately 12.5 h). Although tides are sinusoidal in shape, there is generally a pronounced diurnal inequality in that the magnitudes of successive tidal ranges (and the associated high and low tides) differ markedly.

Tidal levels

Variations in ocean tidal levels are usually expressed as a series of tidal planes relative to a convenient datum below which the tide seldom falls. Figure 7.1, from *NSW Tide Charts* (Department of Commerce 2007), shows the commonly adopted tidal planes and their levels at Middle Head in Sydney Harbour, where the zero datum is at Camp Cove.

Figure 7.1 Tidal reference points, Sydney (not to scale)



Source: Manly Hydraulics Laboratory. Note: Levels are average over one year, starting 1 July 2001

The ocean tidal range varies only slightly along the NSW coast, with a spring tidal range constant at about 1.3 m between Sydney and Tweed Heads, reducing to about 1.1 m at Eden. Consequently, the predictions given in *NSW Tide Charts* can be used as an indication of tidal conditions along the open NSW coast from Tweed Heads to Eden.

If required, tidal predictions for specific sites along the NSW coast can be produced for a fee by organisations such as Manly Hydraulics Laboratory.

Tidal limits and penetration

Saltwater wetlands are generally located within an estuary. Although tidal stage along the NSW coastline does not vary by more than about 10 min, tidal stage within an estuary can lag behind that on the open coast by up to several hours depending on the characteristics of the estuary and the distance upstream from the mouth. *NSW Tide Charts* shows average tidal lags within estuaries along the NSW coast.

Detailed descriptions of typical physical characteristics and hydraulic behaviour in estuaries along the NSW coast are presented in the *NSW Estuary Management Manual* (NSW Government 1992).

In riverine estuaries the interaction between the geometry of an estuary and the tidal wave propagating in it leads to variations in the range of the tide and the strength of tidal currents. Both amplification and attenuation of tides can occur. Amplification is related to the shape of the estuary including channel width and depth with distance. Attenuation occurs due to flow friction effects which depend on bed and bank composition and bed geomorphology, and energy dissipation due to channel cross section shape and channel planform.

Tidal limits for estuaries in NSW are available from DECC.

Tidal inundation

Wetlands can be defined as those areas that are transitory between terrestrial and aquatic or marine systems. However, important distinctions exist: wetlands may be permanently or ephemerally flooded, or characterised by free surface or subsurface flow. Free surface tidal flow regimes in saltwater wetlands are outlined in Table 7.1 (overleaf). Characteristics of subsurface or groundwater flow are discussed in Chapter 8.

Flow channels through a mangrove forest (Adam Gosling, WetlandCare Australia)

Table 7.1 Free surface tidal flow regimes in saltwater wetlands

Regime		Description
Channel flow		One-dimensional flow in which water is constrained to flow in a set direction by channel banks. Width and depth of flow are of comparable size
Overbank flow	well drained	Two-dimensional flow in which water flows across a broad expanse and is not constrained to move in one direction only. Width far exceeds depth of flow. Under well drained conditions, the overbank area becomes entirely wet on the rising tide and becomes completely dry as the tide falls
	poorly drained	As above, except that the area does not have time to drain completely as the tide recedes, leaving wet and dry patches. Drainage is restricted by the hydraulic resistance of the overbank area
	poorly flushed or drained	As above, except that the overbank area does not wet completely under the rising tide and does not dry completely as the tide falls
	dry	These areas usually remain completely dry. However, when inundated by rain or extreme tidal events, overbank flow will occur
Cut-off pools		Large pools are present that are inundated as the tide rises and remain when the tide recedes. Drainage of the pools is restricted by the topography of the site

Estimation of tidal range and tidal prism

The tidal prism is the volume of water that flows into (on a flood tide) and out of (on an ebb tide) the estuary during a tide. The volume depends on the tidal range during the day of measurement. Dialogue Box 7.1 (overleaf) provides a simple means by which the tidal range and tidal prism at a site may be assessed. However, for the purposes of modelling of existing and future conditions in a wetland, a specialised tidal gauging exercise as outlined in Appendix 1 is needed.

7.3 Other processes a ecting water levels

Other processes which may influence surface water hydraulics in saltwater wetlands include a rise in sea level, air–water interface processes, flooding and extreme events, and the effects of opening and closing of ocean entrances.

Climate change and sea level rise

Ocean levels are rising along most coastlines around the world as a result of climate change. During the twentieth century global sea level rise was estimated at a rate of about 1.7 mm per year (Church and White 2006). The rate of rise along the NSW coastline for that period is shown in Fugure 7.2. Recent data shows that global sea level rise is accelerating, with the current global average sea level rise estimated to be approximately 3 mm per year (Beckley *et al.* 2007).

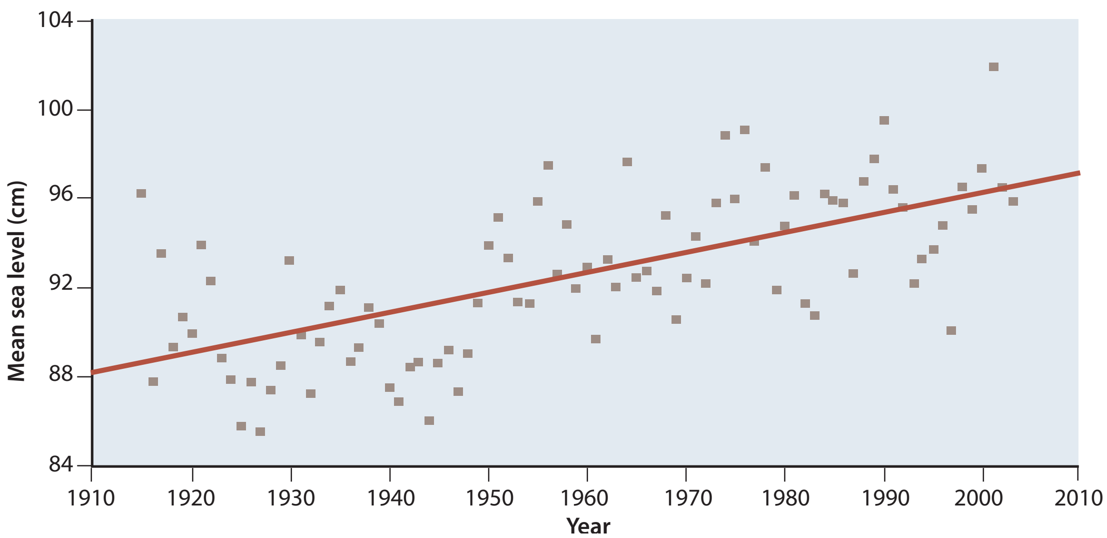
Tidal wetland environments have an ecological zonation that corresponds with tidal levels, in particular with mean high water. A rise in sea level can affect tidal wetlands by extending the limits of tidal penetration and hence also inundation. This may result in a change in flow regimes within the wetland as well as larger-scale changes to the surrounding area.

There is scope for better understanding of climate change impacts on local coastal systems. As predictions are further refined, they should be incorporated into wetland rehabilitation plans (Chapter 1).

An increase in water levels within the wetland will also affect the distribution of flora, but this is unlikely to be a straightforward shift in vegetation communities to higher elevations. Rogers *et al.* (2006) measured vegetation change and surface elevation dynamics in a number of saltwater wetlands in south-eastern Australia. In addition to sea level rise, they concluded that it is also important to account for processes that influence marsh elevations such as subsidence, autocompaction, and groundwater and plant processes.

If sea level rise exceeds the rate of vertical sediment accretion in saltwater wetlands, adaptation strategies could include protecting wetland integrity to improve resilience through prevention of fragmentation or buffer zones that allow for landward vertical migration.

Figure 7.2 Sea level rise at Fort Denison, 1915–2003



Dialogue Box 7.1 Simple method to estimate tidal range and tidal attenuation

The equipment necessary to estimate the tidal range in a wetland is straightforward to obtain and can usually be installed relatively simply.

The aim is to determine the minimum and maximum tidal levels during a tidal cycle at the periphery of the wetland and at several locations within the wetland. Using suitable hand tools, install sections of pipe or solid rod securely into the bed of the wetland. Before installation, clearly mark a graduated scale along the pipe or rod, or attach a tape measure with waterproof tape. This is now your tide pole.

When installing the tide pole ensure that it is close to vertical – you can use a carpenter's level. It is important that the bottom of the tide pole be submerged at low tide, hence it is best to install it an hour or two before low tide, remembering that the tide has yet to reach its lowest level.

Observe and record the highest and lowest water levels at each of the tide poles. Use *NSW Tide Charts* to estimate the time of low tide and the tidal lag at your site, but keep in mind that the microtopography of the wetland may cause further lags. The tidal range for that particular tide is simply the difference between the highest and lowest levels at each of the poles.

In the absence of any anomalies, you can estimate the approximate magnitude of the spring tidal range at each of the tide poles in the wetland by:

$$\text{Tidal Range (Wetland) Springs} \quad \frac{\text{Tidal Range (Wetland) Measured}}{\text{Tidal Range (Reference) Measured}} \quad \text{X} \quad \text{Tidal Range (Reference) Springs}$$

The analysis must be carried out for the same tide at the wetland as at the reference site. Estimate the neap tidal range similarly. In the absence of any tidal anomalies, the tidal range should be close to that measured at a nearby reference site where long term tidal analysis is available. If using Sydney as a reference site, the *NSW Tide Charts* can be referred to. However, to allow for any anomalies which may have occurred on the day of measurement, use the measured tidal range for your reference site, which may be obtained from Manly Hydraulics Laboratory.

The magnitude of the tidal prism can be estimated as the product of the tidal range for your wetland and the average area of the wetland inundated by the tide.

Mixing and air–water interface processes

When the air above a water body moves, momentum is transferred across the air–water interface and motion is induced in the water body. This motion results in shear, which in turn leads to turbulence, causing mixing in the water body.

Wind blowing across the surface of a body of water will induce surface currents that in the shallow nearshore water (less than 10 m in depth) typically associated with wetlands tend to be aligned with the wind direction. Surface currents are accompanied by counterbalancing currents at the bottom of the water column and large-scale lateral circulations. Wind-generated surface currents have speeds of approximately 2–3% of the wind speed and can be a major mechanism for the transport and distribution of floating pollutants such as oil and grease.

Air movement above a water body will also cause the generation and propagation of surface waves. After waves traverse the water surface, possibly for a long distance, they eventually reach shallow water or may encounter an obstacle in the flow, and waves will break. This wave breaking is a highly turbulent process which may induce mixing in the water column at a location where no wind is immediately present.

In locations where tidal currents are weak, wind-driven currents can be one of the main agents leading to effective water movement and mixing within the main water body.

Effects of vegetation on mixing due to wind shear and wave breaking

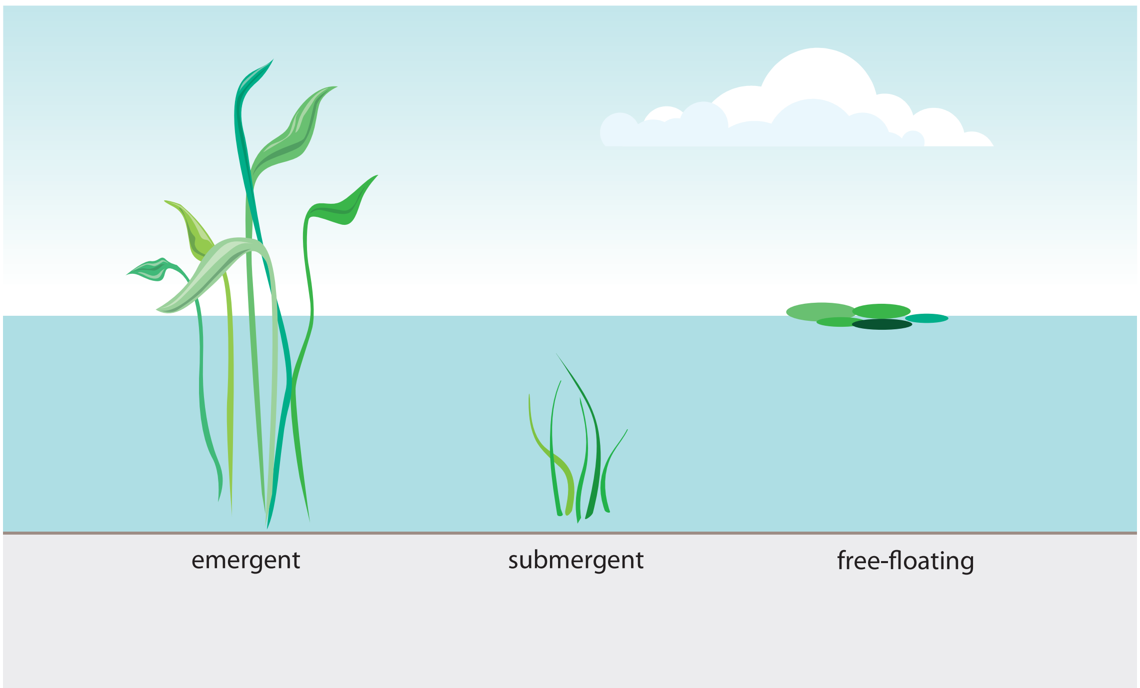
Before considering the effects of vegetation on wetland hydrodynamics, it is useful to classify the vegetation forms within a saltwater wetland. Further details of flora in saltwater wetlands are given in Chapter 11.

Aquatic plants in wetlands may be classified on the basis of whether or not they are rooted in the soil, and on the location of their leaves relative to the water surface:

- **Emergent** plants are rooted in the bed of the wetland and have leaves that extend upward through the water and into the atmosphere; for example, reeds and sedges.
- **Submergent** plants are rooted in the bed of the wetland and have leaves that remain within the water; for example, seagrass.
- Free-floating plants are not attached in any way to the bed of the wetland. In saltwater wetlands, most plants in this category are macroalgae.

Typical features of plants in each of these categories are shown schematically in Figure 7.3.

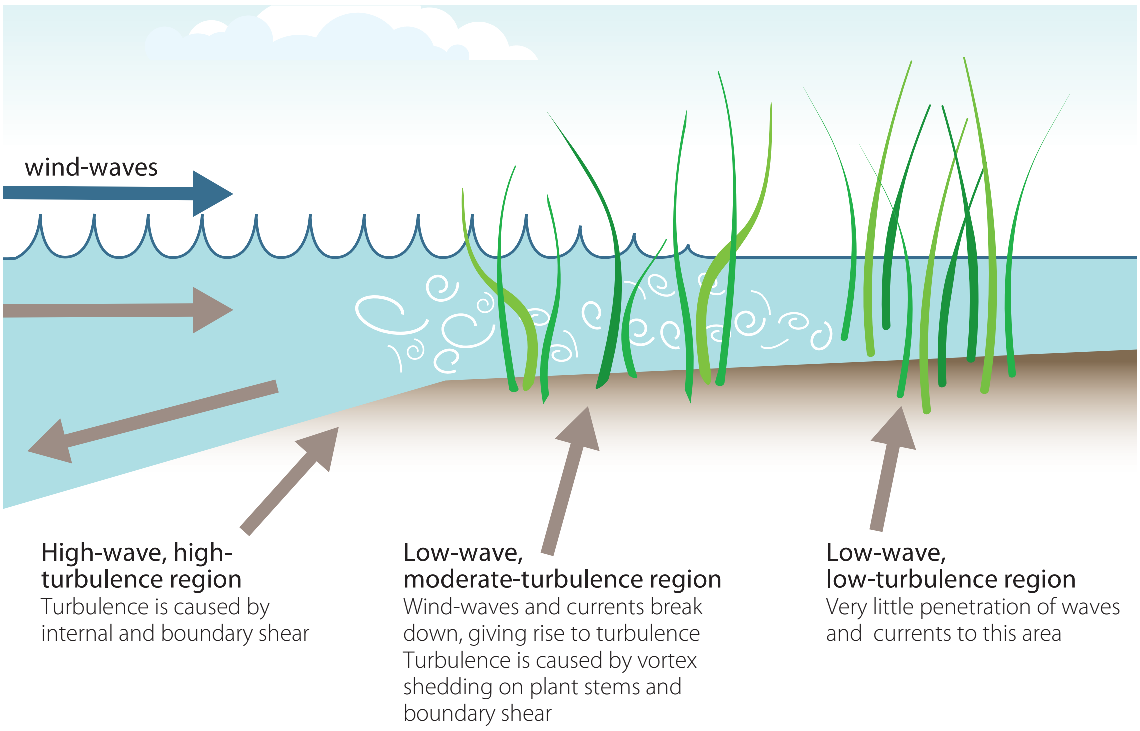
Figure 7.3 Classification of aquatic vegetation forms



The different forms of plants in wetlands each have different effects on mixing in the water column:

- Emergent species reduce the turbulence generated at the water surface, owing to the lower air speeds in the plant canopy. The stems within the water column should play a similar role to that of submergent plants. Figure 7.4 shows mechanisms for the generation of turbulence in wetlands, particularly in fringing reed and sedge communities, resulting from wind-waves and wind-driven currents.
- Submergent species should not affect the generation of turbulence at the water surface. Within the water column we find increased turbulence at their top and reduced turbulence within them compared with open water. More vegetation enhances these effects.
- Free-floating species should transmit shear into the water column, causing movement in the water column and hence turbulence. However, any vegetation at the water surface, even free floating, should reduce the generation of turbulence at the surface. Thus, increasing vegetation cover at the water surface would reduce mixing.

Figure 7.4 Mechanisms for the generation of turbulence in wetlands



Flooding and extreme events

Movement of water into and out of an open estuary is predominantly influenced by tidal motion, and the effects of freshwater inflows are generally small. However, in times of significant rainfall in the estuary catchment, freshwater inflows may dominate the tidal motions, especially in the upper reaches of an estuary. Freshwater inflows impart a net seaward movement of water, flushing pollutants from the estuary. The net seaward movement can result in a significant, albeit temporary, reduction in salinity in the estuary.

The reverse can be true for coastal lakes with only intermittently open entrances, fresh water events tend to be dominant with tides playing a much smaller role.

Opening and closing entrances

A greater effect may be evident in lakes or lagoons which are either relatively large or for the most part closed to the ocean. As a result of evaporation, water in these bodies may become hypersaline over a period of time. For closed lakes, if a fresh inflow is sufficient to breach the entrance, then not only can the lake water change from hypersaline to essentially fresh, but if the entrance quickly re-closes, the lake may become brackish for an extended period. So flora in a wetland within such systems would need to be able to tolerate a range of salinities for extended periods. Within large lakes, such as Lake Illawarra, the influence of evaporation even when the entrance is open can be significant.

The entrance of Meroo Lake is intermittently open to the sea (DECC)

7.4 Buoyancy-driven processes

General

The density of sea water is greater than that of fresh water and varies with both salinity and temperature. Sea water on average has a total salt concentration of about 35 kg/m^3, or 35 parts per thousand (ppt). At a temperature of 20°C, sea water has a density of about 1025 kg/m^3 whereas fresh water has a density of 1000 kg/m^3.

At a given salinity, differences in temperature will also result in density differences within the water body. However, the effect of temperature changes is generally small, resulting in a density difference of only about 0.1% for a 5°C change in temperature from 20°C.

Estuary classification based on salinity structure

In estuaries, circulation of water and mixing processes are driven by the density differences and interaction between fresh and saline waters. Although the density difference between fresh water and sea water is only about 2.5%, it is sufficient to create horizontal pressure gradients which can significantly affect estuarine circulation and mixing.

Estuaries can be classified according to their salinity structure (Figure 7.5).

Well-mixed estuary

In estuaries where the tidal range is large in comparison with the water depth, turbulence produced by bed friction will enhance mixing within the layers. Ultimately this may result in complete mixing between the layers, making the estuary vertically homogeneous, or well mixed.

Partially mixed estuary

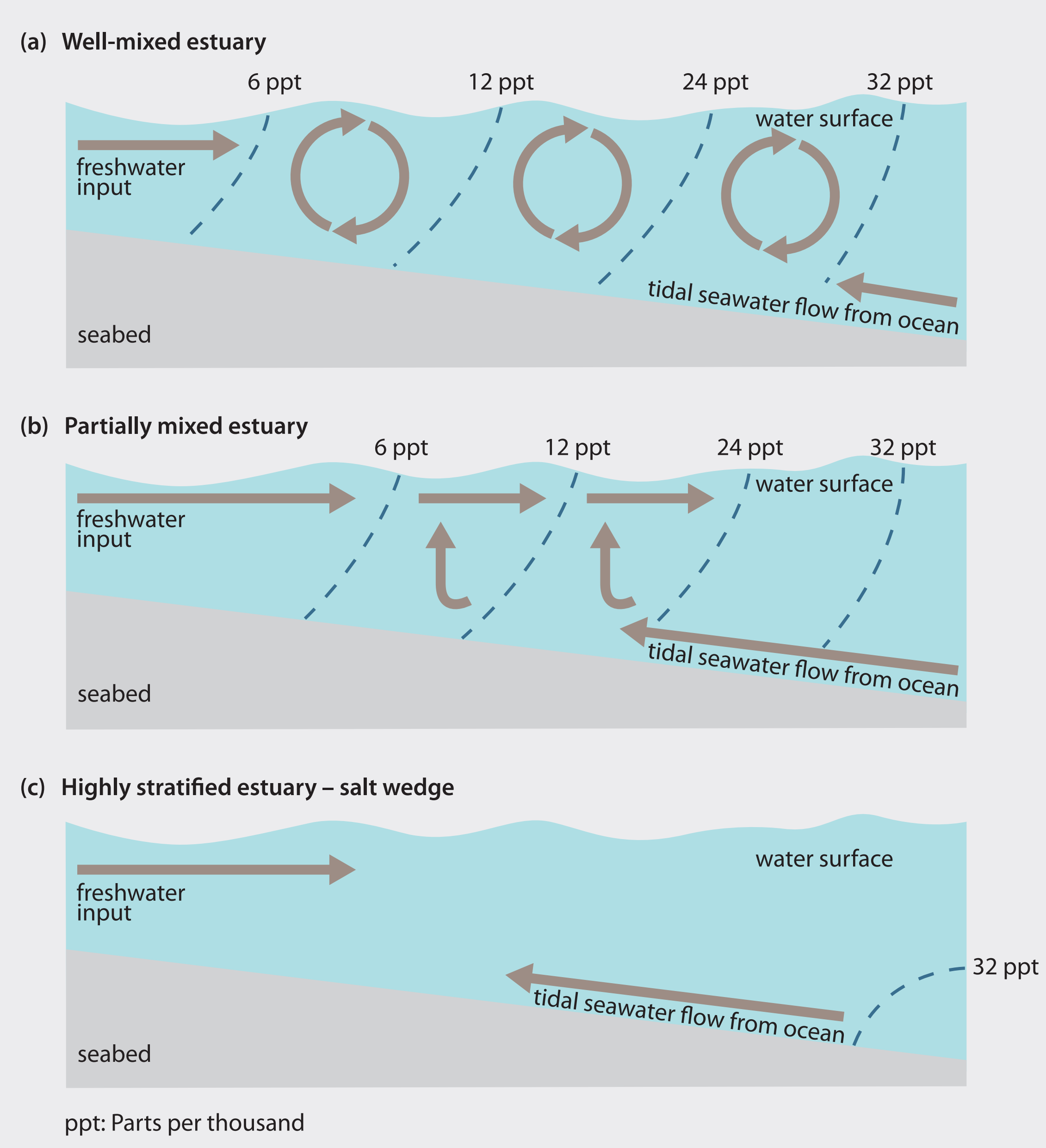
Ocean tides cause the volume of water within the estuary to oscillate to and fro. The energy in this flow will produce turbulent eddies, which will mix the fresh and salt water. Consequently the salinity of the surface layer will increase, while that of the bottom layer will decrease. In time this produces a partially mixed estuary with no distinct layers and the salinity varying continuously throughout its depth. The salinity may vary by as little as 1 ppt or as much as 10 ppt.

Highly stratified estuary – salt wedge

Viscosity and friction cause an interfacial stress between fresh water and sea water. This stress forces the salt water downstream, and its shape changes until the horizontal pressure gradient resulting from the difference in densities of the two fluids balances the interfacial stress. The freshwater outflow will also entrain salt water and hence become more brackish towards the mouth of the estuary.

Further details are given in the *Estuary Management Manual* (NSW Government 1992).

Figure 7.5 Estuary salinity structures



Source: Estuary Management Manual, NSW Government 1992

Buoyancy-driven convection

The density of sea water depends on both its salinity and its temperature, but in estuaries the salinity range is generally large and the temperature range is generally small. Therefore, stratification and buoyancy-driven flows resulting from differential heating take primary importance only in lakes or lagoons which are closed to the ocean for extended periods and hence do not experience the daily flux of tides, which tends to break down stratification.

However, over time the structure within these lakes or lagoons can become well mixed. Evaporation will make the surface layer more saline, and hence more dense than the underlying water. This causes the water at the surface to become unstable, as it develops a negative buoyancy. Packets of denser water then form eddies as they fall through the water column until neutral buoyancy is reached. As the eddies fall through the water, they entrain water and leave behind a wake consisting of the entrained water and some of the surface water. This produces mixing within the water column.

Conversely, heating of the surface layer, especially in summer, can make it less dense than the underlying (cooler) layer, and a stable stratification which inhibits mixing can develop. If this persists for extended periods, then the bed and lower layers in the water column can become starved of oxygen, and **anaerobic** conditions can develop.

Buoyancy-driven convection at the scale of the wetland

Buoyancy-driven processes can also occur on a smaller scale within the wetland itself. During periods of high freshwater inflows, stratified conditions may form either within or adjacent to the wetland, due to the varying densities of saline water and fresh water.

Differential heating and cooling occurs commonly in natural water bodies; for example, between the main body of a lake and its tributaries. By day the tributary and the lake are subject to the same radiation from the Sun. However, the tributary is shallower than the main body of the lake; therefore the tributary undergoes a larger change in temperature, and a temperature difference arises between the waters in these two areas.

Because the water in the tributary is warmer than that in the main body of the lake, it has a positive buoyancy and therefore forms a surface plume, moving out onto the main body of the lake above the cooler, denser water. Simultaneously, the cooler lake water moves as a plume along the bed into the tributary under the warmer, less dense water in the tributary. This process may be reversed in direction at night, as the tributary experiences the same surface cooling flux as the lake, but its smaller depth causes a much faster temperature decrease.

Effects of vegetation on buoyancy-driven convection

Shading in vegetated areas of a wetland will significantly reduce the amount of radiation incident on the water surface. This creates a temperature differential between vegetated and open-water areas, resulting in a density-driven exchange between the two areas.

7.5 Topography

General

Environmental processes within saltwater wetland systems are dominated by the dynamic nature of tides and tidal processes. Consequently, the elevation and slope characteristics of the wetland topography relative to tidal range and period are important factors in determining the chemical and biological characteristics of different regions within a saltwater wetland.

Reconnaissance survey

To assess the effects of tidal processes on the topography of a wetland it is necessary to know the existing topographic and tidal characteristics. Before any modelling (see Section 7.6) to assess the effects of changes to the wetland on the wetland hydrodynamics can be undertaken, site investigations need to be undertaken to determine the existing topography and **bathymetry** of the wetland and the tidal characteristics at the site. Further details of survey requirements are given in Chapter 6.

Tidal ushing

Tidal flushing is an important feature of saltwater wetlands. Constricted tidal flushing can cause significant problems in saltwater wetlands, including:

- overabundance of mosquitoes due to large amounts of stagnant water and the inability of mosquito predators to reach the mosquito habitat
- public health problems arising from mosquito overabundance (see sections 4.8 and 5.5.6)
- water quality problems
- mangrove dieback
- loss of aesthetic appeal to visitors due to odours, coloured water and high numbers of mosquitoes.

In mangrove wetlands and saltmarshes, dendritic systems of channels usually form to drain the flat overbank areas. Local channel characteristics within the dendritic system are determined by tidally induced scour velocities. Channel size reduces with distance from the mouth of the system and reflects the conveyed tidal prism.

7.6 Modelling of surface water

Modelling appropriately

A model is a simplified representation of an element of the real world. Models are used to allow decision making to be undertaken by representing the most significant aspects of the problem being considered and allowing management scenarios to be assessed. Models are therefore useful tools for representing the behaviour of wetlands, both now and after rehabilitation. The type of modelling should be assessed by determining:

- the suitability of the method to provide the necessary information required; for example, peak flows to determine scour velocities versus average tidal exchange for assessing flushing characteristics and water quality, if velocities are required then at least a two-dimensional model will be required
- the time and resources available for the analysis
- the availability of data both to set up the model and to calibrate and verify its operation.

The model must reliably reproduce the relevant aspects of the physical processes, be soundly based on relevant theory, and be calibrated using data that has been derived from the system being modelled. Moreover, the calibrated model should be verified by testing using different sets of appropriate data.

The increasing availability of user-friendly software allows non-technical persons to run models which produce easily understood graphical outputs. However, these outputs are highly dependent on the underlying assumptions used in formulating the models, and on both the reliability and suitability of the data used to set up, calibrate, verify and run the model. Interpretation of the results and an understanding of the models' operation and limitations require informed professional judgement.

Modelling techniques

Models can take on a variety of forms from the simplistic to the highly complex:

Conceptual models represent the way a person conceives a wetland, its essential features the principal processes taking place.

Diagrammatic models include aerial photographs and maps of terrain, vegetation and other features. These may be very powerful ways of representing a wetland, especially when digitised, compiled and presented through computer software such as a GIS.

Analytical models are mathematical models in which the underlying processes are represented by simplified mathematical equations which may be readily solved.

Black box models relate a desired hydrodynamic or water quality variable, such as **dissolved oxygen** (DO), to some other, more easily measured environmental variable, such as freshwater flow or tidal amplitude.

Segment or box models represent an estuary as a series of boxes, each of which is assumed to be uniformly well mixed, such that each of the parameters defining that box may be represented by a single statistic.

Numerical models are mathematical models in which the underlying processes are represented by mathematical equations, but the nature of their formulation requires the use of computers to evaluate solutions.

Hydrodynamic, water quality and sediment transport behaviour within a wetland are well suited to numerical modelling. The numerical modelling of biological wetland processes is less certain because of the complex and often uncertain nature of interactions between biological variables on the one hand (population types and numbers, habitat) and the hydraulic, water quality and sediment transport response of the wetland on the other.

In developing numerical models, simplifications are necessary, first, in developing the theoretical equations, and second, in their solution. Numerical models also tend to require large amounts of data. While some of the data may be readily available, specific and potentially expensive monitoring programs may be required to collect other data.

Prototype models or full-scale physical models allow investigation of the impact of changes to a wetland by using the wetland itself. Unlike other models, a prototype model does not suffer from simplification or omission of processes, as all wetland processes and their interactions are intrinsically included. However, once changes to the wetland have been made, the results (good or bad) may not occur in the short term.

Analytical and numerical models do not suffer from this problem as they are based on the simulation of changes. Furthermore, by representing processes mathematically, a numerical model allows the time response of the changes to be accelerated.

Nonetheless, prototype models are very useful for investigating limited effects. This is especially true with respect to biological response. A limited area of the wetland can often be isolated in which the effects of some past or ongoing change can be monitored. Another example is in refining the operation of management works already in place.

Calibration and veri cation

Important elements in the development of a reliable model are its calibration and verification. When models are calibrated, various parameters or model coefficients are adjusted to provide a good correlation between measured and simulated results. Once calibration is satisfactory verification is undertaken. The model is run against another set of measurements (not used in the model calibration) and the results are compared without the adjusting any model parameters.

For example, a survey and tidal gauging can be used to determine the existing extent of tidal inundation. The wetland could then be used as a prototype model to calibrate and verify numerical models which are subsequently used to assess the effects on hydrodynamics of changes in the wetland configuration.

Hydrodynamic, water quality and sediment transport models

Hydrodynamic models

Hydrodynamic models simulate water levels and discharges within a wetland for various freshwater inflows and tidal conditions. They can be numerical, analytical or box models. They also provide input data for water quality and sediment transport models. Water quality models require velocity and water level data in order to simulate tidally varying **advective** and **dispersive** transport, and discharges in order to evaluate the initial dilution of inflowing pollutants. Sediment transport models require velocity and water level data in order to simulate sediment transport processes.

An example of a simple, analytical, one-dimensional model for the velocity in a channel with uniform flow where the friction slope equals the bed slope is given by Manning's equation:

$$V = (1/n)\, R^{2/3}\, S_o^{1/2}$$

where V = velocity,
n = Manning's roughness coefficient,
R = hydraulic radius, and
S_o = bed slope.

Given a known boundary condition and using Manning's equation and continuity, a simple spreadsheet model can be written to estimate water surface profiles within a dendritic wetland system under steady flow conditions.

The simplest means of examining estuarine flushing is to consider the exchange of water by the tide and river inflow. Water entering on the flood tide is assumed to become fully mixed within the estuary. The volume of salt water and fresh water introduced is set equal to the volume of the tidal prism (the volume between the high and low tide marks). On the ebb tide the same volume of water is assumed to be removed. Consequently, it can be shown that the flushing time T, in tidal cycles, is given by:

$$T \quad (V + P) / P$$

where V = volume of water in the estuary at low tide and
P = tidal prism.

For example, if the tidal prism were 20% of the volume of the estuary at low tide, this simple model predicts that it would take about six tidal cycles to flush the estuary. However, as a general rule, there is incomplete mixing of waters within an estuary. Furthermore, fresher water near the head of the estuary may not reach the mouth during the ebb tide, and some of the water which leaves the estuary during the ebb tide may return on the following flood tide. Consequently, although this model is useful as a first estimate, the assumptions used in its formulation result in a considerably lower flushing time than would occur in reality.

More accurate solutions can be obtained by dividing the estuary into a number of segments or boxes. With such a box model the hydrodynamic parameters are assumed to be constant within each segment but to vary between adjacent boxes.

The predictive ability of models can be further improved by using a numerical model. However, because of their underlying technical complexity and data requirements, the development of numerical models of estuarine processes is a highly specialised field.

In terms of spatial representation, numerical hydrodynamic models can be one dimensional, two-dimensional or three-dimensional:

- *One-dimensional (1D) models* involve the greatest degree of spatial approximation, but are appropriate for long, relatively narrow estuaries. They are for water level and volume flow requirements.
- *Two-dimensional (2D) models* are used when spatial velocity variations are important, due to planform and/or depth variations.
- *Three-dimensional (3D) models* are the most complex of all, and allow for velocity and water level variations in all three dimensions.

The price paid for the incorporation of extra dimensions is increased data requirements, model complexity and developmental costs. However, parameterisations go down due to the inclusion of more physics.

Water quality models

Water quality models simulate the concentrations of dissolved or suspended substances of interest throughout the estuary. The development of such models requires a sound and basic knowledge of the various processes that affect the water quality parameters of interest.

Water quality models are typically numerical. Many are 1D, some are 2D and a few are 3D. Dissolved substances may be either conservative, such as salinity, or non-conservative, such as nutrients that pass into and out of the water mass through various source–sink processes. Concentrations of nutrients within wetlands are influenced by adsorption onto sediment particles, by biological uptake and release and by chemical effects, as well as by the usual processes of advective and dispersive transport.

All source–sink processes affecting the parameter of interest have to be described mathematically before they can be incorporated into a numerical water quality model. The highly complex nature of these processes, together with the often uncertain and highly variable nature of interactions between processes, often leads to the need for additional simplifications to be made in water quality models.

Sediment transport models

Sediment transport models simulate the movement of sediment within a wetland under the influence of freshwater and tidal flows. These models can be used to identify locations of likely scour and deposition and to predict the resultant long-term changes to wetland bathymetry.

There are two sediment transport processes: suspended load and bed load. Physical models are often used to investigate bed load transport.

Sediment transport models are of two types: event and long term. Tidal behaviour is the dominant mechanism in event models, which are used to investigate the short-term consequences (that is, over several months to several years) of some particular event, such as sand and gravel extraction at a particular location. Long-term models are used to investigate sediment behaviour over periods of several decades. In these circumstances, freshwater discharges, especially during flood times, have a marked influence on sediment transport, erosion and deposition within the estuary.

The calibration of sediment transport models is less certain than that of hydraulic and water quality models. Sediment transport processes are slower than hydraulic or water quality processes. Sediment transport data for calibration purposes is also more difficult and more expensive to gather.

Public domain and commercial software packages

Although limited in extent, a number of public domain models are available. In addition, many commercial sites allow free download of demonstration models of their software. These evaluation models are often fully operational but limited in some way. Nonetheless, they provide a basic hands-on overview of the product's features before you part with any money.

A number of suppliers and models can be found on the Internet by searching for 'hydrodynamic models'.

Nelson lagoon (DECC)

8 Groundwater

8.1 What is groundwater?

For our purposes, it is most useful to consider groundwater as all subsurface waters within soils and rocks that either fills the spaces between individual sediment grains (for example, sands and clays) or is located within fractures and other void spaces in underlying bedrock. Strictly speaking, the term 'groundwater' is used by professional **hydrogeologists** to describe only that part of the subsurface water that occurs at or below the water table. However, we are not concerned here with the distinction between water within the unsaturated zone above the water table and that in the saturated zone below it. We will therefore use the term 'groundwater' in the more colloquial sense, to refer to all waters contained within subsurface sediments and rocks.

On a global scale, groundwater is a fundamental component of the **hydrological cycle**, the endless circulation of the world's water resources between the oceans, atmosphere and land. Evaporation of the oceans and subsequent precipitation across the continents results in overland flow at the land surface and the infiltration of water into the subsurface. It may be surprising to know that over 98% of the world's available freshwater resource occurs as groundwater, which clearly far exceeds the volume of more visible freshwater sources such as lakes and rivers.

On the scale of an individual estuarine wetland, groundwater comprises one component of the estuarine water budget. Groundwater may be a source or sink of water within the wetland. Poor groundwater quality may degrade water quality within the wetland, and similarly, poor estuarine water quality may reduce the quality of the surrounding groundwater. It is therefore necessary to consider the possible interactions between groundwater and the wetland in order to develop a complete understanding of the passage of water through the wetland system.

At some sites the exchange of water between a wetland and the surrounding groundwater system may be significant; at other locations, the prevailing hydraulic and geological conditions may reduce the significance of the volumes of water involved in this exchange. At the present time our understanding of saltwater wetland–groundwater processes is in its infancy, and further research effort is required. There are, however, a number of general characteristics of the wetland–groundwater system that can be considered.

8.2 Groundwater movement

The movement of water within the ground results primarily from the force of gravity. Groundwater will flow from a region of higher water table elevation to a region of lower water table elevation. The rate of groundwater flow is essentially determined by the difference in groundwater elevation between two points and the characteristics of the material through which the water is moving. The term 'hydraulic conductivity' is used to describe the rate at which groundwater can flow within differing soils and rocks. Hydraulic conductivity is determined by soil texture, organic matter content and structure. Generally soils with coarse textures and many interconnected pores (for example, coastal sands) have a relatively high hydraulic conductivity of the order of tens of metres per day. In contrast, some estuarine mud and clays have a hydraulic conductivity of <1 mm per day. However, some clay soils have a relatively high hydraulic conductivity: for example, macropores, possibly relic root channels from previous vegetation, can raise hydraulic conductivity (Johnston *et al.* 2004).

Groundwater flow can be considered at a number of scales. At the regional scale, fresh groundwater tends to discharge at the coast via several natural mechanisms. These include evapotranspiration, mixing with saline groundwater to form a subsurface region of brackish water, and direct seepage through wetlands, springs, tidal rivers and the ocean floor. At the local scale, the flow of groundwater near a saltwater wetland may be quite variable. Groundwater levels and resulting groundwater flow vary in response to natural factors such as rainfall and the rise and fall of the tides, and human factors such as groundwater pumping and irrigation. Where groundwater interacts with brackish waters within a wetland, the density difference between fresh and saline waters will also help to drive groundwater flow, with fresher water tending to move over the top of more saline waters.

Dialogue Box 8.1 Simple method to estimate groundwater flow

The equipment necessary to estimate the direction of groundwater flow near a wetland is easy to obtain, and at many coastal sites can be installed relatively simply with the use of a hand auger. The only piece of equipment which may be a little harder to obtain is a simple surveyor's level. Councils, schools, universities and some community groups are good sources of such equipment.

The aim is to determine the depth to groundwater close to edge of the wetland, and at several locations around 20–50 m further away. Using a hand auger, dig a hole down to just below the level of the water table and install a **piezometer**. You can construct a piezometer from a length of PVC plumbing pipe with the end sealed. Use a hand saw to cut some slots in the bottom end of the pipe, then wrap it in a piece of old cloth to prevent the entry of sand and silt. Insert the piezometer into the hole, setting the base at least 20 cm below the water table. When installing piezometers, do this an hour or two after low tide, when the water table is likely to be at its lowest level.

You can use a piece of dowel to measure the depth to water table. Carefully insert the dowel so that it touches the bottom of the piezometer, make a mark where it matches the top of the piezometer, then remove it and quickly use a tape measure to record the distance between the mark and the wet line on the dowel. Do this at all piezometer sites. Once you have surveyed the height and location of the top of each of the piezometers, you can calculate the slope of the water table. In this way you can estimate the direction of groundwater flow in the vicinity of the wetland.

To determine whether groundwater is flowing into or out of the bed of a wetland requires even less equipment. Take a metal cake tin or similar plastic container and cut a 20-mm hole in the bottom, then insert the open end of a plastic bag through the hole into the tin. Fix the plastic bag in place with waterproof tape or glue, then invert the tin and press it firmly into the bed of the wetland. If there is inflow, the bag will slowly fill with water. If the bag does not fill with water, outflow from the wetland may be occurring. To test, fill the bag with water prior to pressing the tin into the bed of the wetland, if the bag then drains outflow may be occurring.

The flow of groundwater can transport soluble materials – nutrients and contaminants – either into or away from wetlands. Some soluble materials will not change in nature or quantity as they move through the groundwater system. Others will change, such as nutrients taken up by plants. Owing to the interconnection between a saltwater wetland and the surrounding groundwater system, you must assume any human impacts acting on the groundwater to act also on the estuarine system.

8.3 Groundwater–wetland flow regimes

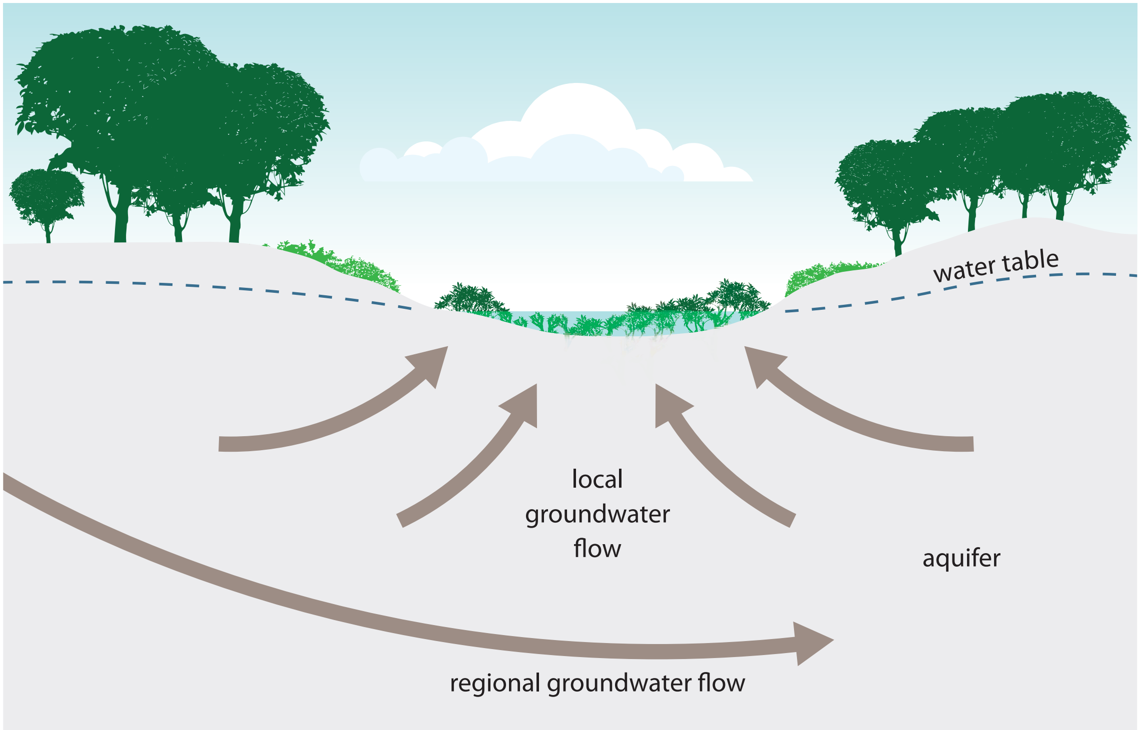
In general terms, groundwater flow in the vicinity of a saltwater wetland can be categorised into one of three flow regimes: discharge, recharge and flow-through.

Discharge regimes

Discharge regimes exist where the net direction of groundwater flow is from the surrounding groundwater system into the wetland. In other words, the groundwater system is discharging water into the wetland (Figure 8.1). Seepage into the wetland will typically occur through the base and banks of the wetland. The flow of groundwater into and out of a wetland tends to decrease significantly with increasing distance from the edge of the wetland, as the bed of many wetlands is relatively impermeable owing to fine sediments.

A discharge regime will tend to occur when the ground surface surrounding the wetland is elevated, and the water table elevation surrounding the wetland is above the level of the wetland. Under such conditions, the groundwater is a source of water to the wetland, and any contaminants present in the local groundwater system should be assumed to be entering the wetland.

Figure 8.1 Discharge regime

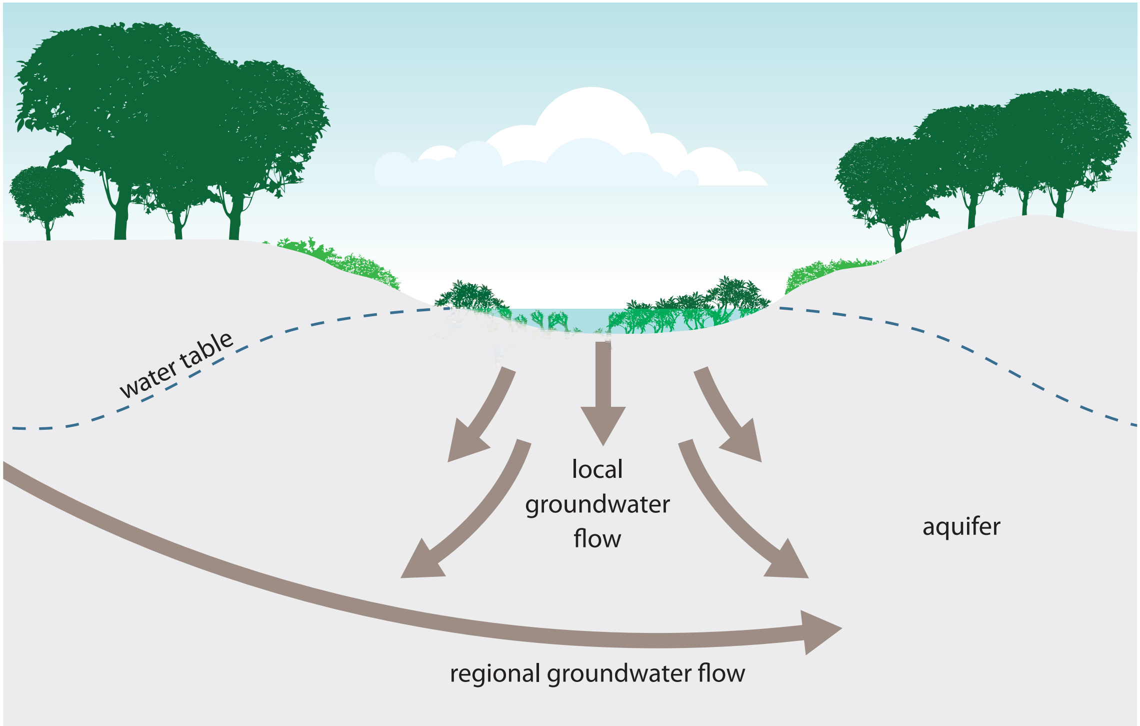


Recharge regimes

Recharge regimes exist where the net direction of flow is from the wetland into the groundwater system. In other words, water from the wetland is recharging the surrounding groundwater system (Figure 8.2). This is less likely to occur in saltwater wetland systems on the coast, but it may occur in areas where groundwater extraction has lowered the water table adjacent to the wetland, for example near a golf course where groundwater is pumped from a bore for irrigation.

Under recharge conditions, water will flow from the wetland into the groundwater system, transporting any contaminants from within the wetland. This may have a detrimental impact on the surrounding groundwater system.

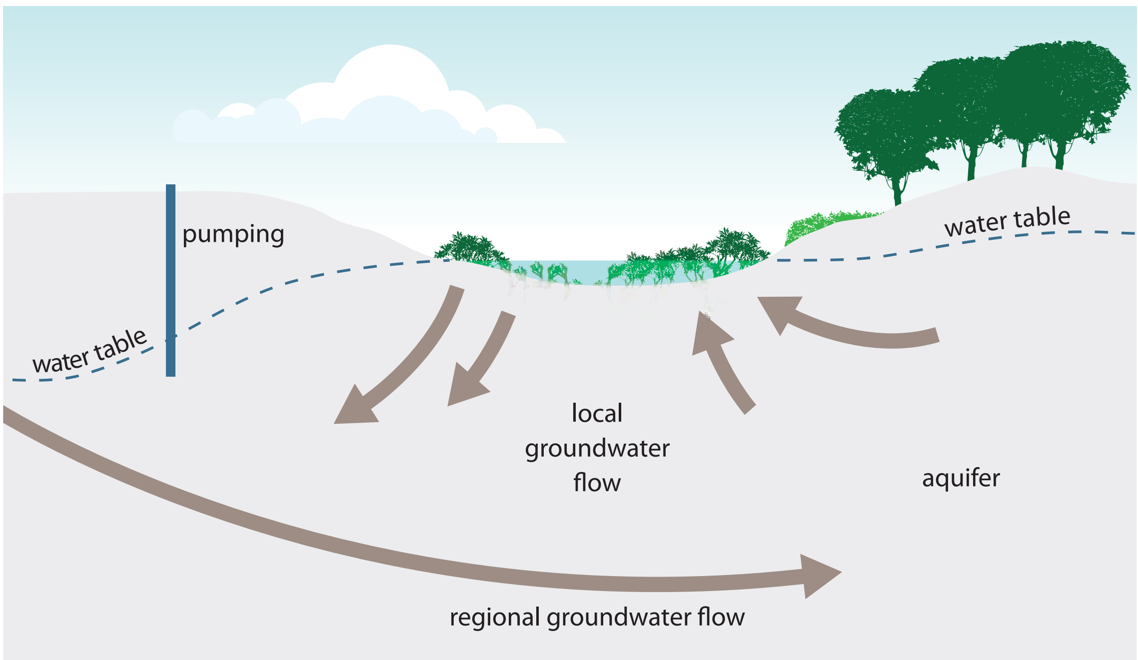
Figure 8.2 Recharge regime



Flow-through regimes

Flow-through regimes exist where the water table adjacent to one region of the wetland is higher than that at another location. Under such conditions, groundwater flows into and then out of the wetland, from the region of higher water table elevation to the region of lower water table elevation (Figure 8.3). Such conditions are likely to be rare in coastal settings, but could occur in response to either localised irrigation or groundwater extraction on one side of a wetland only.

Figure 8.3 Flow-through regime



8.4 Groundwater 'capture' zone

It is important to recognise that wetlands interacting with groundwater can have a relatively large capture zone, meaning that the region from which groundwater may discharge from one to the other is likely to be significantly larger than the surface area and depth of the wetland itself. As illustrated in Figure 8.4, at inland (freshwater) wetlands the horizontal capture zone may typically be twice the width of the wetland. Similarly, as illustrated in Figure 8.5, the vertical capture zone is typically twice the depth of the wetland. The capture zone for saltwater wetland systems is likely to be significantly greater on account of the mixing action of the tides. The existence of a relatively large capture zone is significant because it means that any human-induced changes to either the wetland or groundwater system can affect both systems over an area that significantly exceeds the area of the wetland alone.

Figure 8.4 Horizontal capture zone

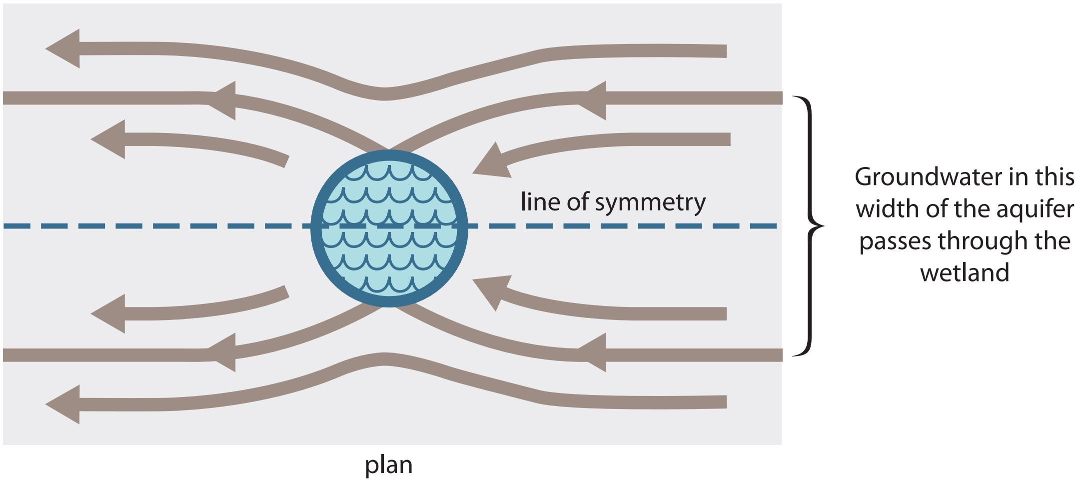
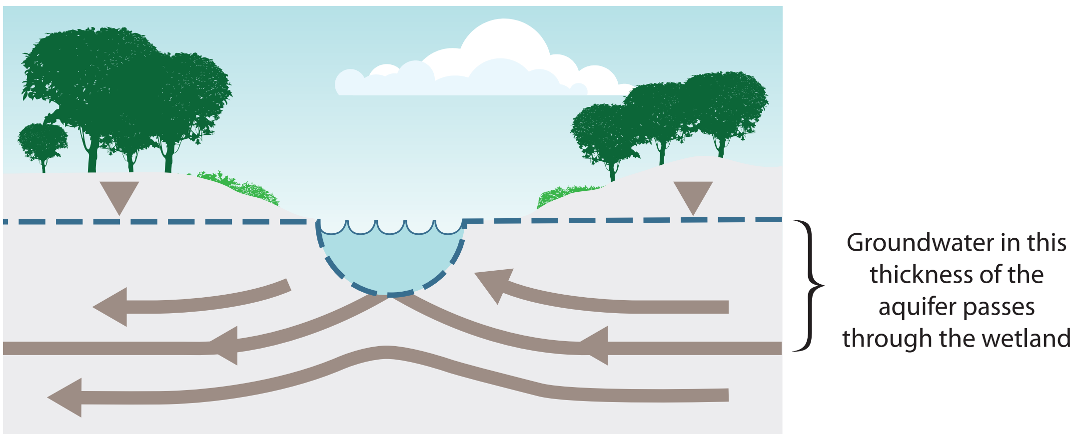


Figure 8.5 Vertical capture zone



8.5 The influence of tides on groundwater–wetland interactions

A saltwater wetland will be influenced by the action of ocean tides to some extent. The regular rise and fall of the water level within a saltwater wetland is important to the surrounding groundwater system, as this process may play an important role in determining the rate of exchange of contaminants between the estuarine and wetland systems. It is therefore a significant shortcoming that our present knowledge of the tidally driven exchange between wetlands and groundwater is limited.

The action of tides will tend to cause a cyclic flow of water between the wetland and the surrounding groundwater system. At low tide, the water table within the surrounding groundwater system may be higher than the water level within the wetland, and therefore groundwater will discharge through the banks and base of the wetland. At high tide, the water level within the wetland may exceed the surrounding groundwater elevation, resulting in the recharge of waters back into the groundwater system. For this reason, the groundwater elevation in the immediate vicinity of a tidal wetland can often be observed to fluctuate at the same frequency as the tides. Owing to the relatively slow rate at which water flows through the ground, the magnitude of tidally driven groundwater fluctuations will tend to decrease rapidly with increasing distance from the wetland. Away from the side bank, the tide and water table fluctuations may show a time-lag of several hours. To determine the average groundwater level surrounding a wetland, it is therefore necessary to monitor at several different stages of the tide, and preferably during both neap and spring tide cycles.

It is likely that the tidal rise and fall of the water level within a coastal wetland will assist the mixing between fresher groundwater discharging towards the coast and saline or brackish waters entering the groundwater from the wetland. If tides were not present, the fresh groundwater would tend to flow over the denser saline groundwater, which would occur at a considerable depth below the ground surface. In theory, if the water table adjacent to a wetland were to be elevated 1 m above the water level within the wetland, in the absence of tides the fresh–saline groundwater interface would stabilise at a depth of about 40 m. However, owing to the action of tides, considerable mixing across the saline–fresh interface occurs, and brackish groundwater may be detected at much shallower depths adjacent to an estuarine wetland. Not only does this process result in a potential increase in groundwater salinity adjacent to the wetland, but any contaminant that may be present in the wetland can enter the groundwater system by this process of tidal mixing.

Another potentially important effect of tides, and one that has been recognised only in recent years, is that the action of tides may tend to elevate the water table adjacent to a tidal water body. The flow of water through the bank of a wetland will be enhanced at high tide relative to low tide, resulting in a local mounding of the water table surrounding the wetland. Such effects have been measured at the coast and in tidal creeks, but not yet in estuarine wetlands. This local mounding of groundwater adjacent to a wetland could decrease the rate of net groundwater discharge to the wetland, and may result in a local reversal of groundwater flow. Further investigations are required to better understand the effects of tides on the processes of wetland–groundwater exchange.

8.6 Potential groundwater contamination by wetlands

Previous sections have discussed the potential movement of contaminants between wetlands and adjacent groundwater systems, as wetlands and groundwater cannot be considered in isolation. To successfully rehabilitate either or both resources, it is important that both wetland and groundwater quality be considered as a whole.

If a groundwater discharge regime prevails, then existing or future degradation of the groundwater should be managed so as to prevent a corresponding degradation within adjacent wetlands. Waste disposal, effluent disposal, industry and farming may all degrade the quality of the underlying aquifer, and thus of the linked wetland. Practices such as the excavation of drainage channels in acid-sulfate-prone coastal regions must be managed to ensure that groundwater is not contaminated, so avoiding contamination of the adjacent wetland.

Groundwater can be degraded by several types of contaminant that may enter the surrounding aquifer from an adjacent wetland. This is particularly the case where liquid wastes from stormwater, agricultural runoff or industry are directed to the wetland. *The Constructed Wetlands Manual* (DLWC 1998) includes a very useful discussion of the various sources of contamination associated with these activities. For convenience, an overview of this material is presented below, supplemented by a discussion of the coastal process of saltwater intrusion.

Groundwater contamination by saltwater intrusion

Under natural conditions, the regional flow of fresh water towards the ocean limits the landward encroachment of sea water. When groundwater is pumped from an aquifer that is hydraulically connected with a source of salt water such as a saltwater wetland system, the flow regime that results may induce salt water encroachment into the aquifer. This migration of salt water into fresh water is know as saltwater intrusion.

As noted earlier, in theory, for every 1 m that the water table adjacent to a wetland is raised above the water level within the wetland, the fresh–saltwater interface will stabilise at a depth of approximately 40 m. For the same reason, for every 1 m that the water table is pumped down for irrigation and domestic use, the fresh–saltwater interface will rise by approximately 40 m. Therefore, pumping must be carefully managed adjacent to saltwater wetlands. Even though the fresh–saltwater interface may be known to be well below the ground surface, a relatively minor lowering of the water table by pumping can result in a large rise of salt water into the upper aquifer.

Groundwater contamination by metals and nutrients

Metals in groundwater can cause environmental and ecological problems as well as human health problems. Although groundwater contamination by metals can affect the potential human use of the resource, it can also affect aquatic organisms when the contaminated groundwater discharges to surface waters or is taken up by vegetation and crops.

The metals of principle concern include lead, copper, nickel, chromium and zinc and arsenic (a metalloid). Research shows that most metals are likely to accumulate within the soils close to their source (such as the base of a wetland). However, in sandy and loamy soils, significant downward movement of copper and iron is observed. Therefore, if the groundwater adjacent to a wetland is acidic, these and other metals can be mobilised and move into the surrounding groundwater system. As the solubility of most metals increases with decreasing pH, the risk of acidification and metal release following **oxidation** could be greatly increased in ASS.

Excessive nutrient concentrations can cause both environmental and human health problems. Phosphorus adsorption is limited in porous soils which are prone to considerable groundwater movement. Phosphorus in its dissolved form (orthophosphate) can move freely from a wetland into the surrounding groundwater system. Nitrates are among the most frequently encountered contaminants in groundwater. Whenever nitrogen-containing compounds come into contact with soil, there is the potential for nitrate to leach into groundwater. Nitrates are highly soluble, and so are easily transferred from a wetland into the surrounding aquifer.

Groundwater contamination by pathogens and pesticides

Pathogens may enter the groundwater via a wetland from sewage, septic systems, stormwater and agricultural runoff. Pathogenic organisms can harm human health. A number of factors influence the movement of viruses and bacteria into the surrounding groundwater system. Viral survival time increases with increasing pH (more alkaline) and decreasing temperature. Higher groundwater flow rates also decrease the rate of virus adsorption in soils, and hence increases the potential area that may be contaminated away from the viral source. Bacterial and viral survival times are also increased by the presence of organic matter within the soil. Higher clay content is associated with a corresponding decrease in the extent to which viruses can move into the aquifer system adjacent to a contaminated wetland source.

Pesticides that enter a saltwater wetland, usually as a result of agricultural practices, may subsequently pass through the banks or base of the wetland and thereby enter the adjacent groundwater system. Pesticide mobility is highest within aquifers composed of coarse-grained or sandy soils. It decreases with increasing clay content and organic matter content. Pesticides decompose in soil and water, but the total decomposition time can range from days to years.

9 Soils

9.1 The need to know about soils

The physical, chemical and biological characteristics of site soils will determine their capabilities for construction and wetland planting and will influence the design, operation and performance of a wetland. For example, highly organic soils will enhance sulfate reduction and ion adsorption and might be better suited for wetlands receiving acid drainage.

An analysis of soils is required in order to:

- determine whether or not *in situ* soils provide a suitable environment for plant growth and establishment, highlighting any constraints such as low organic matter
- identify soil properties that may affect wetland operation and performance (for example, erosion potential, soil acidity, potential for subsidence and **shrink–swell**)
- establish, where relevant, whether soils can be used as construction materials for embankments, what their **saturated hydraulic conductivity** is and whether sealing is required
- establish, where relevant, the soil's capacity to remove and store phosphorus and other pollutants such as heavy metals and pesticides
- establish the nature and extent of site problems and their potential impacts (for example, heavy metal contamination, dispersive soils and acid discharge).

In addition, an analysis of catchment soils may be required to determine potential inputs to the wetland.

Acid water from drainage of acid sulphate soils at Tuckean swamp, Lower Richmond River (Mitch Tulau)

A number of soils classification systems exist for Australian soils including the **Great Soil Group** classification (Stace *et al.* 1968). The **Australian Soil Classification** (Isbell 1996) has been endorsed as the official Australian soil classification.

9.2 Estuarine soil formation

Estuaries lie at the boundary between terrestrial and marine environments. The vast majority of estuarine soils develop within either marine or terrestrial sediments that have been deposited by **fluvial**, tidal or **aeolian** processes. Therefore, soil formation in estuarine environments is dominated by sedimentary processes.

Estuarine systems are dynamic and continually evolving, and therefore their soils are young by comparison with most other Australian soils: many upper estuarine sediments in NSW are Holocene in age (<10 000 years). Consequently, estuarine soils are dominated by the soil types listed in Table 9.1. Most other soil types are either absent or very minor in extent.

Table 9.1 Major estuarine soils

Soil type (Australian Soil Classification)	Great Soil Group equivalent	Main diagnostic features
Organosols	Peats	Dominated by organic material
Hydrosols	Humic Gleys, Gleyed Podzolic Soils and Solonchaks	Prolonged seasonal saturation
Podosols	Podzols	B horizon dominated by compounds of organic matter, aluminium and/or iron (generally highly sandy and acidic)
Rudosols	Many Lithosols, Siliceous Sands and Calcareous Sands	Negligible **pedologic** development
Tenosols	Most Siliceous Sands, Earthy Sands and many Lithosols	Weak pedologic development; typically very sandy

Source: Grey and Murphy 1999 (compiled from various sources including Isbell (1996) and Stace *et al.* (1968)).

In some situations the soil may be frequently inundated beneath 30–45 cm of water, drying seasonally. Proximity to brackish tidal water will result in high salinity and **sodicity** as well as predisposing soils to acid sulfate conditions.

Soils can be very deep (>300 cm), very poorly drained Organosols or acid peats. Peat ash is present in some places, resulting from the burning of organic material. Burning reduces the volume of organic soil to approximately 1/12, significantly reducing ground surface levels and impeding site drainage.

Variation in soil characteristics are due to geomorphic and pedogenic processes, including the presence of peat and sometimes alluvium in the topsoils as well as on the extent and age of any estuarine sands in the subsoils. Iron and **jarosite** mottling may be present if the subsoil materials have been oxidised. These conditions are not reflected in surface variations.

Jarosite mottling in acid sulphate soil (Mitch Tulau)

9.3 Soil distribution in estuarine landscapes

Soil properties and the distribution of soils in estuarine environments are largely controlled by the combination of geomorphological context and the position of groundwater. Sediment geomorphology (section 9.7) determines the general location of various textural groups and hence the hydraulic conductivity, nutrient status and engineering properties of most estuarine soils. Any fluctuation in sea level, from the tidal timescale to the geological timescale, or drainage patterns influences estuarine soil processes.

The distribution of soil material in saltwater wetlands depends on the size of sediment available and the tidal and wave energy of the environment. Sandier materials will be found in high-wave-energy environments and closer to the estuary mouth, where flood tide deltas and barrier sands are the main sediments. Muddier sediments dominate in quiet backwaters. These are known as Hydrosols or Solonchaks and are commonly referred to as saline soils or salt-affected soils (although not all Hydrosols are saline). Soil development takes place above the zone of permanent saturation.

9.4 Common soil properties

Several soil properties may need to be considered in saltwater wetland rehabilitation projects that involve earthworks: saturated hydraulic connectivity, wet bearing strength, plasticity, organic content, aluminium toxicity potential, sodicity and dispersion, and shrink–swell potential.

Saturated hydraulic conductivity

The ability of soil to permit water movement when saturated is measured by its saturated hydraulic conductivity (K_S). Generally soils with coarse textures (sands) and many interconnected pores have high K_S values, although some clay soils can also have high K_S values due to the presence of macropores. Soils with low K_S usually have very slow drainage and are likely to pond water for long periods.

Wet bearing strength

Soils with low wet bearing strength are usually fine-grained, pliable and easily deformed under pressure when wet. They are unsuitable for any sort of foundation and make site access difficult when wet. Such soils suffer severe structural damage if mechanically disturbed when wet.

Plasticity

Soils that deform or change shape without a change in volume are plastic. Soils are plastic between the semi-solid and liquid states (Hicks 1991). Highly plastic soils do not support loads well and have poor trafficability when wet.

Organic soils

Soils with large amounts of organic matter, such as peats and sandy peats, are generally unsuitable for use as engineering materials because they have a low wet bearing strength and their physical properties may change through decay. Most topsoil contains sufficient organic matter to be unsuitable for any engineering purpose.

Aluminium toxicity potential

High levels of soluble aluminium are often toxic to nimals and plants. They occur most frequently in strongly acidic soils, as aluminium becomes more soluble at low pH.

Sodicity, dispersion

Sodic soils are high in sodium, they have an Exchangeable Sodium Percentage of >6. Sodic and dispersible soils are often highly erodible, generally shrink and swell, and may have low wet bearing strengths. They often set very hard when dry and often form surface crusts. They are prone to structural degradation and require careful management.

Shrink–swell potential

Expansive soils shrink and swell with changes in moisture content. The shrink–swell potential can be reduced by compaction, the addition of lime or gypsum, or burial under a stable material. Keeping soil moisture constant or covering soils with an impermeable material can reduce soil movement.

Tracks and trails through a mangrove forest (Kooragang Wetland Rehabilitation Project)

9.5 Dominant soil materials and their limitations

Information on dominant soil materials and their limitations is presented in Appendix 5.

9.6 E ects of soil on water quality and plant growth

The soil within a wetland will support vegetation and provide sites for biochemical and chemical transformations and for storage of pollutants. Selecting a soil with the best possible physical and chemical characteristics is critical, especially in the early stages of development, if the wetland is expected to receive contaminated runoff.

A soil's capacity to remove and retain contaminants is a function of soil–water contact. Soils of medium texture (silty or sandy loams) promote ideal soil–water contact and are recommended for use within wetlands. The long-term success of a wetland therefore depends partly on the physical and chemical characteristics of the soil. For example, soils with a high clay content will aid phosphorus retention.

In general, to promote plant growth and effective water quality improvement it is recommended that the topsoil within the wetland have the following characteristics:

- medium-textured silt or loam with clay content 20%
- a high organic matter content (3–5% w/w)
- a pH between 6.5 and 8.5
- a depth of 150–200 mm
- adequate levels of potassium and a good balance of calcium and magnesium (a Ca/Mg ratio of between 4 and 6)
- low quantities of available aluminium, copper, zinc, manganese, iron, boron, molybdenum and sodium
- moderate phosphorus levels (10–17 mg/kg)
- a **cation exchange capacity** of >15 cmol/kg of soil.

9.7 The importance of geomorphology

Determining geomorphology is an important part of the site investigation. The process can be used to describe landforms, interpret site geology and determine surface build-up. Geomorphology affects the spatial variation of soil properties. Geomorphic information can be gathered from aerial photographs, topographical and geological maps (including soil landscape maps, ASS maps and Quaternary geology maps) and field inspection.

As the wetland is situated within or directly adjacent to a waterway, an understanding of the wider geomorphology is important to an understanding of the potential stability of any proposed works, the stability or potential impacts of adjacent water courses on the wetland, and the presence of sand, gravel or clay deposits.

In addition to understanding the geomorphic features of a saltwater wetland, it is important to look at any trends that may be occurring; for example, the area may have been stable for a long period or it may have been building up or eroding. One way to determine any geomorphic trend is to map the site from aerial photographs covering as long a period as possible. The rehabilitation plan should take these trends into account, favouring stable or naturally growing sites over those that are eroding.

9.8 Landscape limitations and impacts related to soils

Information on landscape limitations and impacts related to soils is presented in Appendix 5.

9.9 Acid sulfate soils

Extent of acid sulfate soils

Acid sulfate soil risk maps (1:25 000) covering the entire NSW coastline are available from DECC. The mapped units are categorised as high risk, low risk or no known occurrence of ASS, based on the likely extent of ASS within each land unit (Naylor *et al.* 1998). Maps include areas of disturbed terrain, where the presence of either actual or potential ASS could not be determined, and the presence of high-risk and low-risk bottom sediments.

Formation of acid sulfate soils

Iron sulfide (pyrite) forms in waterlogged saline sediments that contain iron and have a supply of easily decomposed organic matter (Dent 1986). Bacteria (*Desulfibrio desulfuricans*) break down the organic matter under waterlogged anaerobic conditions and reduce sulfate in sea water to sulfide (Pons *et al.* 1982). The presence of sufficient pyrite indicates potential ASS. Rapid oxidation of pyritic sediments can occur when pyrite is exposed to the air in the presence of the ubiquitous bacterium *Thiobacillus ferrooxidans*. The oxidation produces elevated concentrations of ferrous iron and sulfuric acid, which in turn reacts with clay minerals to produce elevated concentrations of dissolved aluminium (Lin and Melville 1993).

The formation of pyrite in coastal sediments occurs in two main environments. The first and most dominant is saline and brackish lowlands, including tidal flats, saltmarshes and mangrove swamps (Pons and van Breeman 1982). The second is the bottom sediments of saline and brackish estuaries, rivers, lakes and creeks, depending on a number of factors, including rates of sedimentation and degree of tidal flushing.

In many cases, fluvial inputs are the most important sources of infill materials in an estuary and, therefore, to a large extent, determine the rate of expansion of coastal plains. Where coasts advance slowly, intertidal environments tend to persist at a given location for a long time favouring the accumulation of large amounts of pyrite. In rapidly advancing coasts, the time available for the accumulation of pyrite is insufficient, resulting in little pyrite accumulation in the sediments (Pons and van Breeman 1982). Sediment texture (% clay) and temperature are also important.

If a potential ASS is drained or excavated, it will become extremely acidic owing to the exposure of pyrite to the air. A number of oxidation products are formed, principally sulfuric acid. The resulting acid soil layers are called actual ASS.

Typically, potential ASS have a pH of 6 to 7, and are commonly dark grey or dark greenish-grey. They may contain shells and other carbonates and have a pyrite concentration which, when oxidised, exceeds the soil's neutralising capacity. Potential acidity as a result of pyrite formation may be found in sands, peats and clays, but is most extensive in clays, or what are known as estuarine gels due to their buttery consistency (White and Melville 1993).

An indication of an actual ASS is a pH of < 4. In the field, jarosite mottles can be a positive indicator of actual ASS. Jarosite forms during acidic oxidising conditions in the soil (van Breeman 1982). However, not all actual ASS forms jarosite; in particular, organic soils or sands may not.

Sulfuric acid produced upon oxidation of pyrite can low pH in the soil to extreme levels, at times to less than 3. The oxidation of pyrite not only acidifies the soil and groundwater, but also mobilises aluminium, iron and manganese from soils (Sammut *et al.* 1994), and can cause severe nutrient deficiencies (Rorison 1973). Following rain, these oxidation products may enter drains and waterways, forming toxic effluent, which may affect aquatic fauna at some distance from the soil disturbance. Oxidation of pyrite can also contribute acid salts to the soil, causing a high degree of salinity (Fanning 1993).

The release of acidic water often has catastrophic effects on the aquatic populations of estuarine systems, including massive fish kills and habitat degradation (Sammut and Lines-Kelly 2004). Exposure to low pH is directly injurious to fish, and the toxicity of associated inorganic aluminium has been responsible for massive fish kills and for the development of the fish disease epizootic ulcerative syndrome, or red spot disease. Elevated levels of aluminium ions in the water are considered the primary cause of injury and death to fish in acidified water, causing damage to gills, skin and olfactory mucosa.

Estuarine deposits in eastern Australian floodplains are frequently overlain by a relatively thin layer of freshwater alluvium deposited by overbank floods (Langford-Smith and Thom 1969, Walker 1972, Willet and Walker 1982, Willet 1989). This non-pyritic alluvium can markedly control penetration of air into the pyritic estuarine substratum, and thus plays an important role in controlling soil sulfurification under certain drainage conditions (Lin and Melville 1993).

Scald from drainage of acid sulfate soils, Yarrahapinni Wetland (Mitch Tulan)

10 Chemistry

10.1 Introduction

The chemistry of saltwater wetlands is principally governed by local tidal inundation. The mixing of fresh and salt water in the estuary gives the wetlands unique chemical and biological properties, which help dictate the development of plant and animal communities. The main chemical factors that influence plant growth in saltwater wetland areas are salinity, oxygen availability and nutrients.

Macroalgae within a coastal lake (DECC)

10.2 Salinity

Salinity is the defining and most important feature of saltwater wetland chemistry. The high salt content of the tidal waters and of the soil affects species selection and the productivity of the plants and animals. With the exception of hypersaline areas, estuarine salinity ranges from 0.5 to 35 ppt. This range allows a number of different plants and animals to survive in particular niches to which they are specially adapted. Salinity is extremely important for the germination success and survival of many estuarine plant species and accounts for the zonation patterns seen commonly in these areas. The adaptations of estuarine species allow them to inhabit this zone with relatively little competition from terrestrial species.

The salinity of intertidal soils is governed by several factors:

- *Local tidal regime:* The height of the preceding tide determines whether an area of wetland has been flooded or not. Lower elevations will be flooded more often, and their salinity often reflects that of the estuarine water. Higher elevations will dry out between inundations, and evaporation may cause salinity to increase in these areas.
- *Drainage:* The nature of the soil and the proximity of creeks affect the drainage of the wetland and the soil salinity. Fine silty mud retains more water and more salt than do sandy sediments.
- *Gradient:* The wetland slope influences the penetration of tidal waters and the rate at which the water can drain away.
- *Vegetation:* Plant cover reduces evaporation and lowers the salt accumulation at the surface of the wetland.

- *Water table depth:* An elevated water table may reduce soil salinity by dilution or may carry salt to the surface.
- *Freshwater inputs:* The inflow of fresh water from natural or anthropogenic sources tends to dilute the salinity within the wetland environment.
- *Climate:* Rates of evapotranspiration depend on temperature, and the relationship between seasonal rainfall and tides affects dilution of soil salinity.

10.3 Oxygen

Plants and animals need oxygen. In the estuarine environment, frequent tidal inundation commonly leads to waterlogging of the soil that can deplete the available oxygen within the sediments, a situation referred to as anoxia. Water fills the soil pore spaces and reduces the exchange of oxygen between the air and soil. The oxygen remaining is consumed by microbial respiration within the soil. The lack of oxygen in the root zone poses particular difficulties for intertidal vegetation. All species that are able to live in this environment have specific adaptations, such as pneumatophores, to cope with the low soil oxygen in the waterlogged areas of the intertidal zone. Fauna that lives in these areas can improve the aeration of the soil by burrowing into the sediments. This in turn aids the survival of many plant species in this zone. The activity of crabs is particularly important.

10.4 Nutrients

Nutrients are very important in the coastal environment, and nutrient cycling is probably the main ecological function that drives the processes within the saltwater wetland ecosystem. Owing to the substantially different chemical environment in saltwater wetlands, nutrient cycles have different characteristics from those in freshwater wetlands. The two most important nutrients to living organisms within estuaries are nitrogen and phosphorus, which are present in concentrations of three to four orders of magnitude lower than those in typical freshwater wetlands. However, excessive inputs of nitrogen and phosphorus from sewage, urban, agricultural and industrial effluents can lead to eutrophication, resulting in algal blooms if the wetland is not well flushed by the tides.

Nutrient uptake and litter decomposition are important to the functioning of ecosystems because they provide essential components to sustain life in the estuary. A great number of animals found in saltwater wetland habitats can be classified as detritivores or decomposers (for example, protozoans and nematodes). These fauna convert the wealth of plant matter in wetlands to detrital food sources for a rich and diverse invertebrate community which may in turn support other marine and terrestrial species.

Nitrogen

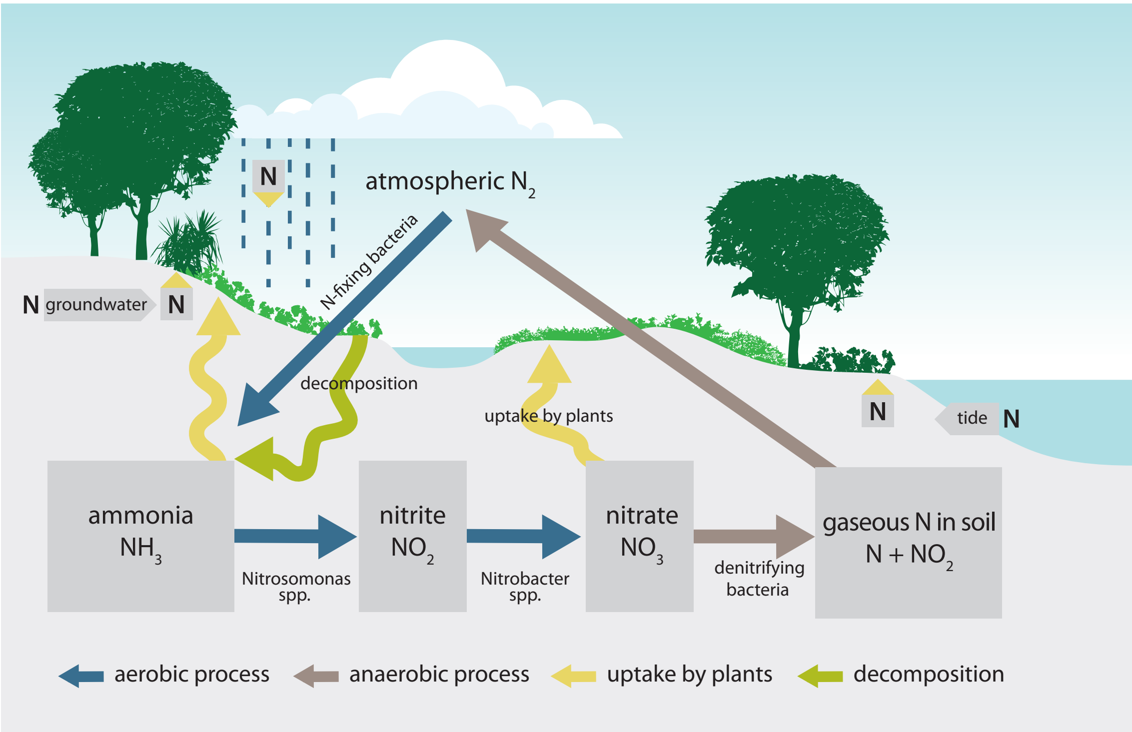
Nitrogen (N) generally arrives in most intertidal areas via tidal water, precipitation, groundwater and sediments carried by the tide. Where tidal influence is infrequent (for example, in saltmarshes), groundwater often carries more N than any other source. The processes associated with N cycling are shown in Figure 10.1. Plants extract nutrients from the sediments via their roots and use them for growth and reproduction. The supply of N may not always be sufficient to maintain the productivity of these ecosystems after denitrification, the process whereby nitrate or nitrite is converted to gaseous nitrogen (N_2).

Denitrification (and thereby the loss of N) is generally enhanced in waterlogged **anoxic** soils that are typical of habitats constantly inundated by the tides. Consequently, other sources of N are important. In N fixation, bacteria convert atmospheric N_2 to organic N (Figure 10.1).

In nitrification, **aerobic** bacteria (*Nitrosomas* spp. and *Nitrobacter* spp.) convert ammonium, produced by proteolytic bacteria and fungi in the soil, to nitrate. Plant decomposition recycles N.

The N cycle varies slightly in saltmarsh environments on account of the infrequency of tidal exchange. The infrequent wetting and drying of soils favours exchange with the atmosphere over exporting nutrients and plant matter to the estuary via the tide. Therefore, a relatively large proportion of plant material is consumed on the saltmarsh by respiratory or burial processes. Denitrification in the soil is limited, because the soils of saltmarshes are typically drier than those of nearby mangroves, thereby reducing the potential for N loss to the atmosphere. Furthermore, saltmarsh vegetation actively transfers oxygen to its roots and consequently to the soil. This background forms the basis for nitrification processes, whereby nitrogenous compounds are converted to biologically available ammonium and nitrate, which are used in plant growth. In addition, during decomposition, nutrients in the plant tissues are released and recycled into new plant growth.

Figure 10.1 Depiction of the main processes of nitrogen cycling in saltwater wetland environments



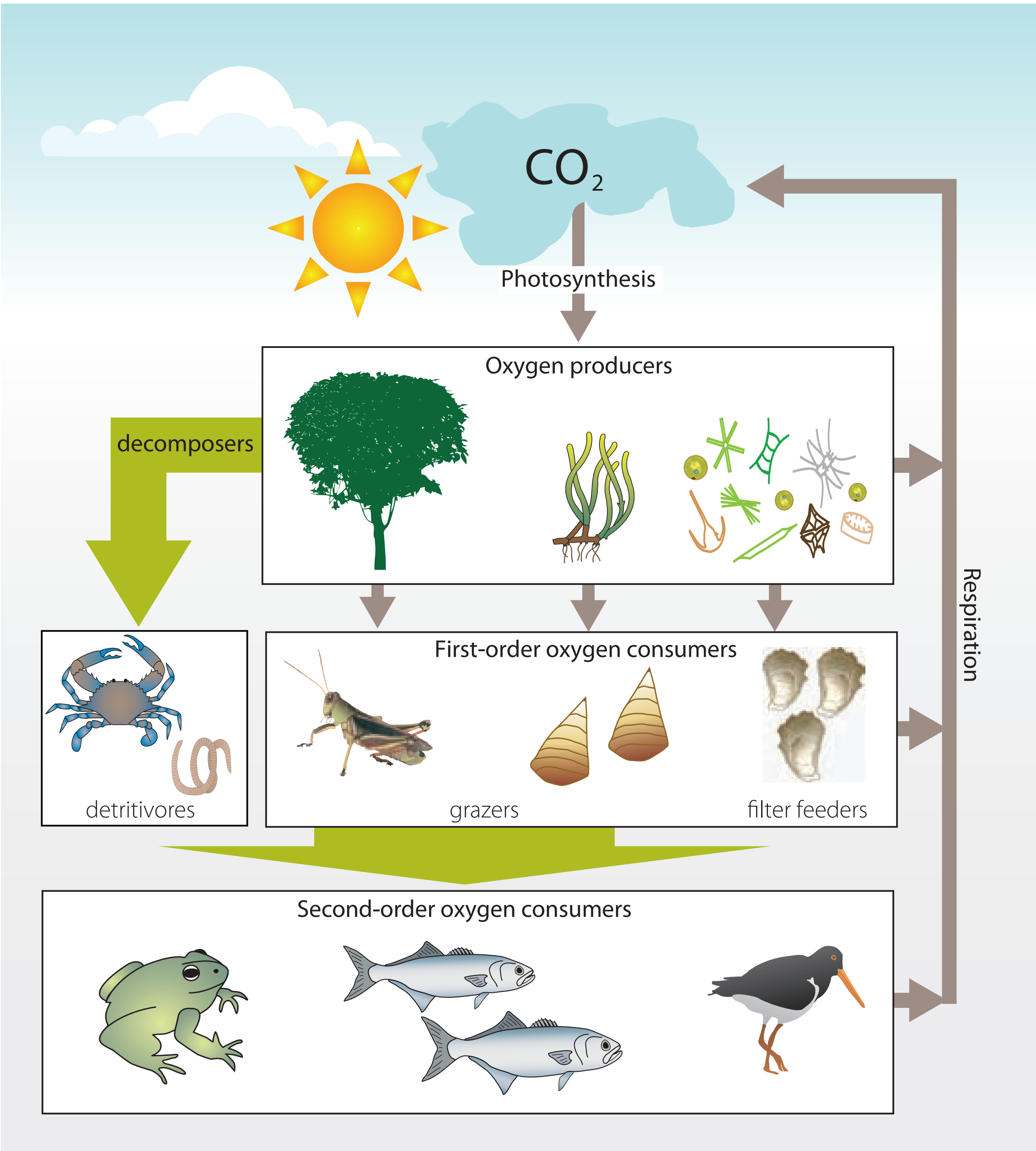
10.4.2 Phosphorus

Phosphorus (P) is very important in the wetland environment, being one of the macronutrients needed for building living tissue. The P cycle in intertidal soils is much simpler than the N cycle: P is taken up by organisms as phosphate and is liberated by excretion or the decomposition of dead matter by microbial activity. By the processes of excretion, death and sedimentation, P bound to organic matter concentrates in sediments, where microbial decomposition converts organic P to inorganic forms, which may again be taken up by organisms. Phosphate ions are also adsorbed to silt and clay particles. Mobilisation of sediments can contribute considerably to P levels within the water.

Carbon

Plant material is the most significant source of organic carbon in estuaries and also of atmospheric carbon dioxide (by respiration). The herbivore, decomposer and detritivore communities play a pivotal role in processing and mobilising this material (Figure 10.2). Saltwater wetlands usually support a substantial biomass of coastal macrophytes, most of which do not support a large number of grazers. Therefore, the majority of the plant material ends up as leaf litter and, eventually, detritus. This detrital material can either be consumed *in situ* by detritivores and decomposers or be exported with the tides to other parts of the estuary. Organic detritus in all states of decomposition is a very important source of particulate organic carbon in estuaries.

Figure 10.2 The process of carbon cycling within saltwater wetlands, showing the importance of the detrital food chain



Many of the most important chemical reactions occurring in sediments are associated with the decomposition of organic matter. Decomposition reactions affect the sediment environment and organic content.

The process of decomposition involves the gradual breaking down of dead material to smaller and smaller particles and eventually to small molecules. It involves the action of physical factors, such as weathering and leaching, and the activities of microorganisms and detritivores. Litter within intertidal areas is derived from several sources. The largest source in terms of mass is usually the higher plants, such as mangroves and saltmarsh plants. Smaller detrital particles derived from **microphytobenthos**, epiphytic algae, phytoplankton and faecal material may also be significant. In addition, a substantial portion of the organic litter in intertidal areas may be of terrestrial origin, washed down by rivers or deposited by the tides.

10.5 Sulfur

The water that inundates saltwater wetlands not only is saltier than terrestrial waters, but also contains relatively high levels of sulfur (S). The lack of oxygen within the soil allows anaerobic bacteria, which can operate on S respiration, to thrive. However, the microbial action and the reduction of sulfate to sulfide under anaerobic conditions creates the potential for ASS (Section 9.9) to form. On exposure to air, these soils can generate potentially harmful levels of sulfuric acid.

In some estuarine environments, the availability of S combined with certain environmental conditions will lead to the generation of hydrogen sulfide (H_2S), or rotten egg gas. H_2S is produced naturally by sulfate-reducing bacteria within the sediments of all marine-influenced environments. The bacteria convert sulfate and organic matter into H_2S, CO_2 and water. The conditions under which the release of H_2S is triggered generally relate to the availability of oxygen. If there is insufficient oxygen available in the water or if the rate of oxygen input to the water (from **photosynthesis** by aquatic plants and atmospheric diffusion) is not fast enough, the H_2S will not be completely oxidised, and it will be released to the atmosphere. While H_2S can prove a nuisance because of its unpleasant odour, it is unlikely to cause health problems in open environments, where it is quickly dispersed into the atmosphere.

11 Saltwater wetland habitats

11.1 The estuarine environment

Estuaries are complex systems where communities have to cope with a variety of stresses. Rainfall reduces salinity by dilution and leaching, while evaporation concentrates salt to high levels in the surface soil, leading to increasing variability in salinity at the higher tidal elevations.

A number of interconnected wetland habitats make up estuarine environments, including mudflats, seagrass beds, mangrove forests, saltmarshes and swamp forest, which are discussed in turn in this chapter. The composition of these habitats varies according to physical, biological and anthropogenic factors and may be highly variable in time and space.

Saltwater wetlands provide habitat for a number of vertebrate and invertebrate species from terrestrial, marine and freshwater environments. Some species may be restricted to a specific habitat type, while others may occupy a wider range of habitats.

Mangrove forest, saltmarsh and swamp forest, Evans River (DECC)

11.2 Mudflats

Environment

Mud and sand flats are the most common habitat type occurring in estuaries. Despite the lack of obvious vegetation, they are productive and support a number of important communities. In particular, diverse and abundant burrowing fauna use mudflats, and in turn support large populations of wading birds. The benthic community provides a significant food source for many fish species (for example, flathead, flounder and whiting).

The intertidal areas of this habitat can support a variety of algae and cyanobacteria, which can underpin estuarine food webs. The top layer of mud can be stabilised by a fine layer of microscopic algae and cyanobacteria. Non-photosynthetic bacteria are also very important to the structure and function of a mudflat. Tidal range, storm frequency and the quantity of material imported from other habitats are often considered the major external influences on mudflats. The finer grains of mud accumulate in sheltered parts of estuaries where there is reduced wave action. The activity of animals complicates this structure, but a mudflat is usually layered into distinct zones based on microbial activity and oxygenation.

Macroalgae

Macroalgal species richness and biomass can be high in estuaries that have a prolonged marine phase and abundant rocky substrata for attachment. Two locations with these characteristics – Port Phillip Bay, Victoria, and Moreton Bay, Queensland – report 404 and 275 macroalgal species respectively (Phillips 1998). Many of these species are components of complex, stratified macroalgal communities, including the kelp communities in Port Phillip Bay and the *Sargassum* and *Cystoseira* communities in Moreton Bay. In contrast, fewer macroalgal species are found on unvegetated mud and sand flats, where the only firm substrates for the macroalgae are pebbles and shells.

Relatively few macroalgal species can tolerate the hyposaline or hypersaline waters of an estuary, but these species often attain high biomass in these systems. Macroalgal species able to live in waters with a wide range of salinities (called **euryhaline** species) include species of the green algal genera *Ulva*, *Enteromorpha*, *Chaetomorpha*, *Rhizoclonium*, *Cladophora* and *Lamprothamnium*, the brown algal genus *Ectocarpus* and the red algal genera *Gracilaria*, *Polysiphonia* and *Chondria*. Euryhaline macroalgae are often key species in the open waters of the estuary, in saltmarsh pools and in coastal lagoons, often driving primary production and nutrient dynamics, as well as being responsible for macroalgal blooms.

Macroalgae (left and centre) and seagrass (right of photograph) (DECC)

Microalgae

On many intertidal sand and mud flats, as well as on the sediments in saltmarsh and seagrass communities, there often exists on the surface and in the top 4 cm of the sediment a complex community of bottom-dwelling microalgae and cyanobacteria called the microphytobenthos. This assemblage is usually composed of microscopic benthic diatoms and sometimes cyanobacteria, the diatoms at times becoming so abundant as to be visible as brownish or greenish shading on the mud surface. The microphytobenthos can develop either as microbial mats or as **biofilms** (Yallop *et al.* 1994). The mucopolysaccharide produced by the microphytobenthos traps and binds the sediment particles, promoting mud accretion and leading to the stabilisation of the sediment. Primary production of the microphytobenthos may be significant, often exceeding that of phytoplankton and macroalgae, and contributing up to one-third of the total primary production in some estuarine systems.

Fauna

Not many animals are visible moving about on the surface of the mud during low tide except for feeding birds. On some mudflats large numbers of soldier crabs (*Myctris longicarpus*) can be seen moving across the mudflat. These crabs climb out of their burrows to feed at low tide on fine organic material trapped in the mud. The crabs sort through the mud, eating the edible portions and compacting the remaining mud into small pellets. These pellets are scattered across the flats and are often the only evidence of crab activity. Soldier crabs are a favourite food for many bird species on the mudflat.

Snails are often visible feeding on the surface of the mud. The mud whelk (*Pyrazus ebeninus*) is a large (up to 10 cm), conspicuous spiral-shelled inhabitant of many mudflats. It feeds on bacteria and microscopic algae in the sediment. A similar but much smaller (approximately 3 cm long) whelk (*Velacumantus australis*) is also common. Occasionally, mudflats can have clusters of oysters (*Saccostrea glomerata* or *Crassostrea gigas*) lying on the mud surface.

Whelks and algae on the surface of a mudflat (DECC)

Snails on the surface of a mudflat (Adam Gosling WetlandCare Australia)

Most of the fauna is found within the mud, and generally most of the evidence of animals comes in the form of holes, burrows, mounds and trails.

Yabbies (*Callianassa australiensis*) are common on mudflats. This elongated prawn-like animal is not often seen, as it remains in its burrow. It is a favourite with bait collectors at low tide. A variety of worms live within the mud, most of which are small and nondescript and require considerable expertise to identify. Some larger worms such as the lugworm (*Arenicola bombayensis*) can be identified by piles of earthworm-like casts that surround the tail end of their U-shaped burrow. The active bright green polychaete worm *Phyllodoce* sp. is easy to spot moving over and feeding on mudflats.

Bivalves lie hidden beneath the mud and may include the large (up to 20 cm long) razor clams (*Pina bicolor*). These large clams orientate themselves vertically within the sediment with the razor-like edge of the shell just below the surface, posing a hazard for people walking on the mudflat. Other, smaller bivalves also inhabit mudflat sediments.

The densities of animals on mudflats can be greatly reduced by extreme low tides combined with very hot conditions. In addition, excessive freshwater input can kill burrowing fauna.

A variety of wading birds can generally be spotted feeding on mudflats. Indeed, most waders have a strong preference for estuaries with expanses of intertidal flats. Within any given estuary, the number of waders is generally determined by the total area of intertidal flat available for feeding and the presence of suitable sites for high tide roosts. These birds come in a variety of sizes and beak shapes that are variously adapted to probing the sediment. Long curved beaks are suited to removing invertebrates that burrow deeply. Smaller beaks can extract those closer to the surface. At certain times of the year, mudflats are important for thousands of migratory waders. Spring and summer are peak times for spotting feeding waders.

A good supply of food on the mudflats is essential for these birds so they can survive their journey north in the winter. These migratory birds are protected under agreements with Japan (**JAMBA**), China (**CAMBA**) and the Republic of Korea (**RoKAMBA**).

11.3 Seagrass

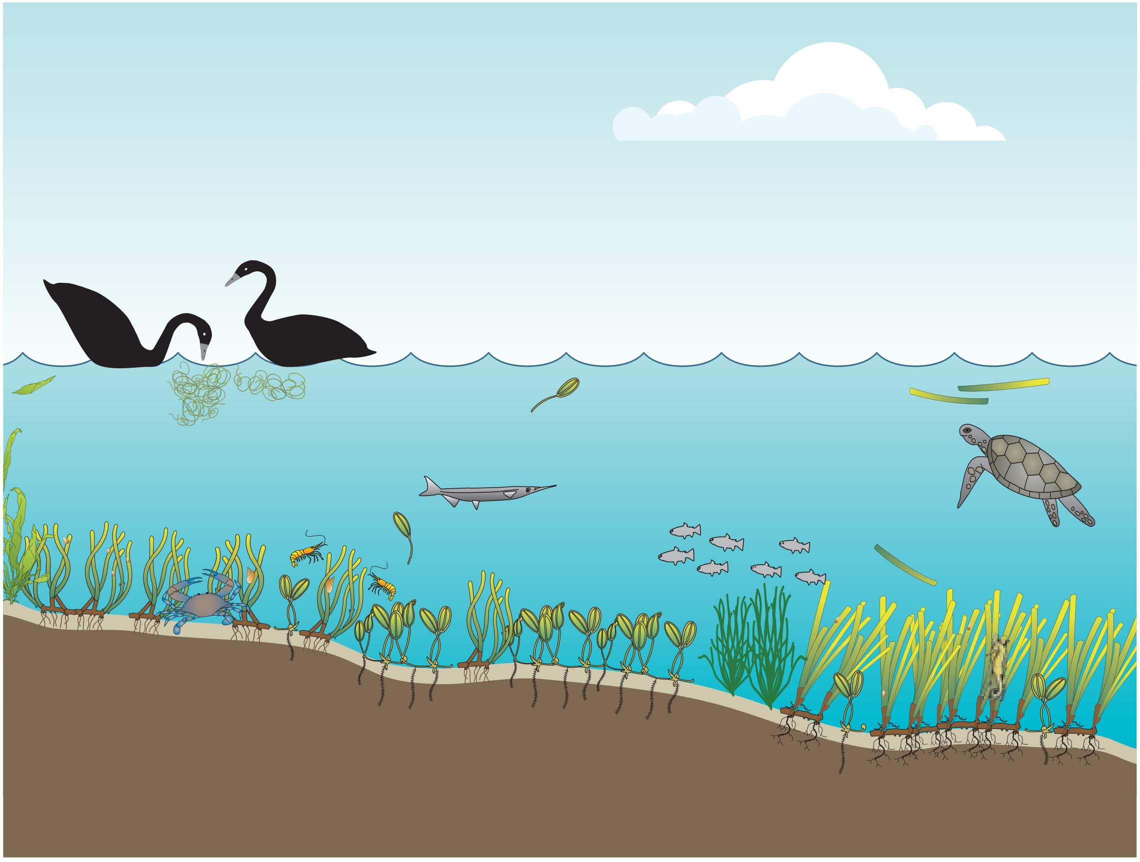
Environment

Several physical determinants affect the location of seagrasses. The most important are depth, water clarity and water movement. Water depth and clarity interact together determine light penetration to the seabed. Some seagrasses can survive with little light (for example, *Halophila ovalis*) and can be found in estuaries that are more turbid, while others are restricted to shallow sunlit sediments. Soft sandy or muddy sediment is a requirement for seagrass establishment. Seagrasses have well-developed rhizomes that run along the seabed from which arise roots adapted to penetrating soft sediment (Figure 11.1, overleaf).

Physical disturbance to the seabed is important in the establishment and maintenance of seagrass beds. Seagrass beds cannot survive in areas with too much wave action and

Seagrass exposed at low tide (Adam Gosling, WetlandCare Australia) consequently are most prevalent in estuaries and bays. Turbulent water dislodges seagrass and limits its ability to survive. Seagrass can be torn out during storms or heavy current flow. Changes to the currents within an estuary can have adverse effects.

Figure 11.1 Seagrass community



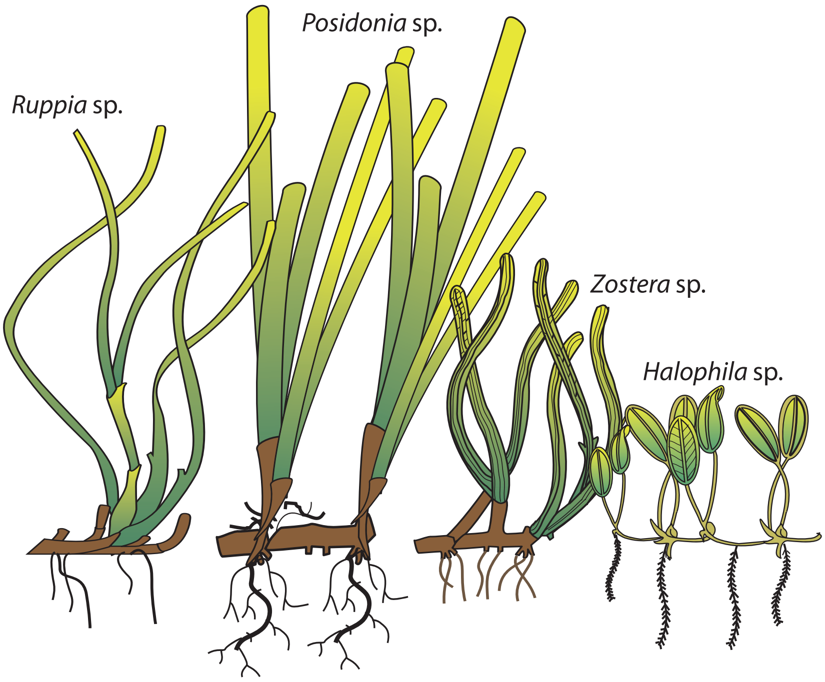
Flora

Seagrasses are flowering plants that have become adapted to living submerged in a marine environment. In common with land grasses, seagrasses possess leaves, veins and roots, grow from the base of the leaves, and reproduce via seeds and flowers. Flowers and seeds are, however, small, seasonal and difficult to see in most species. In the absence of birds and insects as pollinators, seagrasses have evolved different strategies for transferring pollen. In general, seagrass pollen is denser than water and sinks. *Posidonia* takes advantage of water currents by releasing pollen from floral spikes held high above the sea floor so that it is dispersed widely.

Identification of individual seagrasses relies mostly on leaf, root and rhizome characteristics. About 60 species of seagrasses are known worldwide, of which one-third are restricted to southern Australia. Seagrasses can usually be recognised by their colour and dense beds. Seagrass beds are extremely productive, as their leaves grow and shed continuously. These can accumulate as banks of debris or wrack up to 2 m high along some shores.

Although there are many species of seagrass, they generally fall into one of the four morphologies shown in Figure 11.2. The most common seagrass species in NSW are presented in Table 11.1 (overleaf).

Figure 11.2 Typical morphology of the seagrasses



Ruppia sp. seagrass (DECC)

Posidonia sp. seagrass (DECC)

Zostera sp. seagrass (DECC)

Halophila sp. seagrass (DECC)

Table 11.1 Seagrasses found in NSW

Common name (botanical name)	Identifying features	NSW range
Eelgrass (*Zostera capricorni*)	The most common and tolerant of the seagrasses. It can display a variety of morphological characteristics, from very short, narrow leaves to long, wide leaves, depending on environmental conditions. It can be found growing on sand or mud in sheltered areas. Its tolerance to exposure at low tide means it can be found from 0 to 7 m, depending on light penetration. The tips of the leaves are blunt, and 4 or 5 longitudinal veins run through the leaves. Shoots consist of bundles of 4 to 6 leaves. Variations in colour are common, from shades of green to brown.	Throughout NSW
Eelgrass (*Zostera tasmanica*)	This species occurs in shallow coastal water from below low tide level to a depth of approximately 8 m. Leaf blades are generally long and thin with a rounded apex or tip, which is usually deeply notched. The tip may also have fine denticulations. Leaves occur in bundles of 2 to 6 per shoot, measure 200–250 mm long and have 3 longitudinal veins.	Southern NSW from Jervis Bay to the Victorian border
Strapweed (*Posidonia australis*)	This species can tolerate extremes of temperature and salinity but is sensitive to changes in water clarity. It is a long-lived species but is not tolerant of disturbances, being slow to recover. Recruitment occurs only under very favourable, calm conditions. This species is quite distinctive in that is has large, fibrous leaf bases that are contained wholly within the sediment. The leaves are thick and stiff with a width of approximately 20 mm. Groups of 3 to 5 leaves arise from the fibrous bases and can reach a length of 450 mm. Colour varies from bright green to brownish, especially in older sections of leaf.	Southern NSW from Wallis Lake on the mid North Coast to the Victorian border
Paddle weed (*Halophila ovalis*)	*Halophila ovalis* has small, smooth leaves with a length not exceeding 40 mm. The leaves are more or less perfectly oval with a length-to-width ratio of 2:1. The leaves have 10 to 12 relatively straight cross-veins off a central vein. *H. ovalis* can be found in sheltered to moderately exposed areas in shallow water that can range from clear to quite turbid. Typically found in the spaces between other seagrasses, although it can form monospecific beds.	Throughout NSW
Paddle weed (*Halophila australis*)	A small seagrass occurring in temperate waters on sand and mud. Prefers calm water and can be found from low tide level to 23 m depth depending on water clarity. It is characterised by upright, elongated, oval leaves emerging in pairs from runners. Leaves are usually 50–60 mm long and 6–15 mm wide and are narrowed towards the base.	Southern NSW from the Central Coast to the Victorian border

Common name (botanical name)	Identifying features	NSW range
Sea tassel (*Ruppia megacarpa*)	This species can tolerate a range of conditions from fresh through to hypersaline and from clear to turbid water. Often occurs in mixed beds with *Zostera* sp. The leaf blades are narrow (0.5–2 mm) with an indented tip. Leaves are generally dark green and can reach lengths of 50–200 mm. Stems can reach 2 m in length but are generally 200–300 mm.	Throughout NSW

Associated algae

In estuaries, microalgae – mainly diatoms – and the more conspicuous macroalgae commonly grow as epiphytes on seagrass leaves and stems. Algal epiphytes are natural and highly productive components of seagrass communities. The diversity of algal species which grow as seagrass epiphytes is usually high. Epiphytes include approximately 60 species of diatoms and species of the cyanobacterial genera *Oscillatoria*, *Anabaena*, *Nostoc*, *Synechococcus*, *Microcoleus* and *Gleocapsa*, the brown algal genus *Ectocarpus*, the red algal genera *Polysiphonia* and *Ceramium*, and the green algal genera *Enteromorpha*, *Chaetomorpha* and *Cladophora*. The diatoms *Grammatophora marina*, *Melosira moniliformis* and *Pleurosigma angulatum* are the dominant species on seagrass leaves.

Fauna

Tropical seagrass beds support larger, more spectacular fauna than their temperate counterparts. Swans, garfish and leatherjackets are the main vertebrate grazers of temperate seagrass. Dugongs and turtles graze directly on tropical seagrass. Dugongs are occasional visitors to NSW estuaries, having been recorded as far south as the NSW Central Coast (Allen *et al*. 2004).

The complex seagrass environment provides habitat for a variety of invertebrates, such as amphipods, isopods and crabs, which form a major food source for other species, notably many species of fish. Numerous juveniles of fish, squid, prawns and crabs use seagrass habitats as a nursery. Filter feeders such as bivalves, sponges and ascidians can be found among seagrass fronds taking advantage of the baffling effect of seagrass leaves in trapping detrital food particles.

The epiphytic algae on seagrass leaves also attract a myriad of gastropods, crustaceans and polychaete worms, most of which graze on the algae. The majority of fish, prawns and crabs that live in seagrass beds feed on the abundant invertebrate grazers found in this habitat. Some species of fish, such as the pipefish, make seagrass their permanent home, and are superbly adapted to blend in with the environment so as to avoid predation.

Dialogue Box 11.1 Invasive marine alga *Caulerpa taxifolia*

The macroalgal species *Caulerpa taxifolia* resembles seagrass. Erect leaf-like fronds develop from a creeping stem-like structure called a stolon, which allows the alga to grow in mud and sand.

C. taxifolia has been widely used in the aquarium trade as an ornamental plant, as it grows vigorously, is easily propagated, tolerates environmental fluctuations and contains chemicals which deter herbivores. It is thought to have established in the wild by escaping from aquaria. *C. taxifolia* is indigenous to tropical and subtropical seas worldwide, including Australia (Phillips and Price 2002), and has been introduced into the Mediterranean Sea, California and Japan. It has been eradicated from California and has failed to establish in Japan. Since 2000, *C. taxifolia* has established in 10 estuaries in NSW (DPI 2007), south of the former southern distribution limit of Southport in southern Queensland.

C. taxifolia is easily spread by the transportation of fragments. Even the smallest fragment can grow into a new plant. Anchors, anchor chains, boat propellers and even divers are common means of transportation to new sites, where it will colonise any bare substrate.

11.4 Mangroves

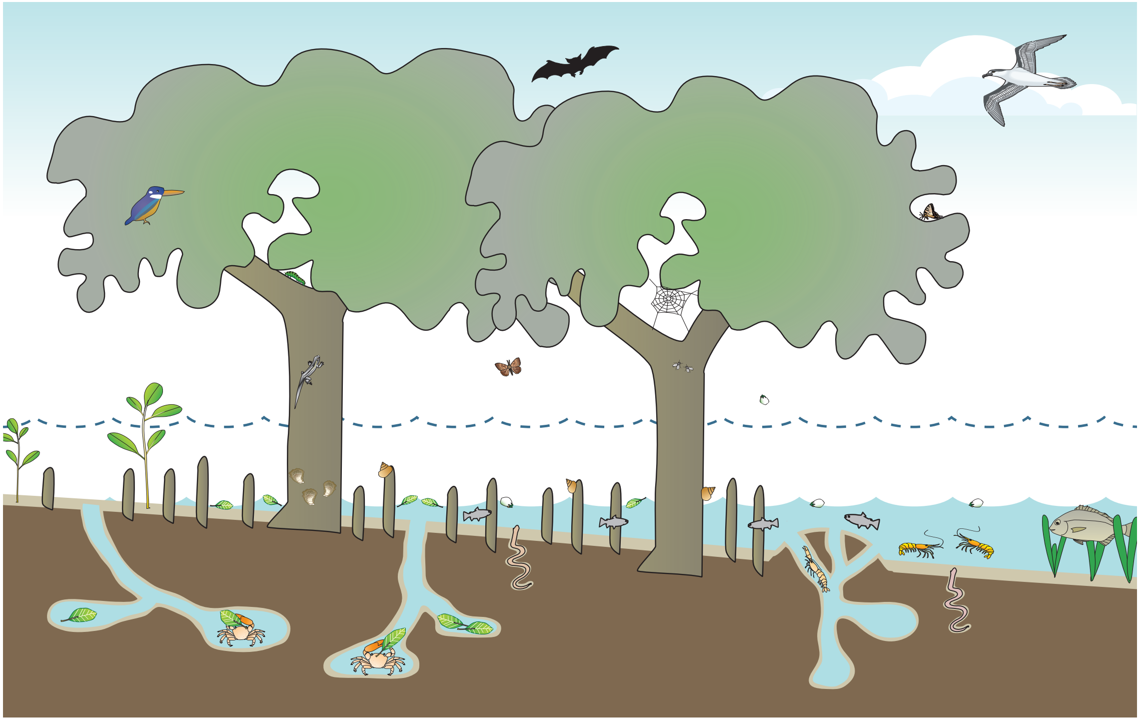
Environment

The term 'mangrove' can refer to both the individual tree and the whole forest. Mangrove communities can consist of many genera and species of plants or be monospecific. Mangroves are characteristic of sheltered tropical and subtropical coastlines. Given suitable conditions for growth, mangrove propagules colonise new areas and establish rapidly. In more tropical locations, species richness is higher and, depending on the environmental tolerances of the species within the community, distinct zonation can occur. Conversely, in more temperate locations, one or two species are common in association with saltmarsh (Figures 11.3 and 11.4, overleaf).

Mangroves are able to grow on a variety of substrata (for example, sand, peat, coral), but they are generally associated with mud. Once established, mangroves trap more muddy sediments transported by tidal water. Some degree of protection from wave action is necessary for successful mangrove establishment. Hence, mangroves are prevalent in bays, lagoons, estuaries and shores behind barrier islands.

Most mangroves grow in salt water, but not all require salt for growth. Genera such as *Rhizophora* and *Ceriops* have been shown to grow poorly in the absence of salt (Chapman 1977), but other species do well without salt. It is argued that the importance of salt to mangroves lies in a competitive advantage: other species are eliminated in saltwater environments, where the slow-growing mangroves are able to grow well. Therefore, salt is an essential requirement for mangrove development. Tidal range is important in determining the extent of mangrove forest. The greater the vertical range of tidal influence, the greater the space for mangrove community development.

Figure 11.3 Mangrove community



Although detailed information on the individual requirements for all the mangrove species is lacking, it is safe to say that if certain conditions prevail (for example, protected shoreline with muddy substrate and suitable tidal range), then a mangrove community is likely to develop, provided propagules are available within the area.

Flora

Mangrove plants share common morphological, physiological and reproductive adaptations that make them suited to their environment. On the basis of the possession of these adaptations, approximately 80 species belonging to about 30 genera in over 20 families are recognised worldwide as mangroves.

Although salt tolerance is essential, few species actually require salt for their cellular processes. Adaptation to some salt in their cells, however, gives mangroves a powerful competitive advantage over salt-intolerant species. Seedlings may, however, require some level of salt for successful establishment (Ungar 1991).

Anchorage may be a problem for mangroves in soft sediments. This is partly overcome by buttress or prop roots, but invariably all mangrove species develop an extensive spreading cable root system with numerous shortly descending roots. The root system is always shallow owing to chronic lack of oxygen at lower depths. Species such as *Avicennia marina* also develop spongy vertical root projections called pneumatophores, which draw air down into the roots. On account of the substrate conditions and the root adaptations, mangroves have a relatively large proportion of their mass above ground.

Stilted mangrove (Adam Gosling, WetlandCare Australia)

On the NSW coast, mangrove species meet their global southern climatic limit. Of 125 estuaries surveyed in NSW, 63 have mangroves, totalling 85.1 km^2 (Williams *et al.* 2006). Only one species, the grey mangrove (*Avicennia marina*), persists south of Merimbula Lake on the South Coast (36°50'S). Along most of the coast, only the grey mangrove and the river mangrove (*Aegiceras corniculatum*) are found extensively. The river mangrove appears more tolerant of a wider range of salinity and is found further upstream in estuaries than the grey mangrove. In addition, being a much smaller tree, the river mangrove is often found as inland fringing vegetation surrounding the grey mangrove stands that line the estuary shores. Three other species common to the tropics occur sporadically in North Coast estuaries. These are the milky mangrove (*Excoecaria agallocha*) north of Coffs Harbour, the red or stilted mangrove (*Rhizophora stylosa*) reported north of South West Rocks Creek, and the large-leaved or orange mangrove (*Bruguiera gymnorrhiza*) north of Wooli. The Tweed River estuary is the only location in NSW where all five species of mangrove are found. Mangrove species are summarised in Table 11.2 (overleaf).

Epiphytic algae

In mangrove communities, epiphytic (attached) macroalgae grow as a turf-like covering on the base of the tree trunks and on the pneumatophores, particularly on the pneumatophores that grow under the mangrove canopy and relatively close to the tree trunk. Species of the red algal genera *Bostrychia*, *Caloglossa* and *Catenella* are common and abundant mangrove epiphytes. These genera comprise the *Bostrychia–Caloglossa* association, which tends to be restricted in ecological distribution to mangrove communities worldwide. Some mangrove epiphytic species such as *Catenella nipae* also grow on rocks in estuaries and marine habitats. In NSW, 15 species of red algae, 6 species of brown algae and 11 species of green algae occur as mangrove epiphytes, with *Caloglossa leprieurii* being the most abundant species and *Catenella nipae* the most widespread (King and Wheeler 1985). Species composition and abundance of mangrove epiphytes varies at different localities and at different levels of the shore within a locality.

Figure 11.4 Typical species diversity and location of mangrove species around Australia (tropical areas have greater species diversity and zonation than temperate areas).

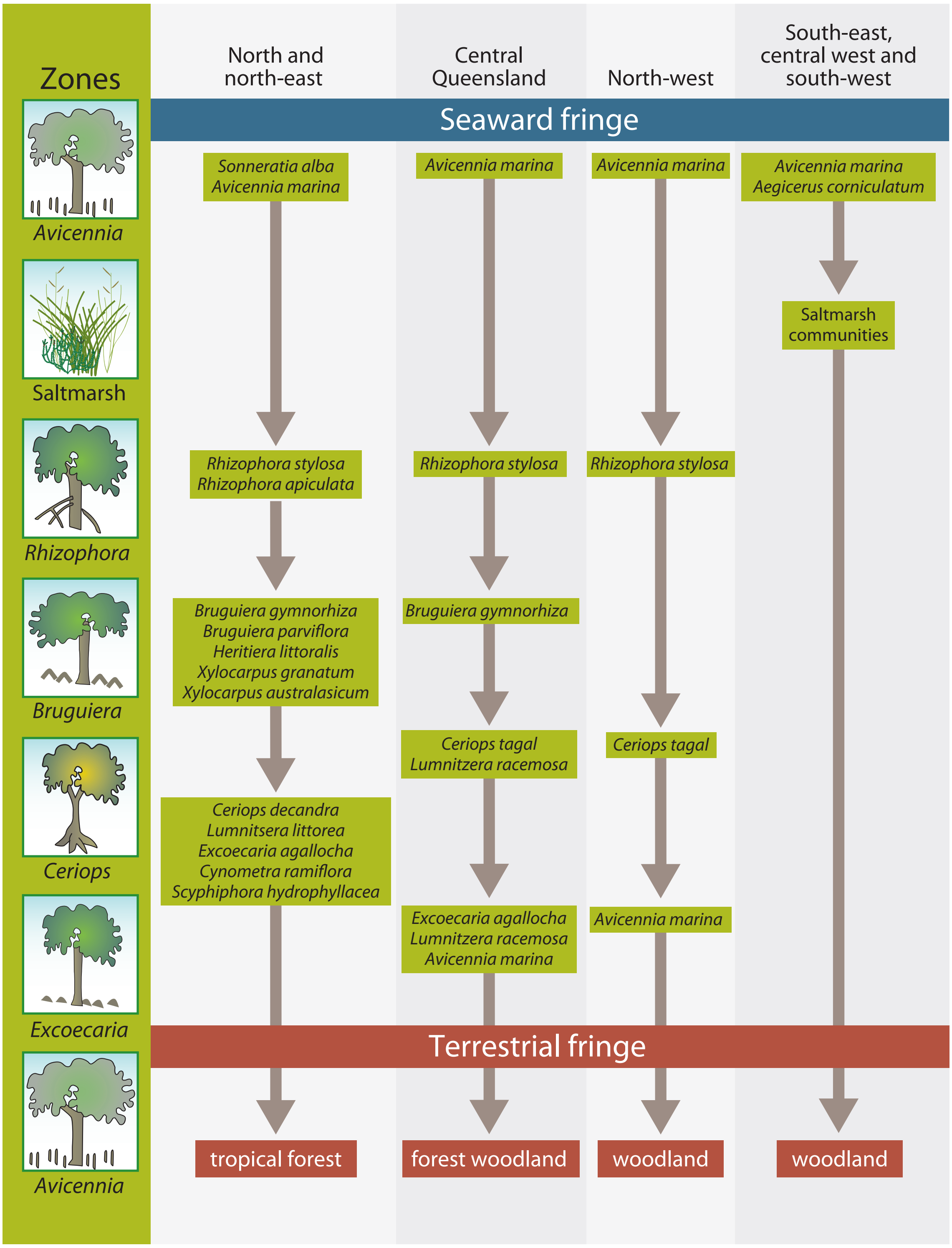


Table 11.2 NSW mangrove species

Common name (botanical name)	Identifying features	NSW range
Grey mangrove (*Avicennia marina*)	Large tree (generally up to 10 m, but in northern latitudes can exceed this) with light green leaves with silvery-grey undersurface. This species produces numerous peg roots at the base of the tree trunk. Small, pale orange flowers give way to almond-shaped fruit, which are green and slightly furry. The bark is grey-white and smooth, though often flaky. Grey mangroves are found on the seaward edge.	Throughout NSW
River mangrove (*Aegiceras corniculatum*)	This species is a shrub that generally grows in association with the grey mangrove as an understorey. There are no obvious above-ground roots, and it can form dense thickets. Small white flowers are arranged in bunches. The fruits are the thickness of a pencil and slightly curved with a pointed tip. Fruits start out green and ripen to red in summer.	Tweed River to Merimbula Lake
Milky mangrove (*Excoecaria agallocha*)	This species is usually found just above the high tide mark, and is distinctive in having milky white sap. There are no above-ground roots. Leaves are 60–100 mm long and are arranged alternately up the stem. Flowers are small and green and arise at the point where leaves are attached to the stem.	Tweed River to Manning River
Red or stilted mangrove (*Rhizophora stylosa*)	This is generally a subtropical to tropical species that occurs in the lower intertidal zone where roots are submerged during high tide. The aerial prop roots are distinctive for this species and link to form impenetrable barriers. The leaves have a lighter green undersurface covered with brown speckles. Small white flowers give way to tapered propagules that are 10–20 mm in diameter and 200–400 mm long.	Tweed River to South West Rocks Creek
Large-leaved or orange mangrove (*Bruguiera gymnorrhiza*)	This species typically occurs in areas that have some freshwater input. It has large buttresses at the base of the trunk and knee-shaped aerial roots. The large leaves grow in clumps at the end of the branches. Flowers are red and remain attached to the green cigar-shaped propagules, which are 100–200 mm long.	Tweed River to Clarence River

Unattached macroalgae

Unattached macroalgae, which originate from hard substrata either outside or within the estuary, are often found in estuarine environments. Species of the green algal genus *Codium* and the brown algal genera *Sargassum* and *Colpomenia* usually survive for only a short time after being washed into NSW estuaries from nearby marine habitats. However, the marine brown alga *Hormosira banksii* and a species of the red algal genus Gracilaria form permanent free-floating populations trapped around pneumatophores in mangrove communities (King 1981). The mangrove form of *H. banksii* has a very limited geographical distribution in NSW, reported as occurring in abundance only in southern Botany Bay and in Carama Inlet, Jervis Bay. Large masses of drifting macroalgae can accumulate in some estuaries and embayments, such as the drifting *Gracilaria* sp., which covered 3 km^2 of the sea floor in Jervis Bay at depths of 12 m (Langtry and Jacoby 1996). Large masses of unattached macroalgae can increase habitat complexity by providing a refuge for small fish and invertebrates, and represent a valuable nutrient source, particularly if imported into the estuary system from the adjacent ocean.

Fauna

The fauna of mangroves can be classified as either marine intertidal or terrestrial. Terrestrial fauna are restricted largely to the forest canopy, while marine fauna are found in and on the substrata or come and go with the tide. The terrestrial fauna present will be influenced by bordering vegetation communities.

Mammals are rare in mangroves, but species that have been known to visit include water rats (*Hydromys chrysogaster*), house mice (*Mus musculus*), canefield rats (*Rattus sordidus*), tree rats (*Mesembriomys* sp.), long-nosed bandicoots (*Perameles* sp.), short-nosed bandicoots (*Isoodon* sp.), northern brush-tailed possums (*Trichosurus arnhemensis*) and swamp wallabies (*Wallabia bicolor*). In addition, two species of flying foxes (*Pteropus poliocephalus* and *P. alecto*) come to mangroves to feed on blossoms. Some species of tree-roosting bats, including the flat-headed mastiff bat (*Tadarida planiceps*) and little northern mastiff bat (*Tadarida loridae*), can also be found in mangroves.

Birds are a conspicuous component of all mangrove forests. Over 200 species have been recorded from Australian mangrove forests (Saenger *et al.* 1977). These range from small terrestrial birds feeding on insects to wading birds feeding off the muddy substrata or tidal water (for example, kingfishers, mangrove bitterns).

Sacred kingfisher (Chris Chafer)

Reptiles are rarely seen in temperate mangrove forests but are common in tropical ones. The few snakes and lizards which regularly occur in mangroves include the diamond python (*Morelia spilota*), the green tree snake (*Dendrelaphis punctulatus*) and the brown tree snake (*Boiga irregularis*) (Hutchings and Saenger 1987). The eastern water dragon, yellow-bellied sea snake and leathery turtle have also been recorded in NSW estuaries. Green turtles are known to eat mangrove propagules at high tide.

Insects are a common component of the terrestrial-based fauna of mangroves. The most notorious of the insects is the mosquito, of which several species inhabit mangrove forests. However, the insect fauna tends to be more diverse than just biting insects, with a variety from most orders being present. Spiders are also a common resident in mangroves, and include orb weavers, jumpers, comb-footed spiders, large-jawed spiders and ornate forms such as jewel and flower spiders. Insects and spiders are an important food source for other mangrove inhabitants.

Many mangrove areas provide nursery areas for fish, many of commercial significance. The varied root structure of mangrove forests provides protection from predators. Adult fish also feed in mangroves at high tide. Species such as gobies and toadfish are common throughout Australian mangroves.

Crab among mangrove pneumatophores (Kooragang Wetland Rehabilitation Project)

Aquatic invertebrates are abundant in mangroves and ranging from nematodes and protozoa to worms, snails and crabs. These can be mobile or sedentary. For example, barnacles are commonly found encrusting mangrove tree trunks where they filter feed when the tide is in, whereas crabs are mobile mostly at low tide, when they scavenge the sediment for food.

11.5 Saltmarsh

Environment and zonation

Saltmarshes are generally known as the expanses of vegetation found between the land and the shore, often in association with mangroves. Typically vegetated by low shrubs, herbs and grasses, they can range from narrow fringes on steep shorelines to nearly flat expanses several kilometres wide (Figure 11.5).

Saltmarsh plants grow to the highest tide levels, meaning that they are rarely inundated by the tide. Since the tide does not actually go in and out each day in most saltmarshes, evaporation causes the saltmarsh to become highly saline. An environment that is saltier than the sea can be a very harsh environment to survive in and requires particular adaptations.

Casuarina glauca trees often dominate the landward edge of saltmarshes, as they can tolerate some salt. Adjacent to them is usually a border of rushes (for example, *Juncus kraussii*).

Figure 11.5 Saltmarsh community

Any other species are usually a selection of smaller herbs. The middle marsh is then dominated by the more common species such as samphire (*Sarcocornia quinqueflora*) and salt couch (*Sporobolus virginicus*). Species such as arrow grass (*Triglochin striatum*) may grow if there is standing water present. At the seaward border the saltmarsh grades into mangroves, and edge-loving species such as seablite (*Suaeda australis*) grow.

Many saltmarshes, however, do not follow any particular stylised depiction. For example there are:

- saltmarshes that grow in the absence of mangroves and form the seaward edge
- saltmarshes that grow where there are no other obvious forms of vegetation such as terrestrial tree borders or mangroves
- areas where *J. kraussii* is not restricted to the terrestrial border
- saltmarshes growing in the middle of pasture land with no link to the tide, mangroves or other estuarine influences.

These exceptions require us to look a little deeper into the causes of zonation. At higher land elevations – and it may only be on the order of centimetres – particular species dominate at the expense of others. Generally, *J. kraussii* and *S. virginicus* favour the higher ground, where the tide is less frequent and they don't need to rely on tidal flushing to get rid of excess salt.

Lower elevations are generally inundated more frequently and therefore favour species that can tolerate inundation and salty water. These areas are usually dominated by the salt-tolerant succulent species that generally require more water to maintain their succulence and salt balance. It follows then that salinity also is very important in determining where certain species grow. Many of the saltmarsh species are actually salt avoiders and prefer a fair bit of fresh water. This means that many of them are not commonly found at the tidal interface. Species like *Centaurium* sp. and *Cotula coronopifolia* are annual and occur during the time of year where there is more fresh water around. Others just occupy the spaces within the saltmarsh that are less salty. In most cases a combination of factors leads to the patterns of vegetation that are present in naturally occurring saltmarshes.

Saltmarsh maturity is another factor that is very important in determining the way a saltmarsh looks. Saltmarshes develop on flat muddy areas that are initially inundated by the tide. During the initial stages of saltmarsh formation, the area is colonised by pioneer species. *S. quinqueflora* are pioneer plants, because they are the most tolerant to salt and inundation, and can exploit low-lying areas of bare ground. Once all the zonation factors have sorted themselves out, mature saltmarshes can take on a variety of forms depending on the local conditions. Depending on elevation, tidal inundation and salinity, a saltmarsh may appear as:

- an expanse of succulents dominated by *S. quinqueflora* with maybe a few other species present
- vast grasslands dominated by just *S. virginicus* or other grassy species
- a herb field dominated by *Samolus repens* or other herbs
- an area dominated by succulent bushes
- a meadow of rushes and sedges
- an explosion of buttons in winter.

Flora

Saltmarsh species generally fall into three broad categories based mainly on types of plants present and tolerances to salinity:

- shrubs and herbs that can tolerate hypersaline conditions, such as the small, colourful succulent species *S. quinqueflora* and *S. australis*
- sedge and rush swamps, usually found in the upper marsh fringe associated with brackish water conditions and dominated by rushes and sedges (for example, *J. kraussii*, *Baumea juncea* and *Cyperus laevigatus*)
- grassland areas, usually inundated less frequently and dominated by grasses such as *S. virginicus*, *Zoysia* sp. and *Distichlis* sp.

Over 200 saltmarsh species are recognised throughout Australia. Bridgewater *et al.* (1981) provide keys to the saltmarsh species found in southern Australia. Most belong to a small number of families, notably the Chenopodiaceae, Poaceae and Cyperaceae (Adam 1981), and most saltmarshes generally contain only four species on average.

Adam *et al.* (1988) described 25 saltmarsh communities within NSW, but there is debate as to whether marshes should be so highly divided or whether mid-marsh communities (dominated by a few species) should be regarded as a single heterogeneous community (Zedler *et al.* 1995). Bridgewater *et al.* (1981) give descriptions of 13 communities around Australia based on the dominant species present in each zone (high, middle, low marsh). However, in considering the ecology and function of a saltmarsh, it is beneficial to regard saltmarsh communities as groups of dominant species, especially since fluctuations in species between years (particularly rare and annual species) are common in Australian saltmarshes (Adam 1993).

The majority of the marshes found in temperate Australia can be considered as a single community complex dominated by one or a combination of *S. virginicus*, *S. quinqueflora*, *S. repens* and *T. striata*. A typical list of saltmarsh species in NSW appears in Table 11.3 (overleaf).

Herb dominated saltmarsh
(DECC)

Saltmarsh dominated by succulents
(DECC)

Sedge and rush swamp
(DECC)

Field of *Juncus kraussii*
(DECC)

Grass dominated saltmarsh
(DECC)

Fauna

Only four types of benthic fauna (fauna that live within the sediment) are known to live in saltmarshes: crabs, polychaete worms, a burrowing bivalve and oligochaete worms, all in very low numbers. This paucity is due to the harsh environment and the thick mat of saltmarsh roots that prevents soft-bodied worms from burrowing.

Crabs spend the majority of their time out of their burrows feeding, retreating to them only when the tide comes in. Four species of crab are common and conspicuous in saltmarshes: the semaphore crab (*Heloecius cordiformis*), the saltmarsh crab (*Sesarma erythrodactyla*), spotted shore crabs (*Paragrapsus laevis*) and the muddy shore crab (*Helograpsus haswellianus*). These crabs are not exclusive to saltmarsh and can be found in the mangroves as well. They feed on detritus that they scavenge at low tide.

Molluscs are the other conspicuous invertebrates in saltmarshes. Fourteen species of mollusc have been recorded in saltmarsh (and common in mangroves as well). *Salinator solida* and three species of *Ophicardelus* are particularly dominant in saltmarshes. These snails are pulmonates (like common garden snails), which means they have a lung instead of gills. This means they can survive for long periods of time with little or no tidal inundation, a perfect adaptation for a saltmarsh inhabitant.

Nevertheless, the crabs and snails are still essentially water creatures and still rely on water for reproduction. They time their spawning with the highest tides of the year. This means a large amount of eggs and larvae can leave the saltmarsh. This is a bonanza for fish which take advantage of the saltmarsh habitat when the tide covers the flats. Crab larvae are a particular favourite, as gut analyses of fish leaving saltmarsh have shown.

Migratory waders recognised under international agreements with China and Japan (for example, sharp tailed sandpiper, eastern curlew, golden plover and bar-tailed godwits) use saltmarshes for roosting and feeding. These birds like the wide open expanses that saltmarshes provide, as they like to be close to their mudflat feeding grounds but like to roost where there is an open view for predator spotting and lots of room for taking off and landing. Many terrestrial bird species also use the saltmarsh for feeding and nesting. Birds of prey (for example, brahminy kites, whistling kites and swamp harriers) are common over saltmarshes. Some birds feed on the saltmarsh seeds and vegetation (for example, galahs). In particular the critically endangered orange-bellied parrot (found in Tasmania, Victoria and South Australia, but previously recorded as far north as Sydney) feeds on saltmarsh seeds. Small insectivorous birds (sparrows and swallows) are common, and it is not unusual to find the nests of some ground-nesting species such as masked lapwings.

Bar-tailed godwits (Chris Chafer)

Table 11.3 NSW saltmarsh plant species

Common name (botanical name)	Marsh range	Description
Salt couch (*Sporobolus virginicus*)	Throughout marsh, often forming broad monospecific stands	A low-growing, fine-leaved couch grass with a single panicle
Samphire (*Sarcocornia quinqueflora*)	Throughout marsh but often the only species in lower marsh	A herb with succulent, leafless, jointed stems often tinged red
Seablite (*Suaeda australis*)	Often as individual plants or small patches in the *Sarcocornia* zone, but may be found throughout marsh	Small shrub with bright green succulent leaves
Streaked arrow grass (*Triglochin striatum*)	Throughout marsh, but primarily in lower marsh and wet depressions	Small tufts of narrow, dark-green, somewhat succulent leaves on rhizomes
Salt sedge (*Cyperus laevigatus*)	Upper marsh	Erect sedge to 600 mm with stiff stems and dense seed clusters
Button sedge (*Isolepis nodosus*)	Fresh to brackish upper marsh areas	Erect cylindrical-stemmed sedge to 700 mm with globular seed heads
Sea rush (*Juncus kraussii*)	In upper marsh often as dense stands or in more permanently flooded brackish situations	Greyish-brown, narrow-leaved spiky rush to 1.2 m occurring as tufts or dense stands
Creeping brookweed (*Samolus repens*)	Usually minor constituent from mid to upper marsh	White star flowers on vertical stems from rosettes of semi-succulent, oblong to lanceolate leaves spaced along creeping stolons
Saltwater couch (*Paspalum vaginatum*)	Upper marsh where freshwater inflows maintain lower salinity	Dark green couch grass with two equal spikes
Saltbush (*Atriplex australasica*)	Upper saltmarsh margins, spring to autumn	Broad-leaved annual herb up to 1 m high
Selliera (*Selliera radicans*)	Damp brackish upper marsh	A creeping herb with light green spoon-shaped leaves appearing singularly or as rosettes
Water buttons (*Cotula coronopifolia*)	Damp brackish upper marsh margins	Bright yellow button-flowered mat-forming herb
Creeping monkey-flower (*Mimulus repens*)	Wet edges of brackish ponds and damp ground	Small, mauve-flowered, mat-forming herb

Saltmarshes support a myriad of insect, spider and mite species. Most of the insect orders are represented and the diversity is high. Flies and wasps dominate the insect fauna, with bugs and beetles coming a close second. Unfortunately, saltmarsh also harbours the saltmarsh mosquito (*Ochlerotatus vigilax*).

Bats rely on the extremely rich insect fauna of saltmarsh plains. Eight species of bats have been identified as being active over saltmarsh: the eastern free-tail bat (*Mormopterus norfolkensis*), little free-tail bat (*Mormopterus* sp.), Gould's wattled bat (*Chalinolobus gouldii*), chocolate wattled bat (*Chalinolobus morio*), large bent-wing bat (*Miniopterus schreibersii*), large forest bat (*Vespadelus darlingtonii*), southern forest bat (*Vespadelus regulus*) and little forest bat (*Vespadelus vulturnus*). Other mammals that frequent saltmarsh areas are water rats (*Hydromys chrysogaster*), kangaroos and swamp wallabies. Kangaroos like to eat salty vegetation and enjoy grazing on salt couch meadows.

11.6 Swamp forest

Environment

The species composition of a swamp forest can vary considerably, but will be determined primarily by the frequency and duration of waterlogging and the texture, salinity, nutrient content and moisture content of the soil. Composition also varies with latitude. The community will also be influenced by the size of the site and by its disturbance history (including fire, grazing, flooding and land clearing). Therefore, the number and relative abundance of species will change with time since fire, flooding or significant rainfall, and may also change in response to changes in grazing regimes. At any one time, above-ground individuals of some species may be absent, but the species may still be represented below ground in the soil seed bank or as bulbs, corms, rhizomes, rootstocks or lignotubers.

The distribution of the various communities referred to as swamp forest (including Swamp Oak Floodplain Forest and Swamp Sclerophyll Forest) has diminished owing to the filling and draining of floodplains for various uses.

Flora

Flora found in swamp forest can vary from site to site. A number of distinct types of swamp forest are recognized. The swamp forest is generally made up of a number of strata, notably trees, understorey and groundcover. The dominance of each stratum may vary considerably. Where soils are more saline, the ground layer may contain saltmarsh species.

As the name suggest, the dominant tree species in the Swamp Oak Floodplain Forest north of Bermagui is the swamp oak (*Casuarina glauca*), yet *Melaleuca ericifolia* is the only abundant tree in this community south of Bermagui. In the Swamp Sclerophyll Forest, the most widespread and abundant trees include swamp mahogany (*Eucalyptus robusta*), paperbark (*Melaleuca quinquenervia*) and, south from Sydney, bangalay (*Eucalyptus botryoides*) and woollybutt (*Eucalyptus longifolia*). Indicative species for Swamp Oak Floodplain Forest and Swamp Sclerophyll Forest are listed in Table 11.4 (overleaf).

Swamp Oak Floodplain Forest and Swamp Sclerophyll Forest on coastal floodplains of the NSW North Coast, Sydney Basin and South East Corner bioregions are listed as endangered ecological communities. Extensive species lists are available from DECC at www.environment.nsw.gov.au/threatspec/index.htm.

Swamp forest fringing Back Lake (DECC)

Fauna

Fauna using the various types of swamp forest vary. Swamp Sclerophyll Forest provides habitat for a broad range of animals. The blossoms of *Eucalyptus robusta* and *Melaleuca quinquenervia* are an important food source for the grey-headed flying fox (*Pteropus poliocephalus*), common blossom bat (*Sycoyncteris australis*), yellow-bellied glider (*Petaurus australis*), sugar glider (*Petaurus breviceps*), regent honeyeater (*Xanthomyza phrygia*) and swift parrot (*Lathamus discolor*). Other animals found in this community include the osprey (*Pandion haliaetus*), Australasian bittern (*Botaurus poiciloptilus*), large-footed myotis (*Myotis adversus*), *Litoria olongburensis* and Wallum froglet (*Crinia tinnula*) (NSW Scientific Committee 2005a).

Unlike most other coastal floodplain communities, Swamp Oak Floodplain Forest is not a significant habitat for waterbirds (NSW Scientific Committee 2005b). However, it does sometimes provide food resources for the glossy black cockatoo (*Calyptorhynchus lathami lathami*) and yellow-tailed black cockatoo (*Calyptorhynchus funereus*). The fauna of Swamp Oak Floodplain Forest also includes the squirrel glider (*Petaurus norfolcensis*) and several species of frogs in the families Myobatrachidae (southern frogs) and Hylidae (tree frogs).

Spider living on a *Casuarina* sp. tree (Kooragang Wetland Rehabilitation Project)

Table 11.4 Species often found in NSW swamp forest (NSW Scientific Committee 2005a and 2005b)

Stratum	Swamp Oak Floodplain Forest	Swamp Sclerophyll Forest
Trees	*Casuarina glauca* (swamp oak) (north of Bermagui) *Melaleuca ericifolia* (south of Bermagui) *Acmena smithii* (lillypilly) *Glochidion* spp. (cheese trees) *Melaleuca* spp. (paperbarks)	*Eucalyptus robusta* (swamp mahogany) *Melaleuca quinquenervia* (north of Sydney) *Eucalyptus botryoides* (bangalay) (south of Sydney) *Eucalyptus longifolia* (woollybutt) (south of Sydney) *Lophostemon suaveolens* (north of Scotts Head) *Acacia irrorata* (green wattle) *Acmena smithii* (lillypilly) *Elaeocarpus reticulatus* (blueberry ash) *Glochidion ferdinandi* *M. linariifolia* *M. styphelioides* (north of Nowra)
Vines	*Parsonsia straminea* *Geitonoplesium cymosum* *Stephania japonica* var. *discolor*	Occasional presence *Parsonsia straminea* *Morinda jasminoides* *Stephania japonica* var. *discolor*
Shrubs	Often only sparse coverage	*Acacia longifolia* *Dodonaea triquetra* *Ficus coronata* *Leptospermum polygalifolium* subsp. *polygalifolium* *Melaleuca* spp.
Groundcover	Under less saline conditions *Centella asiatica* *Commelina cyanea* *Persicaria decipiens* *Carex appressa* *Gahnia clarkei* *Lomandra longifolia* *Hypolepis muelleri* Under more saline conditions *Alexfloydia repens* *Baumea juncea* *Juncus kraussii* *Phragmites australis* *Selliera radicans* Other saltmarsh species	*Gahnia clarkei* *Pteridium esculentum* *Hypolepis muelleri* *Calochlaena dubia* *Dianella caerulea* *Viola hederacea* *Lomandra longifolia* *Entolasia marginata* *Imperata cylindrica*

12 Relevant legislation and policy

12.1 Introduction

This chapter contains a review of relevant Commonwealth, NSW State and local government legislative and policy documents of relevance to saltwater wetland rehabilitation. It does not aim to be definitive on all legal matters pertaining to wetlands, but simply to provide a guide. It includes relevant legislation in force at the time of publication. However, legislation may change or be updated. Seek professional advice for any legal clarification or specific interpretation of the legislation.

School group using mangrove boardwalk (Kooragang Wetland Rehabilitation Project)

12.2 Commonwealth Government legislation

Commonwealth legislation that may be relevant in the rehabilitation of saltwater wetlands is listed in Chapter 3 (Tables 3.2 and 3.4) and detailed in the following sections.
All Commonwealth legislation is available online at the Attorney General's Department website: www.comlaw.gov.au.

The *Environment Protection and Biodiversity Conservation Act 1999*

The *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) protects the environment, particularly matters of national environmental significance. It streamlines the national environmental assessment and approvals process, protects Australian biodiversity, and integrates management of important natural and cultural places.

Under the environmental assessment provisions of the EPBC Act, actions that are likely to have a significant impact on a matter of national environmental significance are subject to a rigorous assessment and approval process. The Act identifies seven matters of national environmental significance:

- World Heritage properties
- National Heritage places
- wetlands of international importance (Ramsar wetlands)
- threatened species and ecological communities
- migratory species (listed under JAMBA, CAMBA, RoKAMBA or the Bonn Convention)
- Commonwealth marine areas
- nuclear actions (including uranium mining).

Further information on activities undertaken in Ramsar wetlands or wetlands supporting migratory species follows in Section 12.8.

The EPBC Act promotes the conservation of biodiversity by providing strong protection for threatened species and ecological communities, and migratory, marine and other protected species. It provides for identification of key threatening processes, protection of critical habitat, and the preparation of plans relating to conservation and wildlife management (including threat abatement plans, recovery plans and wildlife conservation plans).

The regent honeyeater is listed as threatened under the *Environment Protection and Biodiversity Conservation Act 1999* (Chris Chafer)

The *Australian Heritage Council Act 2003*

The Australian Heritage Council is the principal adviser to the Australian Government on heritage matters. The Council replaced the Australian Heritage Commission in 2003. The *Australian Heritage Council Act 2003* defines the constitution of the Council and its responsibilities. The Council administers the Register of the National Estate, which may be searched online at www.ahc.gov.au. Currently 28 coastal wetland areas are either registered or undergoing assessment for inclusion on the Register of the National Estate (Table 12.1).

Table 12.1 NSW coastal wetland areas listed on the Register of the National Estate

Coastal area	Location	Notes
NORTH COAST		
Arakoon State Recreation Area	South West Rocks	Includes Saltwater Lagoon and adjacent wetlands
*Broken Head Coastal Area	Broken Head	Includes Taylors Lake
Clybucca proposed nature reserve	Clybucca	Macleay River floodplain
Corrie Island	Tea Gardens	Island at the mouth of the Myall River
Harrington Inlet and Manning Point	Harrington	Littoral rainforest and mangrove islands at the entrance to the Manning River
Hunter Estuary Wetlands	Kooragang	Diversity of estuarine and freshwater wetlands within the Hunter River estuary
Limeburners Creek Nature Reserve	Port Macquarie	Includes mangrove communities
Port Stephens Estuary	Nelson Bay	Contains the largest area of mangroves and saltmarsh in NSW
Rileys Island and Pelican Island Nature Reserves	Woy Woy	Islands in Brisbane Water supporting mangrove, saltmarsh and swamp forest
*Tea Gardens Wetland	Tea Gardens	Mangrove area of the Myall River estuary
*Wallis Lake	Forster	Seagrass beds and intertidal wetlands
SYDNEY		
*Botany Swamps	Mascot	Botany and Lachlan swamps
Brays Bay Wetland	Concord West	Remnant wetlands of Parramatta River
Ermington Bay Wetlands	Ermington	Remnant wetlands of Parramatta River
Georges River Wetlands	Padstow Heights	Remnant wetlands of the Georges River between Milperra and Como

Coastal area	Location	Notes
Haslams Creek Wetlands	Homebush Bay	Remnant wetlands of Parramatta River
Homebush Bay Wetlands	Homebush Bay	Remnant wetlands of Parramatta River
Kurnell Peninsula and Towra Point	Kurnell	Diverse estuarine and wetland areas
Lower Duck River Wetlands	Rosehill	Remnant wetlands of Parramatta River
Majors Bay Wetlands	Concord	Remnant wetlands of Parramatta River
Mason Park Wetland	Homebush Bay	Remnant wetlands of Parramatta River
Meadowbank Park Foreshore Wetlands	Meadowbank	Remnant wetlands of Parramatta River
Towra Point Aquatic Reserve	Towra Point	Shallow bays and seagrass meadows
Voyager Point Wetlands	Voyager Point	Remnant wetlands of the Georges River
Yaralla Bay Wetlands	Concord West	Remnant wetlands of Parramatta River
SOUTH COAST		
Benandarah Area	Benandarah	Includes Durras, Meroo and Termeil lakes
*Bournda National Park	Tathra	Includes Wallagoot Lake
Narrawallee Inlet and Nature Reserve	Lake Conjola	Includes Narrawallee Creek estuary and Pattimores Lagoon

* Indicative listing only – assessment not yet completed

Dialogue Box 12.1 The precautionary principle

The precautionary principle is stated as an environmental principle within the Intergovernmental Agreement on the Environment 1992. This agreement aims to facilitate a cooperative approach to the environment between all three spheres of government: Federal, State and local. The precautionary principle has been included in the NSW *Fisheries Management Act 1994*, *Protection of the Environment Administration Act 1991*, and Environmental Planning and Assessment Regulation 2000.

It states:

> *Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation. In the application of the precautionary principle, public and private decisions should be guided by:*
> *(i) careful evaluation to avoid, wherever practicable, serious or irreversible damage to the environment*
> *(ii) an assessment of the risk-weighted consequences of various options.*

12.3 NSW Government legislation

NSW legislation that may be relevant in the rehabilitation of saltwater wetlands is listed in Chapter 3 (Tables 3.2 to 3.4) and detailed in the following sections. All legislation in force in NSW is available online at the Parliamentary Counsel website www.legislation.nsw.gov.au.

The *Environmental Planning and Assessment Act 1979*

The objective of the EP&A Act is to encourage proper management, development and conservation of natural and constructed resources. The EP&A Act is the primary legislation controlling development activity in the State, and is administered primarily by the Department of Planning. The Act outlines provisions for allowing development to take place in an environmentally and socially acceptable manner.

The planning framework established under the Act includes provision for:

- plan making (Part 3 of the EP&A Act) – includes EPIs developed by the Department of Planning and local councils, and development control plans and contributions plans prepared by local councils. Three types of EPIs exist:
  - state environmental planning policies (SEPPs), which address matters that are of State significance, such as coastal wetlands, and provide consistency in the development assessment framework
  - regional environmental planning policies (REPPs), which deal with regional issues such as transport planning and economic development thereby providing a framework for detailed local planning
  - local environmental plans (LEPs), which deal with local issues such as urban structure, urban design, heritage conservation, protection of environmentally sensitive land, and reservation of land for public purposes such as roads and open space.
- development assessment (Part 3A of the EP&A Act) – applicable to any development that is identified as a major project by the SEPP (Major Projects) or an order by the Minister for Planning. The consent authority is the Minister for Planning.
- development assessment (Part 4 of the EP&A Act) – most development proposals in NSW are considered by local councils or accredited certifiers. Types of development include:
  - local development, for most types of development proposals a development application (DA) will need to be lodged with the local council
  - complying development, includes development considered common or routine with a predictable and minor impact on the local environment. To carry out the development, you can obtain a complying development certificate from the council or an accredited certifier
  - integrated development, some proposals not only require development consent from the council, but also a permit or licence from a State Government agency. In such cases, the council will refer the application to the necessary agency
  - designated development, some types of development require scrutiny because of their nature or potential environmental impact. These are listed in Schedule 3 of the Environmental Planning and Assessment Regulation 2000. It includes industries that have a high potential to pollute, large-scale developments, and developments that are located near sensitive environmental areas, such as wetlands.

- environmental assessment (Part 5 of the EP&A Act) – establishes an environmental assessment system for certain activities that do not require development consent under Part 3A or Part 4 of the Act. These are often infrastructure proposals approved by local councils or State agencies which are undertaking them.

The *Local Government Act 1993*

The *Local Government Act 1993* defines the powers, duties and functions of all local councils in NSW. Under s. 68, the following approvals may need to be requested for wetland development:

- for building (including temporary structures)
- for the management of wastes
- for sewerage and stormwater drainage.

Before granting approval, the local council must take into consideration the requirements of relevant regulation, local planning instruments, the public interest, and matters for consideration listed in clause 12 of the Local Government (Approvals) Regulation 1993.

The *Coastal Protection Act 1979*

The *Coastal Protection Act 1979* contains provisions relating to the use and occupation of the coastal zone, the carrying out of coastal protection works, the preparation of coastal zone management plans, and certain ancillary matters relating to the coastal zone. The objects of the Act are to provide for the protection of the coastal environment of NSW for the benefit of both present and future generations.

Section 4A of the Act defines the coastal zone as the area bounded by:

- the 3 nautical mile seaward limit (from the mainland and offshore islands)
- 1 km landward from the open coast high water mark
- 1 km landward from all bays, estuaries, coastal lakes, lagoons and islands
- 1 km landward from the tidal waters of coastal rivers to the limit of mangroves or the tidal limit, whichever is closer to the sea.

However, in the case of the Sydney Metropolitan area (Pittwater to Sutherland), the landward component extends only as far as the limit of coastal processes.

The Act also provides for the preparation of coastal zone management plans (including estuary management plans and coastline management plans) by local councils, which may affect activities within or adjoining wetland areas.

The *Crown Lands Act 1989*

The *Crown Lands Act 1989* provides for the administration and management of Crown land, which includes most beaches, coastal reserves, near-shore waters and estuaries. The Act contains a number of principles for managing Crown land:

- Environmental protection principles are observed in the management and administration of Crown land.

- Natural resources of Crown land (including water, soil, flora, fauna and scenic quality) are conserved wherever possible.
- Public use and enjoyment of appropriate Crown land is to be encouraged.
- Multiple use of Crown land is to be encouraged where appropriate.
- Crown land should be used and managed so its resources are sustained in perpetuity where appropriate.
- Crown land is to be occupied, used, sold, leased, licensed or dealt with in the best interests of the State, consistent with the above principles.

Before significant decisions are made in regard to the allocation or use of Crown land, the *Crown Lands Act 1989* requires that a land assessment be undertaken. Assessment is a prerequisite where Crown land is to be reserved, dedicated, sold or leased, and is also required before the granting of any easements, licences or permits. The assessment involves carrying out an inventory of the physical characteristics of the land and determining the capability of the land to support various uses subject to prescribed criteria.

Under Part 7 of the Act it is an offence to clear, dig up or cultivate public land, or to erect fences without authority from the Department of Lands. Crown lands may also be subject to other requirements under the *Fisheries Management Act 1994* (s. 12.3.5) and the *Native Vegetation Act 2003* (s. 12.3.9). Contact your local office of the Department of Lands to determine what approvals will be required if you wish to restore a wetland or foreshore area that is Crown land.

The *Fisheries Management Act 1994*

The objectives of the *Fisheries Management Act 1994* are to conserve, develop and share the fisheries resources of NSW for the benefits of present and future generations, and in particular:

- to conserve fish stocks and protect key fish habitats
- to promote viable commercial fishing and aquaculture industries
- to promote high-quality recreational fishing opportunities
- to appropriately share fisheries resources among the users of those resources
- to promote ecologically sustainable development.

Under the *Fisheries Management Act 1994*, proponents of estuarine constructed wetland development must notify the DPI, which is responsible for the care and protection of fisheries. The removal, damage or destruction of any marine vegetation on public waters, aquaculture leases, or the foreshore of any land requires a permit from the Minister for Primary Industries. Marine vegetation is defined under s. 204 to include mangroves, seagrasses and any other marine vegetation as prescribed by regulations.

The DPI must be notified whenever a dam, weir, reservoir or any barrier to fish movement is constructed, altered or modified, and, if necessary, a fishway must be included in the plans. To assist in the protection of key fish habitats, the Act also provides for the Minister to make Habitat Protection Plans to protect habitat where it is critical for the survival of the species or is required to maintain harvestable populations.

The *Heritage Act 1977*

The *Heritage Act 1977* defines environmental heritage to include buildings, works, and relics of historic, scientific, cultural, social, archaeological, natural or aesthetic significance, as well as places such as natural landscapes. The Act is administered by the Heritage Office of NSW (part of the Department of Planning), which maintains the State Heritage Inventory and provides specialist advice to the community on heritage matters.

A permit from the Heritage Office is required to disturb or excavate land for the purpose of discovering, exposing or moving relics (deposits, objects or material evidence of non-Aboriginal settlement more than 50 years old) which are not already the subject of protection under the *Heritage Act 1977*. If necessary, during the planning of any restoration or construction project, seek the services of a heritage professional such as an archaeologist to advise you on how to design your wetland without affecting any heritage items. Without an adequate assessment of the site's significance by a qualified professional, the Heritage Office will not issue permits for damage or supervised destruction. It is the responsibility of the proponent to have the assessment undertaken.

If non-Aboriginal relics are found during excavation on land not previously identified as having heritage significance, consult the Heritage Office on how best to continue with the excavation.

The *Marine Parks Act 1997*

The *Marine Parks Act 1997* provides for the declaration of marine parks for the conservation of marine biology and marine habitats. It also regulates the activities that may be undertaken within a marine park; for example, the taking of animals, plants or materials from or into marine parks is prohibited. A development application under Part 4 of the EP&A Act must be submitted before any development is carried out within a marine park, and the concurrence of the Minister for Environment and Climate Change must also be obtained. DECC (Marine Parks Authority) must be consulted on any rehabilitation works in or adjacent to a marine park.

The *National Parks and Wildlife Act 1974*

Native mammals, birds, reptiles and amphibians are protected fauna under the *National Parks and Wildlife Act 1974* (NPW Act). It is an offence under the Act to take or kill any protected fauna without authority from DECC (formerly the National Parks and Wildlife Service).

Under the NPW Act, DECC also has a statutory responsibility for the care and protection of sites of Aboriginal heritage throughout NSW. The Act covers 'deposits, objects or material evidence' relating to 'indigenous and non-European habitation' in NSW, both before and after European settlement, excluding handicrafts made for sale (s. 5(1)). The following primary elements of the Act relate to Aboriginal heritage:

- Anyone who discovers a relic must report the discovery to the DECC within a reasonable time unless that person has reason to believe that the DECC already knows of its existence (s. 91).
- It is an offence to knowingly disturb, damage, deface or destroy an Aboriginal relic without the prior written consent of the Director General of DECC (s. 90).
- Sites of traditional or historical significance which do not necessarily contain material remains may be gazetted as Aboriginal Places and thereby be protected under the Act (s. 84).

Aboriginal heritage information can be found by consulting the Aboriginal Heritage Information Management System, which can be done by contacting DECC.

Aboriginal Heritage is also protected federally under the *Aboriginal and Torres Strait Islander Heritage Protection Act 1984* and the *Australian Heritage Commission Act 1975*, and may be listed on the *Register of the National Estate*.

The *Native Vegetation Act 2003*

The *Native Vegetation Act 2003* is the principal legislation controlling the management of native vegetation in rural areas of the State. Native vegetation includes trees, understorey plants, groundcover and plants occurring in a wetland, as long as the species existed in NSW before European settlement. However, mangroves, seagrasses and other types of marine vegetation are excluded as they are managed under the *Fisheries Management Act 1994*. The Act applies essentially to privately owned or leased rural land. Urban land, State Forests, National Parks and conservation reserves are excluded from the Act. The *Native Vegetation Act 2003* repeals and replaces the *Native Vegetation Conservation Act 1997.*

The clearing of native vegetation is subject to differing requirements depending on whether the vegetation is classified as remnant vegetation, protected regrowth or unprotected regrowth.

On account of to the complexity of the Act and the differing requirements for vegetation types and land classifications, we recommended that you seek advice from your local CMA before undertaking any clearing. Further information on the Government's new vegetation reforms and the preparation of property management plans may be found at www.nativevegetation.nsw.gov.au.

Dialogue Box 12.2 Property Vegetation Plans

Property Vegetation Plans (PVPs) are voluntary agreements between a landholder and the local CMA that allow the landholder to manage native vegetation on their land. They are an important mechanism for landholders to gain access to financial incentives offered by the Government for conservation on private land.

PVPs may address a range of issues, including:

- clearing of native vegetation
- identification of native vegetation as regrowth
- thinning of native vegetation
- continuation of existing farming or rural practices
- exclusion of certain types of clearing from 'permitted clearing'
- funding to protect and restore native vegetation
- other provisions prescribed by Native Vegetation Regulation 2005.

Clearing provisions contained in a PVP last up to 15 years, giving landholders security for farm planning and investment. Agreed-on management actions linked to offsets and incentives may continue for a longer period, including in perpetuity. Once a PVP has been approved it will also bind any future owners of the property to its conditions for the term of the plan.

CMAs use a computer-based decision support tool known as PVP Developer to assist them in developing PVPs and in assessing proposals for land clearing. PVP Developer uses high-resolution satellite imagery of properties and incorporates local data to objectively assess the impacts of clearing on water quality, soils, salinity and biodiversity. Contact your local CMA if you are interested in preparing a PVP.

The *Noxious Weeds Act 1993*

The *Noxious Weeds Act 1993* aims to reduce the negative impact of weeds on the economy, community and environment of NSW by:

- preventing the establishment of significant new weeds
- restricting the spread of existing significant weeds
- reducing the area of existing significant weeds
- monitoring and reporting on the effectiveness of weed management in NSW.

The DPI may declare noxious weeds species and is generally responsible for the control of noxious weeds within the State. The Act also gives local councils the responsibility for the control of weeds on public land within the council area, and requires landholders to control noxious weeds on private land. This includes the control of aquatic noxious weeds in creeks, rivers and water bodies (tidal or non-tidal).

It is an offence to scatter any mulch or plant material that contains noxious weeds. Noxious weeds removed from a wetland rehabilitation site must be disposed of appropriately.

The *Protection of the Environment Operations Act 1997*

The *Protection of the Environment Operations Act 1997* makes it an offence to pollute the environment without an environment protection licence issued by the Environment Protection Authority.

Schedule 1 of the Act lists activities that require a licence. Possible activities relevant to marine areas include aquaculture or mariculture in artificial water bodies, dredging works, sewage treatment systems and landfill sites in environmentally sensitive areas. The schedule sets criteria for determining whether the activity requires an environmental protection licence. The criteria generally relate to the size or intensity of the activity or the sensitivity of the receiving environment.

It is an offence to pollute waters without an environmental protection licence. The legal definition of 'water pollution' includes the introduction of any matter – solid, liquid or gas – into waters which changes the physical, chemical or biological condition of the waters. It also includes the placing of any matter in a position where pollution enters or is likely to enter any waters.

The *Threatened Species Conservation Act 1995*

The TSC Act aims to protect and encourage the recovery of threatened species, populations and communities listed under the Act. The integration of the TSC Act with the EP&A Act requires consideration of whether a development or an activity is likely to significantly affect threatened species, populations and ecological communities or their habitat. Where a proposal is likely to have a significant impact on threatened species, a Species Impact Statement must be prepared. This does not apply to fish or marine vegetation, which are covered by the *Fisheries Management Act 1994*.

Schedule 1 of the Act lists endangered species, populations and ecological communities. Endangered ecological communities on the NSW coast include:

- coastal saltmarsh in the NSW North Coast, Sydney Basin and South East Corner bioregions
- littoral rainforest in the NSW North Coast, Sydney Basin and South East Corner bioregions

- swamp sclerophyll forest on coastal floodplains of the NSW North Coast, Sydney Basin and South East Corner bioregions
- swamp oak floodplain forest of the NSW North Coast, Sydney Basin and South East Corner bioregions.

Schedule 2 lists vulnerable species and ecological communities, and Schedule 3 lists key threatening processes. Under s. 91 of the Act, a licence is required if a proposed activity is likely to significantly affect threatened species, populations or ecological communities or their habitats. The likely impact of an activity is determined by DECC following the submission of a Species Impact Statement.

Coastal saltmarsh, an endangered ecological community, at Macquarie Rivulet, Lake Illawarra (DECC)

The *Water Management Act 2000* and related Acts

The *Water Management Act 2000* seeks to promote the integrated and sustainable management of the State's waters for the benefit of both present and future generations. The Act controls how water is managed and allocated, and how it is to be protected in the long term.

The *Water Management Act 2000* contains provisions that:

- give a statutory right for environmental water
- expand and improve the management of development and activities that affect the health of the State's water
- set priorities for the management of issues of greatest environmental need and value.

Most of the Act's provisions commenced in January 2001, but others relating to water access licences and approvals are being progressively implemented. Until such time as these parts of the Act are enabled, these provisions will continue to be administered under existing legislation, including the *Water Act 1912*.

The *Water Act 1912* gives the Department of Water and Energy (DWE) the exclusive right to use and control:

- water in rivers and lakes
- water occurring naturally on the surface
- subsurface water
- water conserved by works, such as dams.

Approval to extract water from any surface or groundwater source (unless for personal stock and domestic use) requires approval from DWE under Part 2 of the *Water Act 1912*. The construction of earthworks, embankments and levees (referred to as 'controlled works') in a designated area requires the approval of DWE under Part 8 of the Act.

Activities on waterfront land are currently administered under Part 3 of the *Water Management Act 2000*. Such 'controlled activities' for which approval is required include:

- the construction of buildings or the carrying out of works
- the removal of material or vegetation from land by excavation or any other means
- the deposition of material on land by landfill or otherwise
- any activity that affects the quantity or flow of water in a water source.

Waterfront land is defined as the area between the bed of any river, lake or estuary, and a line drawn 40 m parallel from the highest bank or shore (in relation to non-tidal waters) or the mean high water mark (in relation to tidal waters). Any wetland restoration work involving digging, dredging, deposition of material or disturbance to vegetation is likely to require an approval. However, any works undertaken on Crown land or by any public authorities are exempt from requiring a permit, although works must still be consistent with the requirements of the Act.

12.4 Natural resource policies

Although statements of policy are an integral part of environmental law, unlike parliamentary acts or EPIs they do not have formal legal status. They are designed to guide, not legally bind, government decision making. However, if a decision maker fails to take into account a government policy, the decision could be subject to administrative review by the courts on the basis that relevant considerations were not taken into account (Finlay-Jones 1997).

The Commonwealth Coastal Policy 1995

The aim of the Commonwealth Coastal Policy (Commonwealth of Australia 1995) is to promote ecologically sustainable use of Australia's coastal zone. The policy has a number of objectives and guiding principles relating to sustainable use of coastal resources, public participation in the planning and management of coastal resources, and enhancing knowledge and understanding of coastal zone ecosystems and processes. These objectives and principles guide the actions and activities of Commonwealth departments, agencies and statutory authorities in the coastal zone and promote coordination in order to achieve an integrated, ecologically sustainable approach to coastal management.

The Wetlands Policy of the Commonwealth Government of Australia

The Wetlands Policy of the Commonwealth Government of Australia (Commonwealth of Australia 1997), and the strategies it details, seeks to ensure that the activities of the Commonwealth Government promote the conservation, ecologically sustainable use and, where possible, enhancement of wetland functions.

The objectives of the policy are to:

- conserve Australia's wetlands, particularly through the promotion of their ecological, cultural, economic and social values
- manage wetlands in an ecologically sustainable way and within a framework of integrated catchment management
- achieve informed community and private sector participation in the management of wetlands through appropriate mechanisms
- raise community and visitor awareness of the values, benefits and types of wetlands
- develop a shared vision among all spheres of Government and promote the application of best practice in wetland management and conservation
- ensure a sound scientific and technological basis for the conservation, repair and ecologically sustainable development of wetlands
- meet Australia's commitments as a signatory to relevant international treaties in relation to the management of wetlands.

The NSW Estuary Management Policy

The goal of the NSW Estuary Management Policy (NSW Government 1992) is to achieve integrated, balanced, responsible and ecologically sustainable use of the State's estuaries. Specific objectives of the policy are:

- protection of estuarine habitats and ecosystems in the long term, including maintenance of the hydraulic regime
- preparation and implementation of a balanced, long-term management plan for the sustainable use of each estuary and its catchment, in which all values and uses are considered, and which defines management strategies for:
  - conservation of aquatic and other wildlife habitats
  - conservation of the aesthetic values of estuaries and wetlands
  - prevention of further estuary degradation
  - repair of damage to the estuarine environment
  - sustainable use of estuarine resources, including commercial and recreational uses where appropriate.

The policy is implemented primarily through the Estuary Management Program, which provides funding to local government authorities for the preparation and implementation of estuary management plans. The process for preparation of estuary management plans is documented in the *Estuary Management Manual* (NSW Government 1992) and the *Coastal Zone Management Manual* (in prep.). The preparation of plans is supervised by estuary management committees, which comprise representatives of local councils, relevant State Government authorities and community groups.

The NSW Wetland Management Policy 1996

The purpose of the NSW Wetlands Management Policy (NSW Government 1996) is to halt and, where possible, reverse loss of wetland vegetation, decline in water quality and natural productivity, loss of biological diversity and decline in natural flood mitigation. The policy encourages projects and activities that will restore the quality of the State's wetlands, such as rehabilitation, re-establishing vegetation buffer zones around wetlands, and ensuring adequate availability of water in order to restore wetland habitats.

To achieve its goals, the policy adopts the following nine principles for the sustainable management of wetlands:

- Water regimes needed to maintain or restore the physical, chemical and biological processes of wetlands will have formal recognition in water allocation and management plans.
- Land use and management practices that maintain or rehabilitate wetland habitats and processes will be encouraged.
- New developments will require allowance for suitable water distribution to and from wetlands.
- Water entering natural wetlands will be of sufficient quality so as not to degrade the wetlands.
- The construction of purpose-built wetlands on the site of viable natural ones will be discouraged.
- Natural wetlands should not be destroyed, but when social or economic imperatives require it, the rehabilitation or construction of a wetland should be required.
- Degraded wetlands and their habitats and processes will be actively rehabilitated as far as is practical.
- Wetlands of regional or national significance will be conserved.
- The adoption of a stewardship ethos and cooperative action by land and water owners and managers, government authorities, non-government agencies and the general community is necessary for effective wetland management.

The NSW Coastal Policy 1997

The aim of the NSW Coastal Policy 1997 (NSW Government 1997a) is to promote the ecologically sustainable development of the NSW coastline.

The policy incorporates the principles of ecologically sustainable development into coastal planning. Local councils are required to incorporate the goals of the policy when making LEPs that apply within the coastal zone, and are required to consider the provisions of the policy when determining applications for development in the coastal zone.

The NSW Fisheries *Policy and Guidelines*

The aim of the *Policy and Guidelines Aquatic Habitat Management and Fish Conservation* (NSW Fisheries 1999) is to improve the conservation and management of aquatic habitats in NSW. The policy provides principles in relation to the conservation of fish, marine vegetation and aquatic habitats. It contains more specific guidelines relating to a wide range of activities that affect aquatic ecosystems, as well as habitat rehabilitation, wetland compensation and environmental assessment.

The NSW Weirs Policy

It is estimated that there are over 3000 weirs on rivers in NSW. The goal of the NSW Weirs Policy (NSW Government 1997b) is to halt and, where possible, reduce and remediate the environmental impact of weirs. A weir is defined as a structure (including a dam, lock, regulator, barrage or causeway) across a defined watercourse that will pond water, restrict flow or hinder the movement of fish along natural flow paths in normal flow conditions.

One of the management principles of the policy is that wetlands and riparian vegetation adjacent to weirs should be protected from permanent inundation.

The policy is implemented through two major actions: approvals for new or expanded weirs, and a review of all existing weirs.

12.5 State environmental planning policies

SEPPs are made by the Minister for Planning and are gazetted as legal documents. Of most relevance for any work in coastal wetlands is SEPP 14, but several other SEPPs may apply, depending on the location and nature of the project site.

SEPP 14 Coastal Wetlands

SEPP 14 Coastal Wetlands protects natural wetlands in coastal areas. Its aim is to ensure that the coastal wetlands of NSW are preserved and protected in the environmental and economic interests of the State. Any development within a SEPP 14 wetland involving clearing, draining, filling or the construction of a levee is deemed a 'designated development' requiring the preparation of an EIS, the consent of the local authority and the concurrence of the NSW Director General of Planning. The land to which SEPP 14 applies is identified on a series of maps held by the Department of Planning. It does not apply to areas managed under the NPW Act, or to areas to which SEPP 26 Littoral Rainforest applies.

SEPP 14 does not guarantee that wetlands will not be destroyed by development, but it imposes an additional requirement of consent for such developments. Under SEPP 14 the Director General of Planning is required to take into account a number of factors in considering whether to grant concurrence to consent.

The consent of the relevant local council and concurrence of the Director General of Planning is required before restoration works can begin in a SEPP 14 wetland. Applicants must lodge a wetland restoration plan prepared in accordance with guidelines issued by the Department of Planning (DUAP 1999).

SEPP (Infrastructure)

SEPP (Infrastructure) outlines the approval process and assessment requirements for infrastructure proposals including dredging works required to maintain or restore tidal flows or safe navigation routes for shipping in tidal waterways. The SEPP allows public authorities to carry out maintenance dredging provided that appropriate consultation and environmental assessment have been undertaken under Part 5 of the EP&A Act.

SEPP 14 wetlands fringing the Moruya River (DECC)

SEPP 19 Bushland in Urban Areas

The general aim of SEPP 19 Bushland in Urban Areas is to protect and preserve bushland within urban areas in order to preserve its natural heritage value, aesthetic value, and value as a recreational, educational and scientific resource. Development consent from a local council is required for any disturbance to natural bushland zoned or reserved for public open space, with the exception of specified activities such as the construction of roads, pipelines and powerlines or bushfire hazard reduction. SEPP 19 applies only to specified local government areas in Sydney and the Central Coast of NSW.

SEPP 26 Littoral Rainforests

SEPP 26 Littoral Rainforests establishes a development control framework for protecting littoral rainforests, a distinct rainforest community adapted to harsh salt-laden and drying coastal winds. The policy applies to mapped areas of littoral rainforest (the 'core' areas) and to a 'buffer area' surrounding the rainforest to a distance of 100 m. Development consent is required for a number of activities in an area of protected littoral rainforest. Those activities are considered to be 'designated development' under the EP&A Act. Any wetland restoration work undertaken within or adjacent to a mapped area of littoral rainforest will therefore require an EIS to be prepared and submitted with the development application.

SEPP 44 Koala Habitat

SEPP 44 Koala Habitat aims to encourage the proper conservation and management of areas of natural vegetation that provide habitat for koalas to ensure a permanent free-living population over their present range. One requirement of SEPP 44 is that a management plan must be prepared for areas of core koala habitat before development consent will be given.

Koala food trees that grow in coastal areas of NSW include swamp mahogany (*Eucalyptus robusta*) and forest red gum (*Eucalyptus tereticornis*).

SEPP 71 Coastal Protection

SEPP 71 Coastal Protection seeks to ensure that development within the coastal zone (with the exception of greater Sydney) is appropriate, suitably located and consistent with the principles of ecologically sustainable development.

The policy applies only to 'sensitive coastal locations':

- land within 100 m above mean high water mark of the sea, a bay or an estuary
- coastal lakes, Ramsar wetlands and World Heritage areas
- marine parks and aquatic reserves
- land reserved under the NPW Act
- land within 100 m of any of the above
- SEPP 14 coastal wetlands
- residential land within 100 m of SEPP 26 littoral rainforests.

SEPP 71 provides a clear and consistent development assessment framework for the coastal zone, gives legal force to certain elements of the NSW Coastal Policy 1997, and introduces additional matters that must be considered by local councils in the preparation of LEPs and the determination of development applications.

Lake Cathie, a sensitive coastal location (DECC)

12.6 Regional environmental planning policies

Regional environmental plans (REPs) are made under the EP&A Act and provide the framework for detailed local planning by councils. They cover issues such as urban growth, commercial centres, extractive industries, recreational needs, rural lands, and heritage and conservation. A list of REPs can be found on the Department of Planning's website (www.planning.nsw.gov.au).

12.7 Local environmental plans

LEPs are prepared by local councils and may apply to all or part of the land under a council's control. They are the main instruments used for land use planning and development control by a local council. An LEP will contain maps and tables identifying various zones and the development that is permissible within each zone. The LEP will list the objectives of each zone, and define those activities that are prohibited or require development consent.

You can obtain the LEP for your local council area by visiting the council's offices, by searching the council's website, or on the website of the NSW Parliamentary Counsel's Office (www.legislation.nsw.gov.au).

12.8 International agreements

The Ramsar Convention

The *Convention on Wetlands of International Importance Especially as Waterfowl Habitat* was signed at the town of Ramsar in Iran on 2 February 1971. Both the Commonwealth and NSW governments are signatories to the Ramsar Convention. The Convention's broad aims are to halt the worldwide loss of wetlands and to conserve, through wise use and management, those that remain.

Countries that are parties to the Ramsar Convention promote wetland conservation through a range of actions such as:

- completing wetland inventories
- preparing policies and promoting the 'wise use' of all wetlands within their territory
- nominating specific sites to the List of Wetlands of International Importance which will then be managed to ensure that they retain their special ecological characteristics
- promoting capacity building and technology transfer through the training of wetland managers
- consulting with each other, particularly in the case of shared wetlands, water systems or migratory waterbirds.

Australia currently has 64 wetlands designated as Wetlands of International Importance. In NSW there are three Ramsar-declared wetlands in coastal areas with a combined total area of 47 970 hectares: Towra Point Nature Reserve, Hunter Estuary Wetlands and Myall Lakes.

The Ramsar Convention has developed guidelines for the wise use of wetlands. This concept of 'wise use' seeks to modify human use of wetlands so as to ensure continuous benefit to present generations, at the same time maintaining the natural properties, such as food webs and other ecological processes, for future generations. The EPBC Act provides a process for the designation and management of Ramsar wetlands. The Australian Ramsar Management Principles have been developed under regulations of the Act to help guide the management of Ramsar wetlands.

JAMBA, CAMBA and RoKAMBA

Bilateral agreements provide a formal framework for cooperation between two countries on issues of mutual interest. Australia currently has bilateral agreements relating to the conservation of migratory birds and their wetland habitats with Japan (known as the Japan–Australia Migratory Bird Agreement, or JAMBA, 1974), China (China–Australia Migratory Bird Agreement, or CAMBA, 1986) and the Republic of Korea (Republic of Korea–Australia Migratory Bird Agreement, or RoKAMBA, 2006).

The EPBC Act enables Australia to give domestic effect to the obligations imposed by the agreements. These two agreements list terrestrial, water and shorebird species that migrate between Australia and the respective countries. The majority of listed species are shorebirds.

The migratory sharp-tailed sandpiper is listed under the China–Australia Migratory Bird Agreement (CAMBA) (Chris Chafer)

The Bonn Convention

The *Convention on the Conservation of Migratory Species of Wild Animals* (also known as CMS or Bonn Convention) is an intergovernmental treaty that aims to conserve terrestrial, marine and avian migratory species throughout their ranges. Currently 92 countries are members of the Convention. The Convention includes a list of migratory species threatened with extinction, and member parties strive towards strictly protecting these animals, conserving or restoring the places where they live, mitigating obstacles to migration, and controlling other factors that might endanger them. The Convention also includes a list of migratory species that need or would significantly benefit from international cooperation.

12.9 Other relevant documents

Through the National Wetlands Program, the Commonwealth Government, in cooperation with State and Territory governments, has compiled an inventory of Australia's nationally important wetlands, known as *A Directory of Important Wetlands in Australia*. The third edition of the Directory (Environment Australia 2001) includes a comprehensive review of existing data and efforts to increase listings in regions of Australia that were previously under-represented or not represented. The current version of the Directory is now available online as part of the Australian Wetlands Database on the Commonwealth Department of Environment and Heritage's website (www.environment.gov.au).

Over 850 wetlands are currently included in the Directory, 58 of these being estuarine or marine wetlands along the NSW coastline. The Directory provides information on the wetland classification, the criteria for including it in the Directory, and background information on the features of the wetland, flora, fauna, values, threats and conservation measures. Inclusion of a wetland in the Directory does not have any legislative implications, but identifies the wetland as a nationally significant site that should be managed appropriately.

References for Part 3

Chapter 7

Department of Commerce. 2007. *NSW Tide Charts 2008*. NSW Department of Commerce, Sydney.

Beckley BD, Lemoinse FG, Lutchke SB, Ray RD, Zelensky NP. 2007. A reassessment of global and regional mean seal level trends from TOPEX and Jason–1 altimetry based on revised reference frame and orbits. *Geophysical Research Letters*, 34.

Church JA, and White NJ. 2006. A 20th century acceleration in global sea-level rise, *Geophysical Research Letters*, 33.

NSW Government. 1992. *Estuary Management Manual.* NSW Government, Sydney.

Rogers K, Wilton KM, Saintilan N. 2006. Vegetation change and surface elevation dynamics in estuarine wetlands of south eastern Australia. *Estuarine Coastal and Shelf Science* 66: 559–569.

Chapter 8

DLWC. 1998. *The Constructed Wetlands Manual*, vols 1 and 2. NSW Department of Land and Water Conservation, Sydney.

Johnston SG, Slavich P, Hirst P. 2004. The acid flux dynamics of two artificial drains in acid sulfate soil backswamps on the Clarence River floodplain, Australia. *Australian Journal of Soil Research* 42, 623–637.

Chapter 9

Dent D. 1986. *Acid Sulfate Soils: A Baseline for Research and Development.* ILRI Publication No 39, International Institute of Land Reclamation and Improvement, Wageningen, The Netherlands.

Fanning DS. 1993. Salinity problems in acid sulfate soils. In: Leith H, Al Masoom, A, eds. *Towards the Rational Use of High Salinity Tolerant Plants*, vol. 1, 491–500. Kluwer Academic Publishers, Dordrecht.

Gray JM, Murphy BW 1999. *Parent Material and Soils – A Guide to the Influence of Parent Material on Soil Distribution in Eastern Australia*. Technical Report No 45, NSW Department of Land and Water Conservation, Sydney.

Hicks RW. 1991. Soil engineering properties. In: Charman PEV, Murphy BW, eds. *Soils – Their Properties and Management.* Sydney University Press, Sydney.

Isbell RF. 1996. *The Australian Soil Classification*. CSIRO Publishing, Melbourne.

Langford-Smith T, Thom BG. 1969. *The Geology of New South Wales*. Geological Society of Australia, Sydney.

Lin C, Melville MD. 1993. Control of soil acidification by fluvial sedimentation in an estuarine floodplain, eastern Australia. *Sedimentary Geology* 85: 271–284.

Naylor SD, Chapman GA, Atkinson G, Murphy CL, Tulau MJ, Flewin TC, Milford HB, Morand DT. 1998. *Guidelines for the Use of Acid Sulfate Soil Risk Maps*, 2nd edn. NSW Department of Land and Water Conservation, Sydney.

Pons LJ, van Breeman N. 1982. Factors influencing the formation of potential acidity in tidal swamps. In: Dost H, ed. *Proceedings of the Second International Symposium on Acid Sulfate Soils*, ILRI Publication No 31, pp. 37–51. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Pons LJ, van Breeman N, Driessen PM. 1982. Physiography of coastal sediments and development of potential acidity, part 1. In: *Acid Sulfate Weathering*, 1–18. Special Publication No 10, Soil Science Society of America, Madison, Wisconsin, USA.

Rorison IH. 1973. The effect of extreme soil acidity on the nutrient uptake and physiology of plants. In: Dost H, ed. *Proceedings of the Second International Symposium on Acid Sulfate Soils*, pp. 223–241. ILRI Publication No. 18, vol. 1, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Sammut J, Lines-Kelly R. 2004. *An Introduction to Acid Sulfate Soils*. NSW Department of Primary Industries, Orange.

Sammut J, White I, Melville MD. 1994. Stratification in acidified floodplain drains. *Wetlands (Australia)* 13: 49–64.

Stace HCT, Hubble GD, Brewer R, Northcote KH, Sleeman JR, Mulcahy MJ, Hallsworth, EG. 1968. *A Handbook of Australian Soils*. Rellim Technical Publications, Adelaide.

van Breeman N. 1982. Genesis, morphology and classification of acid sulfate soils in coastal plains, Part 3. In: *Acid Sulfate Weathering*. SSSA Special Publication No 10, pp. 95–108. Soil Science Society of America, Madison, Wisconsin, USA.

Walker PH. 1972. Seasonal and stratigraphic controls in coastal floodplain soils. *Australian Journal of Soil Research* 10: 127–142.

White I, Melville MD. 1993. *Treatment and Containment of Potential Acid Sulphate Soils*. CSIRO Centre for Environmental Mechanics, Technical Report No 53. CSIRO Publishing, Melbourne.

White I, Melville MD, Wilson BP, Price CB, Willett IR. 1993. Understanding acid sulphate soils in canelands. In: Bush R, ed. *Proceedings of the National Conference on Acid Sulfate Soils*, pp. 130–148. Greenmount Beach Resort, Coolangatta, 24–25 June 1993.

Willet IR. 1989. Causes and prediction of changes in extractable phosphorus during flooding. *Australian Journal of Soil Research* 16: 319–326.

Willett IR, Walker PH. 1982. Soil morphology and distribution of iron and sulphur fractions in a coastal flood plain toposequence. *Australian Journal of Soil Research* 20: 283–294.

Chapter 11

Adam P. 1981. Australian saltmarshes. *Wetlands (Australia)* 1: 8–10.

Adam P. 1993. *Saltmarsh Vegetation Study*. Homebush Bay Ecological Studies 1993–1995. 2. CSIRO Publishing, Melbourne.

Adam P, Wilson NC, Huntley B. 1988. The phytosociology of coastal saltmarsh vegetation in New South Wales. *Wetlands (Australia)* 7: 35–57.

Allen S, Marsh H, Hodgson A. 2004. Occurrence and conservation of the dugong (Sirenia: Dugongidae) in New South Wales. *Proceedings of the Linnean Society of NSW* 125: 211–216.

Bridgewater PB, Rosser C, de Corona A. 1981. *The Saltmarsh Plants of Southern Australia*. Botany Department, Monash University, Melbourne.

Chapman VJ. 1977. Introduction. In: *Ecosystems of the World. I. Wet Coastal Ecosystems*, 1–29. Elsevier, Amsterdam.

Department of Primary Industries. 2007. *Caulerpa taxifolia* http://www.fisheries.nsw.gov.au/threatened_species/general/content/caulerpa. Accessed 9 July 2007.

Hutchings P, Saenger P. 1987. *Ecology of Mangroves*. University of Queensland Press, Brisbane.

King RJ. 1981. The free-living *Hormosira banksii* (Turner) Decaisne associated with mangroves in temperate eastern Australia. *Botanica Marina* 24: 569–576.

King RJ, Wheeler MD. 1985. Composition and geographical distribution of mangrove macroalgal communities in New South Wales. *Proceedings of the Linnean Society of NSW* 108: 97–117.

Langtry SK, Jacoby CA. 1996. Fish and decapod crustaceans inhabiting drifting algae in Jervis Bay, New South Wales. *Australian Journal of Ecology* 21: 264–271.

NSW Scientific Committee. 2005a. *Final Determination – Swamp Sclerophyll Forest on Coastal Floodplains of the NSW North Coast, Sydney Basin and South East Corner Bioregions – Endangered Ecological Listing*. NSW Scientific Committee, NSW Department of Environment and Conservation, Sydney.

NSW Scientific Committee. 2005b. *Final Determination – Swamp Oak Floodplain Forest on Coastal Floodplains of the NSW North Coast, Sydney Basin and South East Corner Bioregions – Endangered Ecological Listing*. NSW Scientific Committee, NSW Department of Environment and Conservation, Sydney.

Phillips JA. 1998. Macroalgae of Moreton Bay: Species diversity, habitat specificity and biogeography. In: Tibbetts IR, Hall NJ, Dennison WC, eds. *Moreton Bay and Catchment*, 279–290. School of Marine Science, University of Queensland, Brisbane.

Phillips JA, Price IR. 2002. How different is Mediterranean *Caulerpa taxifolia* (Caulerpales, Chlorophyta) to other populations of the species? *Marine Ecology Progress Series* 238: 61–71.

Saenger P, Specht MM, Specht RL, Chapman VJ. 1977. Mangal and coastal saltmarsh communities in Australasia. In: Chapman VJ, ed. *Ecosystems of the World: Wet Coastal Ecosystems*. Elsevier, Amsterdam.

Ungar IA. 1991. *Ecophysiology of Vascular Halophytes*. CRC Press, Boca Raton, FL, USA.

Williams RJ, West G, Morrison D, Creese RG. 2006. *Estuarine Resources of New South Wales*. Prepared for the Comprehensive Coastal Assessment (Department of Planning) by the NSW Department of Primary Industries, Port Stephens.

Yallop ML, de Winder B, Paterson DM, Stal LJ. 1994. Comparative structure, primary production and biogenic stabilisation of cohesive and non-cohesive marine sediments inhabited by microphytobenthos. *Estuarine Coastal and Shelf Science* 39: 565–582.

Zedler JB, Nelson P, Adam P. 1995. Plant community organization in New South Wales saltmarshes: species mosaics and potential causes. *Wetlands (Australia)* 14: 1–18.

Chapter 12

Commonwealth of Australia. 1995. *Commonwealth Coastal Policy*. Canberra.

Commonwealth of Australia. 1997. *Wetlands Policy of the Commonwealth Government of Australia*. Canberra.

DUAP. 1999. *Guidelines – Wetland Restoration Plans*. NSW Department of Urban Affairs and Planning, Sydney.

Environment Australia. 2001. *A Directory of Important Wetlands in Australia*, 3rd edn. Environment Australia, Canberra.

Finlay-Jones J. 1997. Aspects of wetland law and policy in Australia. *Wetlands Ecology and Management* 5: 37–54.

NSW Fisheries. 1999. *Policy and Guidelines Aquatic Habitat Management and Fish Conservation 1999* (Smith AK, Pollard DA, eds). NSW Fisheries, Port Stephens.

NSW Government. 1992. New South Wales Estuary Management Policy. In: *Estuary Management Manual*. NSW Government, Sydney.

NSW Government. 1996. *NSW Wetlands Management Policy*. NSW Department of Land and Water Conservation, Sydney.

NSW Government. 1997a. *NSW Coastal Policy 1997: A Sustainable Future for the New South Wales Coast*. NSW Department of Urban Affairs and Planning

NSW Government. 1997b. *NSW Weirs Policy*. Published online at www.naturalresources.nsw.gov.au/water/legislation.shtml.

Appendix 1 Topographic and bathymetric surveys and tidal gaugings

Topography relates to the features of an area, including relief or terrain. Bathymetry is the underwater equivalent. We will use the term topography to describe all features of a wetland whether predominantly wet or dry.

You will need to determine the existing topography of the wetland by a survey of the site to draw up a contour map for any modelling of water flows. You can collect preliminary information from topographical and cadastral maps and aerial photographs. Publicly available contour information is generally at 5 m intervals, and occasionally 2 m. For many projects the -1 to 1m AHD area will be of most interest. It is likely a topographic survey will be required. Site surveys should include site boundaries, drainage channels and any features such as bunds or floodgates.

Carry out survey work as early as possible, preferably before or during the design phase, so you can assess the existing tidal regimes and predict future tidal regimes on the basis of reliable information. The survey datum must be related to the Australian Height Datum so that the topography can be related to the tidal information.

Drainage channels and inundated areas may require boat based surveying, using echo sounders or survey staffs, and is best carried out at high tide. Foot based survey is best carried out at low tides.

Good vertical survey control is essential. The major part of wetland construction will be carried out within the relatively narrow band of the intertidal zone, and gradients within the completed wetland will be relatively flat. Suggested contour intervals range between 0.1 m and 0.5 m depending on the nature of the topography.

Vertical control should comprise one or more benchmarks set up on stable ground and temporary benchmarks in key locations. Levels can be adjusted against spirit levels, laser levels or the tidal water surface. This latter can be a useful technique where sight distances are restricted by vegetation, but take care to ensure that there is no significant gradient due to a flow restriction or discontinuities in the water surface.

Paul (2001) suggests mapping tidal inundation by using a number of people to mark the extent of tidal inundation with stakes, and then mapping the position of the stakes with the help of a GPS receiver.

Horizontal accuracy is not as critical, but it is advisable to have measures in place to ensure that errors do not accumulate to a significant level. The final topography will be critical to the project's success by ensuring satisfactory drainage and minimising ponding.

Horizontal control can be established by placing pegs and determining their horizontal location by measuring tape or electronic equipment. Differential GPS equipment can also be used, but the dense vegetation cover typical of estuarine wetlands may require the antenna to be mounted on a high mast, making movement through the wetland cumbersome.

Survey data can be entered into computer-aided drafting packages and digital terrain models, which will help with the design of the wetland configuration and calculation of earthwork and pond volumes.

Information published in the *NSW Tide Charts* (Department of Commerce 2007) can be used to estimate tidal characteristics along the open NSW coastline. However, for any significant works or any studies in which modelling is to be undertaken, the tide must be gauged at the site. This is necessary as even over short reaches in an estuary or a tidal arm there may be a significant amplification or diminution of the tidal range compared with the open ocean.

We recommend that you gauge the tidal range with a tide recorder (ideally two, to maximise data recovery), logging water levels at 5-min intervals. To enable tidal constituents to be calculated, the recorder must be installed for a minimum of 29 days, but 2 months is preferable to provide some redundancy in the data. A relationship with known tides, for example those in Sydney Harbour, can then be derived, and tidal planes for the site can be determined from the tidal data recorded, enabling the annual frequency of tide levels at the site to be determined.

Hydrosurvey being carried out in Narrabeen Lagoon (DECC)

Water level recorder being used in tidal gauging (DECC)

References

Department of Commerce. 2007. *NSW Tide Charts 2008*. NSW Department of Commerce, Sydney.

Paul S. 2001. A simple and accurate method for tidal mapping in mangrove wetlands. *2nd Asian Wetlands Symposium*, 27–30 Aug 2001, Penang, Malaysia.

Appendix 2 Planting information

A2.1 Planting plans

Where planting is to be a significant part of a saltwater wetland rehabilitation plan, it will be useful to prepare a planting plan or strategy. A planting plan may need to cover a number of years, as initial plantings are likely to have varying degrees of success, and follow-up planting and maintenance may be required. The plan should consider the following steps:

Preparing the site for planting: This may involve loosening compacted soil or placing hessian over bare substrate for stabilisation.

Selecting species: Species selection will be influenced by numerous factors, many of which should already be considered in the wetland rehabilitation plan. Factors to be considered will include wetland type, inundation frequency, hydrology, local species distribution and abundance, legal requirements, and availability of seed and plant stock.

Quantifying plants needed: In considering the number of plants required, determine the planting density from the required plant spacing. Additional plants will be required, as some mortality is likely.

Sourcing of plants: If propagation of plants is not part of the project, plants will need to be sourced elsewhere. If material is to be gathered from donor sites, the donor site should be close to the project site to ensure genetic preservation and to minimise the spread of disease.

Planting methods: Methods are discussed in greater detail in the rest of this Appendix.

Timing of planting: Spring planting will allow plants to establish before the heat of summer.

Protection of plants: In some situations it may be necessary to protect new plantings. For example, Figure A2.1 illustrates a wave barrier installed to protect mangrove plantings. PVC piping has also been used to protect mangrove seedlings, and mesh netting has been used to stabilise seagrass plantings.

Figure A2.1 Mangroves planted along the Shoalhaven River (Allan Lugg)

A2.2 Planting strategies for mangroves

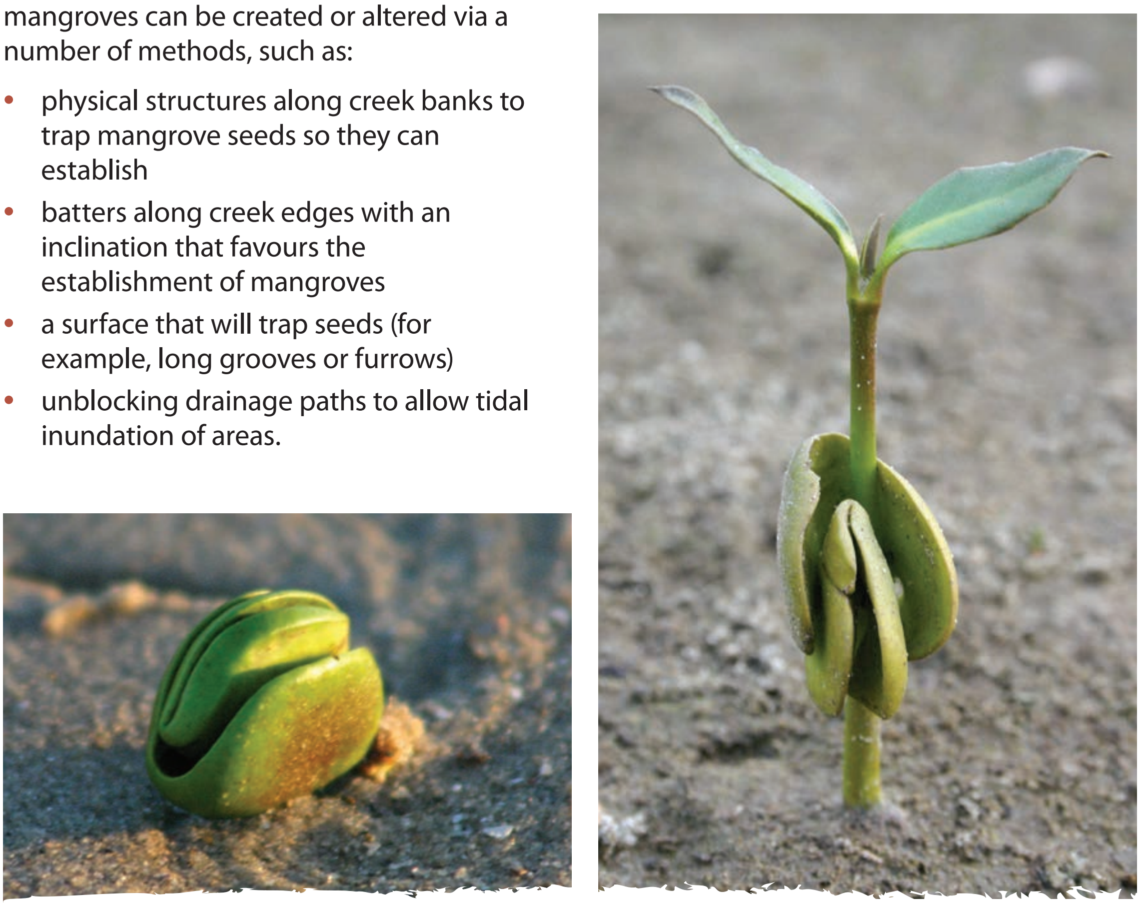
The grey mangrove (*Avicennia marina*) is most commonly used for rehabilitation on account of its wide distribution and hardy nature. Individual flowers open for 2 to 5 days, but flower clusters may have open flowers for 2 to 4 weeks. Flowers are pollinated by insects. The fruit have a single seed that germinates while still on the tree (that is, they are viviparous). Once the seed drops from the parent tree it floats for about 3 days before sinking. If it has landed at a suitable site, it develops roots and establishes. The growth of the seedling to a mature tree depends on a variety of interacting physical and biological factors. Seedlings need lots of light for photosynthesis and growth and are therefore more likely to survive in the open or in a gap in a canopy. Immature plants can be damaged by plant-eating crabs and insects.

Both *Avicennia marina* and *Aegiceras corniculatum* have large viviparous seeds to allow rapid establishment as soon as they lodge in the shoreline substrate. Ample food stores in the seed-leaves (cotyledons) sustain the young plants until they are well anchored by rapidly developing roots. Both species can be found growing in a range of substrates from soft organic silt and mud to sand, gravel and shingle, though the preference seems to be for soft mud or muddy sand. In gravel and shingle, the trees often remain stunted.

Mangroves have specific habitat requirements and therefore cannot be transplanted into areas where they do not naturally occur. Further, in areas where the environment has been heavily modified as a result of development, it may be necessary to substantially modify the site before the wetland environment can be successfully restored.

Habitat suitable for the establishment of mangroves can be created or altered via a number of methods, such as:

- physical structures along creek banks to trap mangrove seeds so they can establish
- batters along creek edges with an inclination that favours the establishment of mangroves
- a surface that will trap seeds (for example, long grooves or furrows)
- unblocking drainage paths to allow tidal inundation of areas.



Grey mangrove seedling (Adam Gosling WetlandCare Australia)

Permits

A permit from the DPI is required to remove seeds or seedlings from mangroves in NSW estuaries. Other local regulatory requirements may also be applicable.

Seed collection and storage

Planting seeds is generally considered more efficient than planting seedlings. There appears to be a positive correlation between seed size and survival. Seeds attain their greatest weight if allowed to fully develop on the tree. For this reason, the most successful seedlings will grow from seeds collected after they have fallen rather than from the mangrove trees.

The floating mangrove seeds move with the tide and accumulate in drainage lines and tidal creeks. This concentration of seeds offers an opportunity to harvest large numbers for later planting or shadehouse development. Simple seed traps constructed of mesh can be anchored in the stream around low tide at points observed to collect seeds on the outgoing tide.

As many mangrove species' seeds germinate and produce roots while still on the tree, the seeds cannot be stored for any great length of time for later planting. Survival decreases rapidly after collection, with few remaining viable after 2 weeks of storage, necessitating the timing of mangrove rehabilitation projects to be managed so as to minimise seed storage. Only limited success has been achieved with storage of seeds in wire baskets in the stand from which they have been collected.

Seedling collection

Planting of seedlings is likely to give a better result at sites that are sandy and subject to wave action, as seeds readily wash out or are covered with sand unless protected. Mature mangrove forests typically have large numbers of small seedlings on the forest floor which survive for a number of years while waiting for a gap in the canopy due to death of a large tree. Judicious harvesting of these plants if they are available locally can provide a convenient source of stock for mangrove stand creation. The number of seedlings harvested, however, should not be allowed to compromise the sustainability of the supplying forest.

Seedlings can be removed from mature mangrove stands by using a 100-mm corer. PVC pipe is a suitable material for making a corer. The roots are removed largely intact within a plug of soil 20–25 cm deep. If seedlings can be harvested from a very muddy location, a spade can be used as a lever to ease them out without too much root damage. This method also allows for several seedlings to be transported in a bucket (using cores will generally allow transport of only two seedlings per bucket) (pers. comm. Allan Lugg, DPI, 23 April 2007)

To minimise storage time, do not collect the seedlings until after any ground preparation at the new site is completed. If the seedlings are to be retained for any length of time before planting, the root ball must be kept moist.

Collect young straight seedlings about 50 cm high and no more than 18 months old. Such seedlings will not show any lignification of the trunk and will have six to eight leaves and (for *Avicennia marina*) no pneumatophore development.

Planting mangroves

After collection, seeds can be kept in a bucket of water (about 50% sea water) for a day while the seed coat (pericarp) peels off and they lose their buoyancy. To plant, simply push the seeds into the mud for about ¾ of their diameter, if the mud is hard, use a stick to make an indentation in the mud. Larger seeds collected later in the season will give better results due to larger stores of nutrients and energy.

On sandy shores exposed to waves or wash, seeds will need to be protected until they are anchored in the substrate.

Seeds can be successfully raised in pots in a shadehouse using standard horticultural techniques. Transplant survival rates may be higher for shadehouse-raised plants than for field transplants, but owing to the relative ease of obtaining seedlings in the field, cost effectiveness of raised seedlings is realised only for very large numbers of plants.

Mangrove seeds cannot take root until the seed coat is shed. Seed soaking in 50% sea water for a day is required when planting in pots. Coarse sand is the normal potting mixture used. Add enough water to saturate the soil and cover the surface to a depth of 2 cm.

Planting densities should take into account the growth form and size of the mature plants.

Some degree of gentle slope is essential for drainage. It is important that the site be sheltered, as seedlings are susceptible to physical damage from flotsam, and cannot withstand strong winds or currents. If the site is subject to wave action, barriers may be needed.

Establishment of areas for planting saltmarsh vegetation at Scott Park, Sans Souci (Rockdale Council)

A2.3 Planting strategies for saltmarsh

Several studies in Australia have examined the active transplantation of saltmarsh plants raised in greenhouses or taken from donor populations. Several species of saltmarsh plants can be propagated and grown for transplantation (Burchett *et al.* 1998a). Saltmarsh plants that are transplanted from donor sites into rehabilitation sites survive and spread, although often slowly (Nelson 1996, Dick 1999).

In transplanting from natural sites, it is important to consider the impact on the donor site, which may require some time to recover. Within donor sites the time required for saltmarsh plants to recover their natural densities varies with species and location. Laegdsgaard (2002) removed 25 cm^2 plots from donor saltmarshes and found that *Sporobolus virginicus*, took 4–5 years to recover regardless of position within the saltmarsh. *Sarcocornia quinqueflora*, however, took longer to recover at higher sites (4–5.5 years) than at lower sites (14–17 months).

Permits

Coastal saltmarsh has been listed as an endangered ecological community in NSW under Part 3, Schedule 1, of the TSC Act. A permit is likely to be required from DECC for removal of plants or plugs from donor marshes.

Transplanting saltmarsh plugs

Saltmarsh soil is frequently very heavy with a high clay content. To collect plugs of plant material from the donor marsh in these circumstances you must use a robust implement. A soil corer or a 10- to 20-cm-diameter posthole digger with straightened tines is suitable.

Saltmarsh on sandy soil may present a different problem, in that the soil around the roots will fall away easily, leaving the roots exposed and vulnerable to drying out. In this case, you may need to handle the plugs carefully and transport them packed closely in containers or pots. Place the plugs in holes at the recipient site dug with the same implement used to collect them. Although good topsoil is desirable, we have found no evidence that fertiliser application in tidal conditions is beneficial.

Suaeda australis planted through jute mesh at Scott Park, Sans Souci (DECC)

The removal of plugs with saltmarsh plants can be deleterious to the donor marsh if the volume of material removed is large in proportion to the area of the marsh. The use of plugs for transplants is possible only if the viability of the donor marsh is not compromised by their removal, or if the donor marsh is to be destroyed by reclamation or flooding.

Taking cuttings

Standard horticultural techniques for propagating shoot cuttings is successful for generating large numbers of plantlets of some saltmarsh species (Burchett *et al.* 1998b). This technique uses fogging tents, bottom heating and hormone application to encourage root development (see Dialogue Box A2.1).

Dialogue Box A2.1 Propagation of saltmarsh plants from cuttings

New-season tip-and-stem cuttings were taken from as many plants and clumps as possible both to avoid damage to individual plants and to maximise genetic diversity of the planting stock. The cuttings were placed between sheets of wet horticultural capillary matting for transport back to the glasshouse.

The cuttings were first washed in tap water to remove any salt build up, then dipped for 5 s in 1% sodium hypochlorite solution for surface sterilisation, and rinsed in distilled water. Except for *Sporobolus virginicus*, for which internode segments were used, tip segments were used, and sometimes two or three single-node segments from immediately behind the tips. On the basis of pilot test rates of root production, the cut ends of all but *Lampranthus tegens* and *Sarcocornia quinqueflora* were dipped into root-promoting hormone gel (Clonex Purple; Growth Corporation, Fremantle, WA, Australia).

The cuttings were set in germination trays containing a 1:1 sand–peat mixture. The trays were then placed in a fogging tent in the glasshouse with bottom heat under a sand base (25 ± 5°C). When root and shoot growth were established, the plantlets were hardened off, first by lifting the fogging tent flaps and lowering the level of fog, then on the glasshouse bench. They were then potted on into small pots usually containing 3:2 sand–peat mixture.

After approximately 10 days to acclimatise, the plants were gradually salinated over 2 weeks to a final watering concentration of half-strength sea water, before being planted out.

Source: Based on Burchett *et al.* (1998b)

A2.4 Planting strategies for seagrass

Seagrass meadows have been re-established *in situ* where their density and health have been reduced by mechanical damage, pollutants or sediment inputs.

Despite projects spanning more than a decade, seagrass rehabilitation has had limited success in Australia, and the amelioration and restoration of seagrass beds has been little studied (Kirkman 1997). Ganassin and Gibbs (2008) reviewed seagrass habitat restoration techniques to assess if they can be used as a measure to compensate for the loss of seagrass habitat resulting from development activities. The policy concerning habitat compensation for marine vegetation in NSW recommends the re-creation of the type of habitat lost on a 2:1 basis so that both the indirect and direct impacts of development can be compensated for. They concluded that seagrass restoration is a costly process that is still somewhat developmental and that seagrass restoration techniques are still only successful in replacing small areas of habitat. The techniques cannot be used with confidence as a habitat compensation measure, and that protection of existing seagrass beds should remain the highest, most cost-effective priority.

Rehabilitation or creation of seagrass meadows is hampered by such problems as finding suitable propagules, damaging donor sites, preparing and modifying the recipient site, keeping the propagule bank alive, attaching the propagules, the slow rate of rhizome spread, and the technical and resource difficulties of large-scale planting.

Permits

A permit from the DPI is required to disturb or remove seagrass in NSW estuaries. Other local regulatory requirements may also apply.

Obtaining plants

Plugs

Excavated units of leaves, roots and rhizomes with the sediment intact are extracted from natural meadows and transported to the rehabilitation site, where they are placed in pre-dug holes 10–15 cm deep and backfilled with surrounding sediment. When using this technique, it is essential to obtain rhizomes with growing shoot tissue. Take care to minimise disturbance of the donor site, and do not collect plugs close to one another. The plugs can be circular or rectangular, but the diameter must be appropriate for the species.

Plugs have provided good results, but the method has some disadvantages, including the cost and time in transferring large amounts of substrate and damage to the donor beds.

Turf

Gather the turf with a trowel or a shovel to a depth just below the rhizome mat, and keep the mat intact. Do not try to obtain the entire root and rhizome system by cutting deeply into the substrate. At the recipient site, dig a shallow hole or trench to receive the turf and the small amount of sediment.

Sprigs and mats

Sprigs and mats are vegetative shoots consisting of excavated intact roots, rhizomes and leaves. Wash the sediment from the mat, and re-cover the rhizomes and roots with sediment at the recipient site. You can break the mats into individual shoots (sprigs) or leave them intact. Sprigs require shoot tips to ensure the spread of rhizomes. They have the advantage of being easier to handle and transplant, and their use has a lower impact on the donor meadow. The absence of sediment on the seagrass transplants allows checking for growing tips.

Alternatively, you can plant individual shoots in a rich potting mix in degradable pots, and bury the pots in the sediment.

Using seeds

The use of seeds depends on having enough of them, their successful germination and your ability to sow the seeds effectively. A good understanding of the dissemination strategies of the species is required for successful application of this technique. You can mix seeds with sand and broadcast them over the site, or more selectively place them in the sediment by hand or with a purpose-designed mechanical planter. You can also sow seeds to raise seedlings for later planting out. Some researchers have used root dip to enhance growth.

The broadcasting of seeds may be a cheaper, non-destructive alternative to planting plugs or sprigs. The lower cost of planting out the site, the increased ability to control disease and plant stock characteristics, and the reduced reliance on donor beds makes seeding methods worth pursuing.

Planting techniques

A number of methods have been trialled to prevent removal of the transplanted material by wave action or currents:

- Individual leafy shoots fixed with rubber bands to pipes or construction rods. The rods are placed in shallow trenches into the sediment and covered over. Avoid metal rods as the oxidation of the metal has proved lethal.
- Coated or uncoated wire staples inserted into the sediment.
- Wire and plastic mesh grids held down by staples or buried in the sediment.
- Biodegradable mesh and paper.
- Plants woven in between strands of string or paper.
- Plants fixed to concrete rings and bricks and cast from a boat.
- Seedlings held in sediment by plastic anchors wrapped around them.
- Seeds woven into tapes.

A2.5 Planting strategies for swamp oak forest

As is noted in Chapter 11 the species composition of swamp forest (including Swamp Oak Floodplain Forest and Swamp Sclerophyll Forest) will vary considerably with latitude, frequency and duration of waterlogging and the texture, salinity, nutrient and moisture content of the soil. As such species to be used in rehabilitation projects need to be determined with consideration of the above factors. There are quite a number of successful swamp forest rehabilitation projects, many of which involve a substantial weed removal component, and that have involved community groups.

Permits

Swamp Oak Floodplain Forest and Swamp Sclerophyll Forest on coastal floodplains of the NSW North Coast, Sydney Basin and South East Corner bioregions have been listed as endangered ecological communities in NSW under Part 3, Schedule 1, of the TSC Act. A permit is likely to be required from DECC for removal of plants or material from donor sites.

Information resources

Information is available on the propagation of plants for swamp forest rehabilitation:

- *NRM Estuarine Species Finder* (NSW Department of Environment and Climate Change, 2008).
- *CPR Coastal Plant Regeneration* (Fiedler and Glover 2003).

Propagation techniques

Many swamp forest species can be readily propagated from seed. Seed propagation is generally the preferred method of producing plants for swamp forest rehabilitation projects. To ensure genetic integrity, collect seed from the local area and from the same habitat if possible. Take care not to collect too much seed from a site. Generally about 10% of seed present on an individual plant can be collected. Aim to collect seed from several plants. A number of species useful in swamp forest rehabilitation can be obtained from commercial, council or community nurseries – be sure to ask for local provenance. Propagation techniques for a number of key species are listed in Table A2.1.

Table A2.1 Examples of methods of propagating swamp forest species (adapted from Fiedler and Glover 2003 and DECC 2008).

Species	Propagation technique	Usefulness
Casuarina glauca (swamp oak)	Propagate with freshly collected seed from ripe fruit. Collect unopened seed cones and store in a paper bag till seeds fall out of cones. Plant immediately in clean seedling mix (2/3 washed river sand and 1/3 peat moss or organic matter). Seed germinates readily in 2–4 weeks. Seed will store if kept cool and dry and protected from insect and vermin attack.	Excellent as a pioneer species. Essential species for most swamp forest rehabilitation projects.
Eucalyptus robusta (swamp mahogany)	Propagate with freshly collected seed from ripe fruit. Place fruits in paper bag until seeds fall out of gumnuts. Plant immediately in clean seedling mix. Pick out seedlings into tubes at cotyledon stage if possible. Store seed as above.	Pioneer and climax species.
Acmena smithii (lillypilly)	Propagate with freshly collected seed from ripe fruit (winter). Remove skin and flesh from seed and plant immediately in clean seedling mix. Germination can take 6–8 weeks. Plants also strike readily from tip and semi-hardwood cuttings taken in late summer to early autumn.	Climax species. Can be used as a pioneer species.
Acacia longifolia (Sydney golden wattle)	Propagate with freshly collected seed from ripe fruit. Treat seed to break dormancy: Pour just-boiled water over seed and let stand for 12–24 h. Dry seed on newspaper or paper towelling for 24 h and plant immediately in clean seedling mix. Store untreated seed as above.	Pioneer species, but care is needed as plant can form monocultures. Part of climax community. Can be confused with *Acacia sophorae*. Better suited for estuarine areas a distance from the entrance.

Species	Propagation technique	Usefulness
Juncus kraussii (sea rush)	Transplant clumps of this rush or divide to produce planting material. Rhizomes with 2 or more nodes have been successful. Can also be propagated from seed. Store seed heads in a paper bag until seed falls out. Plant immediately in clean seedling mix. Planting several seeds in a tube has proved successful. Store seed as above.	Ideal for areas around saltmarsh and along toe of estuary banks, particularly in flat areas that are periodically inundated. Will grow successfully in sand, mud and peaty acidic soil. Can be used as a protective plant around commercial and developed sites.
Lomandra longifolia (spiny-headed mat rush)	Propagate with freshly collected seed from ripe fruit. Remove seed head from plant and place in a paper bag until seed falls out. Do not let seed become dry. Soak seed in water for 12–24 h and then plant immediately in clean seedling mix.	Pioneer species. Climax species, especially on toe and middle estuarine bank areas. Excellent for recreational, commercial and developed sites.
Commelina cyanea (native wandering jew)	Can be propagated by seed, but is very easily propagated from tip and stem cuttings, which can be placed *in situ* and kept moist. Can be divided and replanted very successfully.	Pioneer and climax species. Particularly useful for stabilisation of sandy banks. Very similar to introduced commelinas. Can form a dense ground cover.
Viola hederacea (native violet)	Divide plants by cutting out small plugs from established sites. These can be directly planted *in situ*, but do better if tubed up until well established. Can also be raised from seed. Remove seed heads from plants and place in paper bags until seeds fall out. Plant immediately in clean seedling mix.	Excellent pioneer and climax species. Can be used for recreational, commercial and developed sites.

References

Burchett M, Pulkownik A, Grant C, MacFarlane G. 1998a. Rehabilitation of saline wetlands, Olympics 2000 site, Sydney (Australia) – I: Management strategies based on ecological needs assessment. *Marine Pollution Bulletin* 37(8–12): 515–525.

Burchett MD, Allen C, Pulkownik, A, Macfarlane. 1998b. Rehabilitation of saline wetlands, Olympics 2000 site, Sydney (Australia) – II: Saltmarsh transplantation trials and application. *Marine Pollution Bulletin* 37 (8–12): 526–534.

Department of Environment and Climate Change. 2008. *NRM Estuarine Species Finder*. NSW Department of Environment and Climate Change, Sydney.

Dick TM. 1999. *Decomposition of Saltmarsh and Mangrove Vegetation on and around Kooragang Island*. University of Newcastle.

Fiedler M, Glover R. 2003. *CPR Coastal Plant Regeneration*. NSW Department of Infrastructure, Planning and Natural Resources, Newcastle, and Coastcare, Sydney.

Ganassin C, Gibbs P. 2008. *A Review of Seagrass Planting as a Means of Habitat Compensation Following Loss of Seagrass Meadow*. NSW Department of Primary Industries – Fisheries Final Report Series No 96. NSW Department of Primary Industries, Cronulla.

Kirkman H. 1997. *Seagrasses of Australia*. Department of the Environment, Canberra.

Laegdsgaard P. 2002. Recovery of small denuded patches of the dominant NSW coastal saltmarsh species (*Sporobolus virginicus* and *Sarcocornia quinqueflora*) and implications for restoration using donor sites. *Ecological Management and Restoration* 3(3): 202–206.

Nelson P. 1996. *The Ecology of Saltmarsh Restoration on Kooragang Island*. University of Newcastle, Department of Biological Sciences.

Appendix 3 Construction materials in saline environments

Chapter 4 discusses both structural and non-structural works, including excavation equipment and techniques for soft ground, dredging and bunding. This Appendix details a number of construction materials.

A3.1 Earth and sand

In most locations an adequate local source of earth and sand exists for use in dikes, fills and foundations. Earth is easily handled with conventional earth-moving equipment and transportation methods. Sand is handled similarly. The cost will increase if the material must be sorted into grain size ranges. It is not necessary to protect earth and sand used in coastal projects from physical or chemical deterioration, but it is necessary to prevent or retard removal of material by wind or water erosion. The only maintenance costs will be associated with replacing eroded material, and will be affected by site access.

A3.2 Stone

Igneous rock is considered to be the most durable, but this depends partially on the geology of the rock. Sedimentary rock is usually stratified and subject to failure through shear stress, impact, chemical deterioration or changes in water content. Sedimentary armour stones generally are more easily worn down by abrasion. Any armour stone that develops small cracks may eventually spall owing to salt precipitation, irrespective of type. Stone is generally abundant in most regions of continental Australia. However, some wetlands can be far from sources. Other locations may have huge quantities of stone, but the quality may not be adequate for coastal projects because of low density or low strength. The main concern with stone is reduction in size through abrasion and splitting. Armour stones broken into smaller pieces can be washed from a structure by wave action. Maintenance consists of replacing damaged or missing stones, which can entail significant mobilization costs. Preservation of stone material is generally not feasible.

A3.3 Concrete and asphalt

Concrete is considered to be durable and is usually expected to last throughout the lifetime of most coastal projects. Cracks in concrete may lead to spalling of the surface and exposure of the steel reinforcement, which will immediately begin to rust. Cement and sand suitable for use in concrete mixtures are available in all coastal regions in Australia. Concrete quality is determined by the quality of its component materials and the method of mixing and placement. Air or water temperature and underwater placement may have an impact on concrete and asphalt handling requirements. Protective coatings can be applied to exposed concrete surfaces to help prevent flaking and to seal cracks that might allow water to penetrate the surface and cause corrosion of the steel reinforcement.

Asphalt it not considered to be a durable material because it has low strength in both compression and tension, it is subject to chemical reaction, its stiffness changes with temperature, and it is not resistant to impact or abrasion. Maintenance of asphalt structures consists primarily of patching or replacing damaged areas. Underlying earth materials may shift and settle, opening large cracks in the asphalt cover layer. These cracks must be repaired before the fill material erodes. Also, repeated cycles of large temperature change may open significant cracks in the asphalt.

A3.4 Steel

Steel must be protected from chemical and galvanic corrosion, unless it is made of special alloys such as stainless steel. Standard grade steel is considered very durable if properly protected. Bare mild steel will rapidly deteriorate in the corrosive estuarine and coastal environment. Sacrificial anodes will protect steel exposed to sea water, especially in the wet-and-dry regions and at the sand line, where sand particles continually abrade the paint and protective rust. Most steel maintenance involves reapplying protective coatings, replacing corroded structural members and fasteners, and replacing sacrificial anodes. Standard grades of steel in common cross-sections and stock lengths are generally available for coastal projects. Special cross-sections or less common steel specifications (such as high-strength steel or even stainless steel) are less likely to be available locally and may require additional transportation costs. Although stainless steel is more durable, its advantage is often offset by increased cost.

A3.5 Wood

Although wood is considered less durable than concrete, it can provide lengthy service life. Wood durability depends on its characteristics, usage and exposure to the elements, and on project maintenance. Wood is an organic material and can be attacked by land and marine animals at all places except below the mud line. Most wood deterioration occurs in the wet-and-dry tidal range. Fasteners and connectors, such as bolts and nails, must be protected from corrosion to ensure structural longevity. Dry wood is the least fire-resistant material commonly used in estuarine and coastal projects. Where available locally, hardwood often compares favourably in terms of cost and utility to other construction materials for structures such as bulkheads. Typical wooden structural components present no difficulty in transporting and handling.

Wood maintenance consists of reapplying protective surface coatings and replacing damaged members. Surface coatings include antifouling paints and coating materials that resist borer penetration, such as a 0.5-mm-thick coating of epoxy paint. Broken structural members should be replaced immediately to avoid additional damage to adjacent components.

A3.6 Geotextiles and plastics

Geotextiles and many plastics are generally resistant to chemical and biological attack, but will deteriorate when exposed to ultraviolet radiation. The rate of deterioration can be reduced by adding UV inhibitors, by coatings, or by a cover of soil, sand, water or even algae. The use of synthetic materials in estuarine and coastal construction projects is relatively new, and thus long-term durability of some materials has yet to be determined. Some synthetic materials are vulnerable to fire and can generate toxic fumes when ignited. For these reasons and other functional requirements, geotextiles are generally covered with soil.

Geotextiles and plastics can be economically transported by conventional means to all regions of Australia. Special handling equipment and techniques may be required to place fabrics, particularly underwater. If the geotextile is less dense than water, provisions must be made to hold it in place until it is overlain with denser material. Similarly, in above-water applications, wind can lift sections of fabric unless it is weighted down.

Maintenance requirements of synthetic materials vary widely, depending on the material and its application.

Appendix 4 Elements of operation and maintenance plan

A4.1 Description of the saltwater wetland

A description of a saltwater wetland should cover its physical, biological and chemical components. These include topography, soils, surface water, groundwater, quality, control structures, flora and fauna. Detailed information should be provided on how the processes involved in these components operate and relate to one another.

It can be helpful to describe the site by areas such as seagrasses, mangroves, saltmarshes, swamp forest, beaches, and sandy and rocky shores.

The management strategies or structures should also be described briefly to explain their purpose and how they are intended to operate.

A4.2 Specific management objectives

The list of specific management objectives should include the value of the saltwater wetland, how the value is being maintained or improved, which area of the saltwater wetland it applies to, and the planned outcome.

It may be helpful to present the management objectives in a table, for example as shown in Table A4.1. Such a table places the management objectives in context and displays any linkages between objectives.

Table A4.1 Management objectives table

Description of management objective	Value	Management activity	Subject area	Planned outcome
To improve flushing of the saltwater wetland	Water quality	Maintenance of constructed runnels	Open water area	Minimum tidal prism on neap tide of 1500 m^3

A4.3 Management activities or tasks

The list of management activities or tasks should address all the main elements of management, that is, operation, maintenance, monitoring and inspection, and emergency management. It follows on from the list or table of specific management objectives, and should be related to the objectives and areas or zones. Again, it is wise to prepare a table of management activities, repeating some of the information in the above table but adding detail. By tabulating the project in terms of activities, it is possible to show when one management activity addresses two or more management objectives. This is important to ensure that there is no conflict between objectives, or if such conflict is unavoidable that it is manageable with the proposed management activities.

The table of management activities should include details of the activity such as how to do the activity, and information on any precautions and safety issues. The list of management activities could be tabulated as in Table A4.2.

Table A4.2 Management activities table

Management activity	Management objective	Subject area	Planned outcome	Specification of what and how to do	Precautions and safety issues
Maintenance of constructed runnels	To improve flushing	Open water area	Minimum tidal prism of 1500 m^3	Inspect every 6 months and remove any obstructions >0.5 m^3 by back hoe	Ensure sediment is disposed of in accordance with approval conditions Excavation to be undertaken by a qualified operator

A4.4 Timetable for activities and resource availability

The timetable presents the time frame within which the activities are implemented and when the necessary resources are required. One way to present this information is with the activities listed down the left-hand side of a table and with months presented at the top of the table, with resource requirements presented down the right-hand side, as shown in Table A4.3. Such a timetable will help to implement activities at the appropriate time, to ensure that resources are available when required, and to identify any conflicts and minimise any disruption they may cause.

Table A4.3 Timetable of activities and resources

Activity	Month 5	Month 6	Month 7	…	Month *n*	Resources
Maintenance of constructed runnels		Six-monthly inspection and obstruction removal				Backhoe and operator
Activity 2						Resource 2

A4.5 Monitoring activities

The description of monitoring activities should include the operation or maintenance activity, objectives, duration, performance indicators and sampling methods.

Specific monitoring activities should be related to specific operation or maintenance activities so that the effectiveness of the management activities can be assessed, and improvements and modifications can be made as necessary.

A monitoring activities table can be prepared as shown in Table A4.4 (overleaf). More details on monitoring are presented in Chapter 6.

Table A4.4 Monitoring activities table

Monitoring activity	Related operation and maintenance activity	Monitoring objectives	Monitoring location	Monitoring duration	Performance indicators	Sampling method	Comment on monitoring result and required action
Recording water level at controlled outlet	Maintaining minimum tidal prism of 1500 m^3	Ensure minimum tidal range is 0.5 m	Immediately upstream of controlled outlet 1	28 days	Continuous water level – neap tide range	Temporary water level recording station	Install water level station for at least 30 days and check it once a week. Analyse results to compute minimum tidal range

A4.6 Inspection checklist

The inspection checklist is a subset of the monitoring activities and their outcomes. The checklist allows a record to be kept of the inspections required, the results of the inspection and any subsequent action taken. and whether or not follow-up action is required. A sample inspection checklist is shown in Table A4.5.

Table A4.5 Inspection checklist

Component to be inspected	Required frequency of inspection	Result of inspection	Action taken	Additional follow-up required
Floodgate 2	Monthly and following coastal storms and floods	Inspection on 28-11-05 following major flooding indicated moderate damage from floating log	Culvert cleared of debris and floodgate repaired and tested to be operating satisfactorily on 25-12-05	Method of diverting logs from floodgate and improved method of clearing debris to be devised

A4.7 Contacts

A list of contacts for approvals and advice is helpful to ensure that there are no delays in operation and maintenance work being implemented in accordance with the timetable, and that work is done in an effective way suitable for the site.

A4.8 Emergency management plan

An emergency management plan is required in the event that some part of the management fails or there is an unexpected 'outside' influence on the wetland. An example of failure would be a breach in a bund so that water is not directed as planned. Examples of outside influences are oil spills, dumping of waste and flooding.

It is important to consider the possibility of failure in each of the management activities, and to list the main types of failure along with appropriate mitigation measures.

Boardwalk construction (Kooragang Wetland Rehabilitation Project)

Appendix 5 Soil information

During saltwater wetland rehabilitation, soil can be handled in three phases of the construction process:

- excavation or cutting of soil from its original location
- removal and transport of soil from its original location to the deposition site
- deposition or placement and manipulation of soil on site or in a landfill.

A5.1 Soil information and testing

If soil is to be handled as part of a saltwater wetland rehabilitation project, it will be necessary to investigate a number of aspects relating to soils on site and any soils to be imported. Site soil information can be obtained from the following:

- SPADE Pro: DECC maintains the Soil Profile Attribute Data Environment (SPADE Pro) program to help users find the data they need. SPADE Pro allows you to zoom in to the area you are interested in, click on one of the soil profile points displayed, and retrieve a report with details about the landform and soil at that site. The information presented by SPADE Pro comes from SALIS, a centralised database that compiles descriptions of soils, landscapes and other geographic features from more than 58 000 collection points across NSW.
- Soil landscape reports, soil landscape 1:100 000 maps, soil landscape derivative maps and 1:25 000 acid sulfate soil risk maps.

If existing survey information is not available, a sampling program must be designed and undertaken, looking at the risks associated with permanently saturated saline or acidic soils and potential ASS to determine whether the soils will provide a suitable environment for plant growth. An investigation of site history may indicate the presence of contaminated soil or ASS. If inadequate soil investigation is undertaken, the consequent effects on the environment and the public may not be acceptable. If the site is contaminated, advice about management of contaminated sites is available in guidelines available from the Department of Planning (DUAP and EPA 1998).

The number of samples and the type of tests undertaken will depend on site complexity, site size and project budget.

A range of physical and chemical tests can be carried out to determine suitability for construction and plant growth. DECC has prepared a series of standard test methods for soil surveyors and those interested in interpreting or performing soil tests. The tests are reasonably simple and aim to ensure that accurate and consistent methods are used in laboratory tests. The methods are available from the DECC website: www.environment.nsw.gov.au. Tests may measure the following parameters:

pH

pH is a measure of a soil's acidity or alkalinity. Neutral soils occur in the range pH 6.5–7.3. Soils with a pH lower than 6.5 are classified as acidic, and soils with a pH above 7.3 are alkaline (Hazelton and Murphy 1992). Soil pH influences the availability of nutrients and metals to plants. Measuring soil pH will therefore help identify any problems that may be encountered during plant establishment. In strongly acidic soils (below pH 5), aluminium, manganese, copper and zinc are more available to plants and may reach toxic levels. At a pH above 5, calcium, magnesium, molybdenum and phosphorus may be unavailable, and iron, zinc and copper may be less available.

pH can be easily measured in the field using a mixture of soil and distilled or deionised water (in the ratio of 1:5) and a portable meter. Laboratory analysis of soil pH is recommended to confirm field tests. DECC's standard test methods should be followed.

Salinity (electrical conductivity)

Salinity is due to soluble salts, mainly sodium chloride. Electrical conductivity (EC) measures the amount of soluble salts (as ions). The level of salt will determine the type of plants suitable for revegetation projects.

Like pH, EC can be easily measured in the field using a mixture of soil and distilled or deionised water (in the ratio of 1:5) and a portable meter. The results should also be confirmed through laboratory analysis. DECC's standard test methods should be followed.

Organic matter content

Organic matter (OM) is important in soils. It is a reservoir of plant nutrients, helps conserve moisture, improves soil physical structure, and provides a favourable environment for soil microorganisms. As OM decomposes, it slowly releases nutrients for plant uptake. Soils with very low OM content are therefore less desirable than soils with a higher content. In Australian soils, an OM content of 3.5% (3.5 g/100 g) is considered high, and 0.5–1.5% is considered very low (Hazleton and Murphy 1992).

OM in soils immobilises metals in soils with low pH and mobilises metals at high pH. The rates depend on the mineral composition of the soil. Testing for OM in soils will determine the potential of these mechanisms to mobilise heavy metals.

OM, expressed as organic carbon, is determined by laboratory analysis. DECC's standard test methods should be followed.

Exchangeable cations and cation exchange capacity (CEC)

Cation exchange capacity (CEC) is a general indicator of soil storage capacity for available, positively charged plant nutrients such as calcium, magnesium, potassium and sodium and, in many acidic soils, aluminium. DECC's standard test methods should be followed.

A5.2 Dominant soil materials and their limitations

Soil limitations for dominant coastal soil materials are summarised below.

Saline black fibric peat (organic surface material): Salty black fibric peat with a spongy consistency and a greasy or highly organic feel. pH is about 6. Salt crusts occur on bare soil surfaces. High plasticity; low wet bearing strength; organic soils; very strongly sodic, high erodibility; ASS potential; strongly saline; high Al toxicity potential; low fertility.

Fibric peat (organic surface material): Waterlogged, dark reddish-brown fibric peat to black sapric peat. Highly saline with OM content of 20–30% and pH of usually 5–5.5. Low wet bearing strength; organic soils; sodic, acidity; salinity; high Al toxicity potential.

Black humic peat (topsoil or A horizon): Waterlogged, brownish-black humic peat or granular peat. Strongly saline with OM content of 20–30% and pH 5–5.5. Spongy or greasy feel, texture of loam to silty clay loam. Low wet bearing strength; organic soils; sodicity; acidity; salinity; high Al toxicity potential.

Yellow calcareous sand (surface and subsoil): Frequently saturated, saline, dull yellow-orange, loose, calcareous coarse sand with sandy fabric and pH 8.5. The material is commonly dredged and used as fill. Low wet bearing strength; organic soils; very strongly sodic; high erodibility; ASS potential, strongly saline; low fertility.

Jarositic grey mottled clay (subsoil, B horizon): Extremely acidic (pH 3.0–4.0), grey light clay with distinctive yellow mottling from ASS reaction product jarosite. Structure is 20- to 1000-mm sub-angular blocky. Cracks allow water movement, usually saturated. Originates from the oxidation of pyrite contained within the soil. High plasticity; extremely low wet bearing strength; sodicity; ASS; extreme acidity; Al toxicity potential; salinity; low fertility.

Grey saline sulfurous clayey sand (subsoil, D horizon): Permanently saturated, saline, grey, calcareous, coarse clayey sand with massive structure, sandy fabric and pH 8.5. Hydrogen sulfide (H2S) gas can be detected from fresh exposure. High plasticity; low wet bearing strength; very strong sodic; high erodibility; ASS potential; strongly saline; low fertility.

Unripe grey clay (subsoil, D horizon): Waterlogged, whole-coloured, grey, medium clay with massive structure and soft plastic 'buttery' consistence, indicating permanently saturated reducing conditions. Known as unripe material or potential ASS. pH is slightly acid to alkaline (6.0–8.5). Occasional fine rust/root-channel mottles. High plasticity; extremely low wet bearing strength; sodicity; alkalinity (localised); salinity; low fertility.

A5.3 Landscape limitations and impacts related to soils

Engineering and landscaping constraints

The identification of engineering hazards requires an assessment of the effect of the prevailing soil and landscape limitations on foundation stability. The most obvious engineering hazard is soil movement, which is related to the soil's physical properties, soil moisture regime and weight loadings. Soil chemical properties such as extreme acidity and salinity can also affect foundations through the corrosion of concrete and services. All of these factors can affect coastal soils in NSW. Significant soil qualities and limitations that affect foundation stability are soil reactivity (shrink–swell), soil plasticity, wet bearing strength, acid sulfate potential, salinity and organic matter content.

Limiting landscape factors that may be present include unconsolidated materials, high water table (seasonal and permanent), waterlogging, and high to severe water, wave and wind erosion hazards. Field observation and the analysis and interpretation of laboratory soil tests can identify limitations.

Subsidence

Estuarine mud and clay which have not consolidated are gel-like and cannot bear a heavy load (White and Melville 1993). Consequently, foundations or earthworks built on these materials may settle or subside unevenly over a long period as pore water is squeezed out. White *et al.* (1993) found a good relationship between overburden depth and level of loose mud. At a site near the Tweed River, changes to the level of the surface soils have caused variable depth of overburden. As loose clay extends to a depth of nearly 10 m, any surface structure at this site requires either deep piles or the laying of an extensive membrane. A comprehensive drainage system must also be designed in conjunction with the structural and geotechnical design.

Subsidence is also a problem when loose mud is drained. For each 1 m the water table is lowered, the soil surface will fall by at least 0.4 m (White *et al.* 1993).

Bank erosion

Upper bank erosion and toe erosion are problems where vegetation has been removed from banks and nearby floodplains. Possible long-term causal mechanisms include devegetation, waves and disturbance of the water table. The loss of the root mat component of the soil mass's cohesion is undoubtedly a vital factor in bank erosion.

Potential on-site impacts from soil-related activities

Plant growth

Drainage from ASS and pyritic rocks uncovered in cuttings or used in fills will affect plant growth. Waterlogging and salinity will also be a factor in plant growth in coastal lowland soils.

The soil-water in ASS (or drainage from pyritic materials) can limit plant growth in several ways:

1. Certain chemicals in the soil-water are directly toxic to plants. These chemicals include H^2S, Al^{3+}, Fe^{2+}, Fe^{3+}, Mn^{2+} and H^+. The toxic levels of each depend on factors including pH and whether the sediment is anaerobic or aerobic (that is, whether there is oxygen in the sediment or not). Fe^{3+} is unlikely to be toxic above pH 3, Al^{3+} above pH 5 and Fe^{2+} above pH 7 (Dost 1972).

   Aluminium is particularly harmful. Dissolved Al^{3+} is generally toxic to plants in concentrations of 0.04–0.08 mmol/L. Its toxicity does not depend on the amount of aluminium present, but on the change in the balance of other ions caused by the presence of Al^{3+}.
2. ASS prevent base nutrients and minerals such as calcium, magnesium and potassium from being available for plants to use. This is particularly so for phosphorus at a low pH, because aluminium and iron can form insoluble phosphates.
3. ASS can cause an increase in attacks by plant pathogens and a decrease in soil microbes, particularly those responsible for carrying nitrogen to plants.

The effect of ASS on plant growth can be confused when there is peat or alluvium overlying the ASS. Plant roots may be restricted to the surface layer of peat or alluvium, and plant growth may thus be less affected. Soils with different alkaline buffering capacities will also alter plant responses to acidic soil-water.

Release of heavy metals from contaminated soil

Where sediment contaminated with heavy metals has been deposited, spilled or dumped into streams or rivers, acidic drain water may release the heavy metals. At the normal pH of estuarine waters (close to 7), most heavy metals remain tightly bound to sediment. However, estuarine sediment contaminated with heavy metals from stormwater runoff may release these heavy metals when exposed to acidic drain water.

Clogging of aquifers and subsoil drains

Groundwater pumping in coastal aquifers where significant oxidation of pyrite has occurred can draw sea water into the aquifer. When well-buffered sea water meets acidic, iron-rich waters, ferric hydroxide and oxide can precipitate in the aquifer. If this takes place, sea water may be 'frozen' in place with little likelihood of moving back out to sea.

As well as the clogging of aquifers when iron-rich waters are exposed to air (owing to the precipitation of iron hydroxide and oxide floc or the trapping of long strands of bacterial mats and filaments), water wells, drains and pumps can be blocked or clogged. The red ochre, iron hydroxide and oxide flocs that precipitate when fresh or neutral pH water meets water of pH 4 or iron-rich waters can clog air voids in the subsoil almost completely.

Iron floc within a wetland (Adam Gosling WetlandCare Australia)

Potential off-site impacts from soil-related activities

Acidic waters from drains can cause lethal and sublethal effects on fish in estuaries. Observations linking acid drainage waters and fish kills include the association of several kills with heavy rains following prolonged dry spells and with rapid clarification of the water. It has been assumed that acidic products formed by the oxidation of sulfidic subsoils during dry periods are flushed into the rivers during rainy periods. The clarification of the river appears to be related to the flocculation of the suspended sediment by dissolved aluminium.

Potential hazards associated with soil-related activities

Rust

A significant hazard for rusting of iron or steel in soil occurs when:

- pH (1:5 soil–water) < 3.6 or
  pH (1:5 soil–$CaCl_2$) < 2.9
- clay content > 35%
- salinity > 0.8 dS/m ECe (USDA 1983).

When any one of these conditions occurs, rust is likely to result. The presence of sulfides and pyrite is also likely to contribute to the rust hazard. Site conditions such a fluctuating water table, poor drainage and the intersection of several different soil materials across any iron or steel structure will also contribute to rusting.

Concrete corrosion

A significant hazard for corrosion of concrete in soil occurs when:

- organic matter > 12%,
  clay < 10% and
  pH (1:5 soil–water) < 5.1 or
  pH (1:5 soil–$CaCl_2$) < 4.3
- clay < 35% and
- pH (1:5 soil–water) < 4.6 or
- pH (1:5 soil–$CaCl_2$) < 3.9
- salinity (ECe) > 15.6 dS/m (indicates previous presence of sea water) (USDA 1983).

Other significant soil conditions contributing to concrete corrosion include high amounts of sodium or magnesium sulfates.

References

Bush R, ed. 1993. *Proc Natl Conf Acid Sulfate Soils*, Coolangatta, Qld, 24–25 June 1993. CSIRO, NSW Agriculture and Tweed Shire Council.

DUAP, EPA. 1998. *Managing Land Contamination: Planning Guidelines*, NSW Department of Urban Affairs and Planning, Sydney.

Hazelton PA, Murphy BM. 1992. *What Do All the Numbers Mean? A Guide for the Interpretation of Soil Test Results*, NSW Department of Conservation and Land Management, Sydney.

US Department of Agriculture. 1983. *National Soils Handbook*. National Cooperative Soil Survey, USDA 430. VI. Govt Printer, Washington DC.

White I, Melville MD. 1993. *Treatment and Containment of Potential Acid Sulfate Soils*. CSIRO Centre for Environmental Mechanics, Technical Report No 53, CSIRO Publishing, Melbourne.