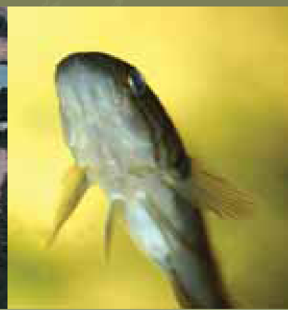
Understanding Ecological and Biophysical Processes in Queensland's Wetlands:

Literature Review and Gap Analysis



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Understanding Ecological and Biophysical Processes in Queensland's Wetlands:

Literature Review and Gap Analysis

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This is the final report for the Understanding Queensland's Wetlands: Literature Review and Gap Analysis project (WL NRM 01) of the Queensland Wetlands Programme, a joint initiative of the Australian and Queensland governments. The Queensland Wetlands Programme was established in 2003 to protect and conserve Queensland's wetlands.

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Disclaimer:

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Contents

List of tables

Executive summary

Introduction

This project has been funded under The Queensland Wetlands Programme, which is a joint initiative between the Australian and Queensland governments. The program objective is to produce long-term benefits for sustainable use, management, conservation and protection of Queensland wetlands. This project aims to support wetland management by reviewing current scientific literature and identifying and prioritising information needs pertaining to ecosystem services provided by wetlands.

The review has focused on information originating from Queensland, and where this is lacking, information from Australia and international sources has been included. Major topics in wetland science that have been addressed in the review are:

- wetland functions: an overview for selected wetland types
- quantification of valued biophysical processes occurring in wetlands. Emphasis in this topic was given to the role wetlands have in improving downstream water quality
- implications of information (or lack of) covered for the protection, management, assessment and rehabilitation of wetlands.

The report has focused on estuarine, lacustrine and palustrine wetlands. Wetlands not included in this review are:

- marine wetlands, such as seagrasses and coral reefs
- lotic waters, such as rivers
- impoundments
- karst and subterranean wetlands.

Findings

General understandings of important issues gathered from this project are listed below.

1. The definition of wetlands used in this project (and the Queensland Wetlands Programme) was too broad for a detailed discussion of the functions, threats and management of different aquatic ecosystems. The adoption of the concept of 'systems' such as those used by EPA's Wetland Mapping, Classification and Inventory project for use in policy, management and monitoring documentation could assist in developing a better information base. However, for each of these systems the development of a more detailed classification scheme is needed.
2. There were broad literature and knowledge gaps for palustrine wetlands (classified in terms of vegetation, those off-stream areas traditionally thought of as 'wetlands'). These wetlands are widely represented in Queensland, yet basic information on these types of wetlands was lacking. This highlighted a general need to prioritise these wetland types for further investment.
3. Tables (i) and (ii) illustrate the level of research (geographically based) found by the project. A relative paucity of information about wetlands occurring in inland non-arid areas is highlighted for further investment.
4. Spatial and temporal variation is a dominant factor for characterising and understanding wetland ecosystem components, processes and functions. There is a need for long-term monitoring programs.

5. Evidence exists that management regime impacts on wetland ecosystem components and functions. For example reduction in hydrological connectivity can impact on fish life history stages and also the values placed on wetlands associated with fish production.
6. A number of generic values are often attributed to wetlands. These values are largely unquantified and are variable depending on wetland type, position in the landscape, climate and a range of other factors. There is a lack of acknowledgement of the importance of understanding the distinct ecological characters and environs for wetlands along with their common features.
7. On-ground works and the protection of wetlands can be undertaken based on current knowledge; however, good management practices are needed to ensure that systems are monitored for the influence of these activities on changes to a wetland's ecological character and ecosystem services. The information gained will increase our understanding of wetland ecosystems, which will in turn provide a better knowledge base for future projects.
8. Information detailing the effects of implemented management actions is often unavailable. Constructed wetlands are used and proposed for the control of water quality issues in agricultural areas. However, information relevant to Australia, especially for tropical and subtropical regions, is sparse. Information from international sources also lacks clarity on the beneficial role that agricultural-based constructed wetlands can have on improving downstream water quality. Temporal variation in much of the current research suggests long-term studies are essential.
9. Groundwater is potentially an important source of water quantity and quality for wetlands, and the current level of understanding of groundwater-surface water interactions in wetlands is low. Where groundwater connectivity is identified as a process important to wetland functioning, indicators specific to groundwater ecosystem assessment should become part of standard wetland assessments.
10. While there is international evidence that a number of anthropogenic processes impact on the ability of wetlands to retain nutrients, causal relationships between high-risk agricultural activities, wetlands and near-shore water quality are not clear. This is a result of:
    - a lack of quantification on the ability of wetlands to significantly improve the water quality in diffuse agricultural settings
    - international literature suggesting that to improve the water quality of near-shore areas, relatively large areas of the drainage catchments must be returned/left as wetlands. Landscape placement of wetlands is also likely to be important. These factors have not been considered or validated at this time for tropical Queensland
    - activities that are likely to impact on a wetland's ability to improve water quality (although known to some extent) not being well quantified, and therefore a wetland's ability to improve water quality is hard to predict.

Knowledge gaps

A number of knowledge gaps are identified as part of this project and priority issues are listed below.

- A need for more detailed process studies is evident, in particular:
    - Long-term whole–of-system studies of wetlands are needed, as there is a lack of understanding of their different ecological characters and functions, in particular palustrine wetlands. This understanding is critical in managing and rehabilitating wetlands to maintain the functions and processes that provide the ecosystem services often attributed to wetlands.
    - Changes to the ecological character of wetlands have been linked to reduction in wetland functions such as biodiversity and water quality improvement. Further information about the nature and extent of modification of wetlands through anthropogenic processes is needed if these functions are to be maintained.
    - Most research on wetlands document high spatial and temporal variability. Longer-term studies will therefore enhance understanding of the natural ecological and hydrological processes that contribute to variability that occur in wetlands. This understanding will be important in assessing ecosystem services provided by wetlands which are currently masked by natural variability, for example water quality improvement.

- o While hydrological modification is often cited as a threat to wetland ecosystems, explicit impacts are not well understood in Queensland. Hydrological and ecological connections between wetlands and other aquatic ecosystems are altered in many agricultural and urban settings. This currently has large potential ramifications for the wetland ecology and delivery of ecosystem services to all freshwater and near-shore aquatic and associated ecosystems.

- If wetlands are to be constructed or restored to meet water quality objectives, the following issues should be further investigated:
  - o the ability of wetlands to improve water quality in diffuse agricultural settings. The CSIRO is currently running a project in the Wet Tropics; however, more study may be required, given variation in design, climate and the documented spatial and temporal variability of wetlands
  - o guidelines for constructing and restoring artificial wetlands for specific objectives. Guidelines are required, especially in agricultural settings. Designs should incorporate, where possible, features that enhance habitat values of these wetlands. Findings of the Sugar Industry Infrastructure Package wetlands project in the Tully-Murray and Herbert catchments and the CSIRO project in the Tully-Murray are envisaged as being an initial reference for this issue
  - o international studies estimate that 2-7 percent of a catchment area needs to be left as, or restored to, wetlands for a significant reduction in nutrients exported from a catchment to be achieved. This estimate requires validation for Queensland, in particular in tropical areas
  - o the flux of water quality parameters entering and exiting wetlands constructed for the purpose of water quality improvement. Currently, monitoring is limited but would be a valuable information source
  - o Given the number of wetland construction and restoration projects occurring worldwide, a further dedicated review, accessing international literature, is recommended to add to the information already recorded.

- The ecological benefits of artificial wetlands need assessing. This should be conducted in terms of the whole aquatic ecosystem because in many areas artificial wetlands may act as habitat or refugia for aquatic organisms where other wetlands have been removed or are in decline (e.g. dams, constructed wetlands and bore drains). However, artificial wetlands are unlikely to replace all the attributes, processes and values provided by intact original wetlands.

Conclusion

Many functions are attributed to wetlands, such as water quality improvement, water regulation, shoreline protection, biodiversity functions and carbon sequestration; however, while there is empirical evidence to support indications that some wetlands perform these functions, others do not. Processes that occur within and between wetlands are complex and highly variable and much remains to be understood. Key questions when looking at research into the landscape functions of wetlands include: Do the processes that lead to the provision of ecosystem services occur in all wetlands?; What are the biological, physical and chemical attributes of wetlands that govern these processes?; and At what levels are anthropogenic influences impacting on wetland processes?

This review of the current understanding has in part highlighted answers to some of these questions; however, in many cases the necessary information needed to efficiently manage wetlands for their physical and ecological functions is lacking. A number of current projects are investigating wetlands in Queensland and this knowledge coupled with further research into the knowledge gaps (cited throughout this document) will benefit management of wetlands for the provision of ecological values and functioning.

Table i: Availability of research in Queensland, based on wetland type

Wetland type reviewed by report	Region in Queensland *							
	South-east Queensland	Wallum	Central	Wet Tropics	Eastern Cape and Jardine	Western Cape and Gulf	Lake Eyre and Bulloo Basins	Murray-Darling Basin
Mangroves	C	C	C	C	R	R	NA	NA
Saltmarshes and flats	R	L	R	L	L	L	NA	NA
In-stream waterholes in arid areas	NA	NA	R	NA	NA	L	C	R
Coastal dune lakes	R	C	U	L	L	L	NA	NA
Terminal and subterminal lakes	NA	NA	L	NA	NA	U	R	R
Billabongs/lagoons	L	L	L	L	L	L	L	R
Forest and woodland wetlands	R	L	L	L	L	L	L	L
Wetlands dominated by shrubs	U	U	L	U	U	L	L	L
Wet heath and fen	L	L	U	L	L	U	NA	NA
Sedgelands/ grasslands etc.	L	L	L	L	L	L	L	L
Claypans	NA	NA	L	NA	NA	U	L	R
Spring wetlands	U	U	R	R	R	R	R	R

Key

NA: not applicable

L: Lack of research; type is known to area

U: Unclear if this wetland type exists in area

R: Research available; a number of gaps still exist

C: A good knowledge base exist

* Broken down into freshwater biogeographic provinces after Marshall *et al*. 2006

Table ii: Availability of research in Queensland, based on wetland functions

Wetland value reviewed by report	Region in Queensland *							
	South-east Queensland	Wallum	Central	Wet Tropics	Eastern Cape and Jardine	Gulf catchments	Lake Eyre and Bulloo Basins	Murray-Darling Basin
Improvement of water quality	L	L	R	R	U	L	L	L
Water regulation and shoreline stabilisation	L	L	L	L	L	L	L	L
Groundwater interactions	L	R	R	R	L	L	L	L
Biodiversity values	R	R	R	R	L	L	R	R
Production export	L	L	L	L	L	L	L	L
Carbon storage	L	L	L	R	L	L	L	L
Buffering acid sulphate soils	R	L	R	R	U	U	U	U

Key

NA: not applicable

L: Lack of research; type is known to area

U: Unclear if this wetland function is applicable to the area

R: Research available; a number of gaps still exist

C: A good knowledge base exists

* Broken down into freshwater biogeographic provinces after Marshall *et al*. 2006

1. Background

Introduction

Queensland's wetlands are situated in all landscape types from the arid Lake Eyre Basin of inland Australia to the Great Barrier Reef. This diverse and extensive array of wetlands is important for its ecological characteristics and the ecosystem services it provides. In terms of functions these wetlands potentially provide:

- water quality filters or sinks for nutrients, sediment and other contaminants
- habitat, which in many cases includes habitats for rare and endemic species and nursery and breeding habitats for many marine and freshwater species including commercially important fish and crustaceans
- refuges for fauna and flora in times of drought
- sinks for mitigation of floodwaters and for replenishment of groundwater.

Recently the Australian and Queensland governments implemented a joint initiative titled 'The Queensland Wetlands Programme' that aims to produce long-term benefits for sustainable use, management, conservation and protection of Queensland wetlands (Department of Environment and Heritage, Australia, 2006a). Management of wetland areas in Queensland is currently controlled by a number of mechanisms, including planning measures under all levels of government, industry and landholders. As no single institution, whether industry, research institution, government department or university, is responsible for all research and development related to wetlands, it follows that research findings for the protection, restoration and management of wetlands have not been fully scoped and assessed. This project aims to review the scientific literature pertaining to wetlands, in particular the ecosystem services provided by wetlands. Part of this scoping will identify knowledge gaps and where possible provide recommendations on filling these gaps. In this way, base scientific knowledge can be built on in successive phases of investment under the program.

Scope and prioritisation

Given the potentially broad scope of the review, and limited timeframe around report completion, focus on priority areas (described below) has been instigated in terms of the types of wetlands included, geographical regions and the areas of wetland science addressed. The review has tried to focus, where possible, on information originating from Queensland, then where necessary Australia and international sources.

Geographical regions

Within Queensland, regions categorised as a priority (in order of priority) are:

- catchments discharging to the Great Barrier Reef
- south-east Queensland
- Gulf catchments
- Lake Eyre Basin
- mid-west Queensland.

Wetland science

The following are the main topics addressed in the review:

- an overview of wetland functions for selected wetland types based predominantly on literature from Queensland and Australia, to assist in the development of an understanding and conceptual framework of how wetland types function
- research that quantifies the biophysical processes that occur in wetlands that are thought to be valuable to other ecosystems or to humans. Emphasis has been given to the role wetlands have in improving downstream water quality
- the implications of state of research into the above topics on the protection, management, assessment and rehabilitation of wetlands.

1. Background

Report structure

A brief description of the content and objectives of each section is described below:

- Chapter 1 is the introduction and includes details of the report structure.
- Chapter 2 deals with a brief summary of the research that has been undertaken on wetlands of different types, predominantly in Queensland, with examples taken from elsewhere when necessary. This section presents an overview on the quantity of research into different ecosystems in terms of the wetland science this review is addressing.
- Chapter 3 scopes and reviews the existing knowledge on selected functions that wetlands provide. This section reviews scientific knowledge from Australian and international literature.
- Chapter 4 is a brief review of some of the major threats to wetlands, and the Australian research undertaken to manage the impacts of these threats.
- Chapter 5 discusses the implications of the research reviewed in all sections on the assessment, management and rehabilitation of wetlands. In particular this section concentrates on areas where further investigation is needed.
- Chapter 6 gives some broad recommendations and lists the main priorities for future research.

Definitions

In order to provide clarity and ease of reference, this work makes cross-reference to, or has adopted, definitions of relevant key terms as used by the Ramsar Wetlands Convention (Ramsar 2006a). These terms and their definitions include:

- ecosystem services — the benefits that people receive from ecosystems, including provisioning, regulating, and cultural services
- ecological character — the combination of the ecosystem components, processes and benefits or services that characterise the wetland at a given point in time
- change in ecological character — the human-induced adverse alteration of any ecosystem component, process, and/or ecosystem benefit or service
- functions of wetlands - activities or actions which occur naturally in wetlands as a product of interactions between the ecosystem structure and processes. Functions include floodwater control; nutrient, sediment and contaminant retention; food web support; shoreline stabilisation and erosion controls; storm protection; and stabilization of local climatic conditions, particularly rainfall and temperature.

Ramsar has recently updated its terminology to accord with those of the Millennium Ecosystem Assessment (MA) that assessed the consequences of ecosystem change for human well-being. Comparative terminology for describing wetland ecosystems is given below and MA terminology has been incorporated into this report.

MA ecosystem terms	Ramsar terms
Ecosystem components: physical; chemical; biological (habitats, species, genes)	'components', 'features', 'attributes', 'properties'
Ecological processes within and between ecosystems	'processes', 'interactions', 'properties'; 'functions'
Ecosystem services: provisioning; regulating; cultural; supporting	'services', 'benefits', 'values', 'functions', 'goods', 'products'

Source: Ramsar 2006b

Ramsar provides a conceptual framework incorporating these terms to illustrate wetland use and values (Ramsar 2006b). The term 'value' used in this document refers to something that is worthy, desirable or useful to humans (Mitsch and Gosselink 2000b) and as such provides an ecosystem service. The values of wetlands are determined not only by their functions, but also by human perceptions (Mitsch and Gosselink 2000b).

Ecosystem services in a local context are illustrated in Ramsar's toolkit for maintaining the ecological character of wetlands (Ramsar 2006b). The MA definitions adopted also provide unambiguous and informative terms and provide a global ecosystem context for wetlands and their management considerations.

This report investigates literature on various functions of wetlands, which are thought to provide the ecosystems services that are commonly associated with wetlands. Cultural, social and economic values of wetlands will not be reviewed; however, previous reviews have investigated these types of values, for example Bennett and Whitten (2002).

The agreed definition of wetlands under the Queensland Wetlands Programme foundation projects is:

> *Wetlands are areas of permanent or periodic/ intermittent inundation, with water that is static or flowing fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6 m.*

To be classified as a wetland the area must have one or more of the following attributes:

- at least periodically the land supports plants or animals that are adapted to and dependent on living in wet conditions for at least part of their life cycle
- the substratum is predominantly undrained soils that are saturated, flooded or ponded long enough to develop anaerobic conditions in the upper layers
- the substratum is not soil and is saturated with water, or covered by water at some time. (Environmental Protection Agency 2005g).

The definition above is derived from the definition used by Ramsar (Ramsar 2006), which is necessarily broad as it defines aquatic ecosystems on a global scale. For the purposes of this review it was necessary to restrict the number of ecosystems considered to reach some useful conclusions, and to remain within the committed timeframe of the project. Not included in this review are:

- marine wetlands, such as seagrasses and coral reefs
- lotic waters, such as rivers
- impoundments
- karst and subterranean wetlands.

To further break down the resulting group of aquatic ecosystems, the review discusses wetlands under the broad ecological systems of estuarine, riverine, lacustrine and palustrine (Environmental Protection Agency 2005g). The definitions of each system are provided below and essentially follow those of Cowardin *et al*. (1979).

Estuarine: Wetlands with oceanic water that are occasionally diluted with freshwater run-off from the land. Estuarine wetlands reviewed are mangroves, saltmarshes and salt flats.

Riverine: Riverine systems include all wetlands and deepwater habitats contained within a channel, with two exceptions: wetlands dominated by trees, shrubs, persistent emergent vegetation, emergent mosses, or lichens; and habitats with water containing ocean-derived salts in excess of 0.5 percent. A channel is 'an open conduit either naturally or artificially created which periodically or continuously contains moving water, or which forms a connecting link between two bodies of standing water' (Langbein and Iseri 1960). The only riverine wetlands reviewed in this report are waterholes.

Lacustrine: Lacustrine systems include wetlands and deepwater habitats with the following characteristics: situated in a topographic depression or a dammed river channel; lacking trees, shrubs, persistent emergents, emergent mosses or lichens with greater than 30 percent areal coverage; and total area exceeds 8 ha. Similar wetland and deepwater habitats totalling less than 8 ha are also a lacustrine system if an active wave-formed or bedrock shoreline feature makes up all or part of the boundary, or if the water depth in the deepest part of the basin exceeds 2 m at low water. Lacustrine wetlands reviewed in this report are coastal dune lakes, inland saline and freshwater lakes, billabongs, lagoons and pools.

1. Background

Palustrine: Palustrine systems include all non-tidal wetlands dominated by trees, shrubs, persistent emergent vegetation, emergent mosses or lichens. It also includes wetlands lacking such vegetation which have the following three characteristics: (a) where active waves are formed or bedrock features are lacking; (b) where water depth in the deepest part of the basin is less than 2 m at low water; and (c) salinity due to ocean-derived salts is still less than 0.5 percent. Palustrine wetlands reviewed in this report are forest/woodland swamps; swamps dominated by shrubs; wet heath and fens; swamps dominated by grass, sedge, reed or rushes; pans; and spring wetlands. (Cowardin *et al*. (1979), and Blackman, Spain and Whiteley (1992), slightly modified to fit the Australian environment)

Methodology

Information for this report was gained from two sources:

- a literature review, focusing on literature from Queensland, but also drawing from literature from other areas in Australia, and the international literature where studies were not identified from Queensland
- a series of interviews and workshops with individuals and organisations involved in research or management of wetlands in Queensland. This was undertaken to gather information from regional areas in Queensland and the perceived knowledge gaps in each of the regional areas visited.

Literature review

Given the wide focus of the report, a number of sources where used to collate reports and articles. These major sources are listed below:

- databases such as Scopus, Current Contents and Google Scholar to capture published literature
- searches of library catalogues of Queensland Government departments, in particular the Department of Natural Resources and Water, the Environmental Protection Agency and the Department of Primary Industries and Fisheries
- on-line searches of a number of websites of government, industry, recreational, conservation and research organisations, including:
    - federal and state government departments
    - the website of a number of research bodies, for example, CSIRO, cooperative research centres, and universities
    - the websites of funding bodies, such as Land and Water Australia and the Fisheries Research and Development Corporation
    - The Australian Digital Thesis website
    - The Australian Agriculture and Natural Resources Online database
    - the websites of community and industry groups, for example regional natural resource management bodies and Sunfish.

Workshops

As part of the project a number of workshops were conducted at different locations in Queensland, targeting individuals that have been undertaking research or management on wetland ecosystems. The main objectives of these workshops was to gather information on research that had been undertaken on wetlands in the area, to assist in the formulation of knowledge gaps in relation to wetland ecosystems in Queensland.

It was initially proposed that three scoping and gap analysis workshops would be conducted in Townsville, Rockhampton and Toowoomba. In the early stages of the review it was also decided to hold an additional workshop in Brisbane. The Townsville workshop was cancelled, as there were a large number of workshops that had been conducted or were being planned for the Townsville region, which were also dealing to some degree with the effects of wetlands on downstream water quality. In order to lessen the time demands on researchers and managers in the region, each organisation was visited separately.

In addition to workshops a number of other individuals were contacted to collate literature and other information for assimilation into the final products. These discussions are not included as part of the appendices of this report.

Participants of the workshops included representatives from a number of Queensland Government departments, CSIRO, Great Barrier Reef Marine Park Authority, Sunfish, Central Queensland University, James Cook University, the University of Southern Queensland, and a number of natural resource management regional bodies.

Questions were formulated for the workshops; however, due to the diversity of people attending them, it was decided to keep the interviews/ workshops informal and these questions were used as prompts.

The main points of discussion were:

- projects that were being undertaken into wetlands in the region
- discussion around the proper management of wetlands, both natural and constructed
- restoration of wetlands
- monitoring and assessment of ecosystem health in wetlands
- gaps in wetland research
- other contacts in the region.

Workshop reports for Rockhampton, Brisbane and Toowoomba and a report on the series of interviews undertaken in Townsville and Cairns have been produced. These reports are included in the Appendix.

Limitations

As discussed in the section on Definitions (see page 2), the Ramsar definition adopted by the Queensland Wetlands Programme is broad. Using this definition, wetlands exist over a range from shallow marine to alpine (although the latter do not exist in Queensland) and include running waters. Given the timeframe it was difficult to provide an overview of research on all wetland types, as 40 of the types listed in the Directory of Important Wetlands are present in Queensland (Environment Australia 2001). This review has tried to overcome these issues by:

- grouping wetlands, for example fens and wet heath
- not reviewing the wetlands listed in the Definitions section (see page 2) (rivers, karst, impoundments and marine wetlands)
- limiting the review predominantly to the biophysical processes that occur in wetlands and the functions provided by wetlands
- providing an overview of literature predominantly from Queensland, unless information was not available
- providing comment on any perceived lack of study of groups of wetlands where little literature exists in Queensland.

Given the complexity of the subject matter, it has been necessary to summarise complex subjects that, in some cases, could be the subject of a review of similar size themselves.

2. Wetland ecosystems

Functions of estuarine wetlands

In Queensland and elsewhere, estuarine wetlands, in particular mangroves, appear to be the most comprehensively studied of the wetland types discussed in this report. Estuarine wetlands have many values and functions attributed to them; in particular they are often cited as having an important role in connecting nutrients and other resources, such as fish, between coastal habitats and the marine environment (Cappo and Kelley 2001). Some of the values of saltwater wetlands are listed in Table 2.1.

Table 2.1: A qualitative list of values and functions of saltwater wetlands

Water	Store floodwaters
	Conserve water during drought periods
	Desalinate salty water
Organic productivity	High primary productivity
	High secondary productivity
	High export of organic foods to other ecosystems
	High wood production in mangroves
Biogeochemical	High capacity to recycle nutrients
	High storage of organic matter and CO2 sink
	Net oxygen production
	Many biochemical cycles are closed by reducing N, C, S, Fe, etc. in anaerobic muds
	Heavy metals, radioactive isotopes and other poisonous chemicals are sequestered in anaerobic muds
Geomorphological	High potential for erosion control
	Protection of coastlines against storms, tides and wind
	High potential to build land
Biotic	Serve as fisheries nurseries, bird rockeries and refuges for terrestrial animals
	Gene banks for haline and euryhaline plant and animal species
Other values	Natural laboratories for teaching and research
	Location for recreation and relaxing
	Rich organic soils used in agriculture, aquaculture, or as fuels
	Location for solid waste disposal or construction activities
	Importance as natural heritage
	Representative of personal intangible values

Source: from Lugo and Brinson 1978

While ecosystem services and ecosystem components and ecological processes of wetlands in general are often listed in relevant literature as in Table 2.1 above, they are rarely quantified. Furthermore, wetland type is rarely specified, which makes interpretation difficult as it is unlikely that all estuarine wetlands fulfil all functions. The following is a review of the functions and processes occurring in tropical and subtropical estuarine wetland types in Australia.

Pathways of material and energy movement in ecosystems are highly complex in estuarine and other wetland ecosystems; however, in a general discussion of the topic, a model for mangroves and estuaries has been proposed (Pearson and Connolly 2001).

Mangrove forests

Mangroves are commonly found on intertidal mud flats along the shores of estuaries. In Queensland, this occurs in the region between saltmarshes and seagrass beds. Mangrove trees have variably adapted to cope with the stress of being periodically inundated with saltwater and employ methods of salt secretion, exclusion and accumulation (Lovelock 1993). Queensland has the largest area of mangroves in Australia (Lovelock 1993). The composition of mangrove plant communities varies throughout Australia, but in general terms species diversity decreases with increasing latitude south (Cappo and Kelley 2001). Of the 69 species recorded worldwide, 34 species have been recorded in Queensland with 3 hybrids (Lovelock 1993). Information on the distribution, conservation status and management of mangroves can be found in the EPA management profile on mangroves (EPA 2006f).

Mangrove habitats have been simplified to three functional types: basin, river-dominated and tide-dominated, as a framework to differentiate the ecosystem services provided by stands that occur in different environmental settings by Ewel, Twilley and Ong (1998). Mangrove forests have been classified in several ways, for example based on mangrove physiognomy or environmental setting (Woodroffe 1992).

This is a brief review of mangrove ecosystem understanding and has drawn heavily from previous reviews that deal with aspects of mangrove function (Cappo *et al*. 1998; Lee 1998; Cappo and Kelley 2001). The functions of mangroves most often listed in literature include:

- visual amenity and shoreline beautification
- shoreline protection
- nutrient uptake, fixation, trapping and turnover
- carbon sinks and sequestration
- primary and secondary production
- sediment trapping
- habitat for specialised fauna
- forest products, although this is not widely used in Australia
- fisheries production (Schaffelke, Mellors and Duke 2005)

Some of the functions mentioned above, such as carbon sequestration and value to fisheries, will be discussed for wetlands generally in Chapter 3. A brief discussion of sediment trapping, nutrient uptake, carbon sequestration, and primary and secondary production follows.

Sediment trapping

Mangroves are depositional environments, characterised by the long-term import of sediment (Woodroffe 1992). Mangroves can help reduce sedimentation in adjacent marine habitats by reducing the velocity of water and trapping sediments using tangled roots, pneumatophores and trunks. Along with this ability to trap sediment, associated river-borne nutrients and other pollutants are likely to be trapped and recycled within mangroves (Duke 1997). Riverine mangroves are thought to trap some of the sediments from river water, basin mangroves may trap finer sediments that are carried further into the mangrove stand by floods and tides, and fringe wetlands are thought to trap riverine sediment that has been recirculated in near-shore waters (Ewel, Twilley and Ong 1998).

Studies of the tropical embayments in Hinchinbrook Channel, Cleveland Bay and Trinity Bay by Wolanski, Spagnol and Lim (1997) found a high turbidity zone in intertidal areas during spring tides, especially high tides. This high turbidity zone was generally restricted to a narrow barrier along the coast. This study demonstrated that mangroves accelerate the formation of macro-aggregates, by providing an organic nucleus in spring tides when mangrove detritus is exported into the coastal boundary layer. This nucleus initiates the aggregation of sediment particles and small inorganic flocculations (flocs) into much larger flocs, which settle faster than fine sediment so that along mangrove-fringed coasts the width of sediment trapping zones is greatly reduced and much of the sediment does not reach the 5 metre depth. The flocs may then be recirculated back into mangrove areas where they settle. There is a theory that where mangroves trap sufficient material, coastal waters are relatively free of turbidity and this process has allowed other near-shore ecosystems such as seagrass to develop (Wolanski, Spagnol and Lim 1997; Duke and Wolanski 2001). The dynamics of the coastal boundary layer and the mangroves and tidal flats which trap, transform and store sediment and organic matter in the coastal zone may also help to explain why coral reefs on the middle and outer shelf have remained relatively unscathed despite a significant increase in sediment delivery (Alongi and McKinnon 2005).

If mangrove forests remain intact then sediment trapping will occur (Ewel, Twilley and Ong 1998). This is an important ecosystem service that wetlands provide; however, their capacity to effectively trap sediment is finite and care should be taken in the catchment to ensure that sedimentation is not so great that pneumatophores, prop roots and young stems are buried, as this is detrimental to the health of mangroves (Ewel, Twilley and Ong 1998).

Nutrient processes

Mangrove wetlands are thought to be efficient at retaining and recycling nutrients by several mechanisms including:

- re-absorption or re-translocation of nitrogen prior to leaf fall
- burial of fallen detritus by crabs
- rapid uptake of dissolved materials by bacteria and comparatively high nitrogen content in trees
- high rates of plant growth and productivity within the forests
- nutrient transformation processes in mangrove sediments (Alongi 1996).

Environmental factors such as tidal inundation, sediment types, rainfall, climatic disturbances and topography will also affect the nitrogen retention capacity of mangrove stands (Alongi, Boto and Robertson 1992). Some international authors discuss differences in the ability of mangrove forests to retain nutrients within a framework based on the environmental setting (Ewel, Twilley and Ong 1998) (see Mangrove forests, page 7). Basin mangroves are thought to be more likely to serve as sinks and fringing mangroves more likely to export nutrients to adjacent habitats (Woodroffe 1992; Ewel, Twilley and Ong 1998).

Studies in Queensland have found that mangrove ecosystems appear to have the capacity for nutrient retention and transformation. A study of variation in benthic nutrient pools and rates of dissolved nutrient exchange between the forest floor and tidal water, over a five-year period, in mixed *Rhizophora* forests lining Coral Creek, Hinchinbrook Island, Queensland, found that intertidal forests accounted for 95 percent of the net annual import of total dissolved nitrogen, and 66 percent of the net annual import of total dissolved phosphorus, into the tidal basin (Alongi 1996). These imports came from adjacent coastal waters.

Calculations of the ability of mangroves to assimilate elevated nutrients released from aquaculture systems have also been attempted. Budgets for nitrogen and phosphorus output in prawn ponds have been combined with estimates of total net primary production to further estimate the ratio of mangroves necessary to remove nutrients from pond effluent (Robertson and Phillips 1995). Results of these calculations showed that for a 1 ha prawn pond, between 2 and 22 ha of mangrove forest are needed to assimilate all of the effluent nitrogen and phosphorus. The uncertainty in the size of mangrove area needed was due to a number of pond management factors. The authors stated that the study results could not be extrapolated to larger scales and direct experimentation on the effects of mangroves on pond effluent was needed (Robertson and Phillips 1995; Lee 2004).

Primary and secondary productivity

Mangroves are commonly cited as being highly productive ecosystems, for example Lee (2004). This is often misleading, as while some mangrove systems have been shown to be highly productive, others are not (Clough 1998). Estimates from Hinchinbrook Channel, Queensland, show that these mangrove ecosystems are highly productive (Clough 1998), as they were found to be net autotrophic with the amount of carbon fixed greatly exceeding that respired and buried (Alongi *et al*. 1998). These areas have the potential to export large amounts of carbon to coastal waters; however, carbon transport in this system does not only occur in one direction, with some organic matter imported into mangrove creeks (Mueller and Ayukai 1998; Wolanski, Spagnol and Ayukai 1998).

The degree to which productivity from mangrove forests is exported to near-shore consumers has been the source of some debate, which is still continuing today to some degree (Cappo *et al*. 1998). Early overseas studies supported a paradigm in which mangrove forests were important in supporting near-shore secondary production via detrital-based food chains; however, investigations of the connectivity of materials in the Great Barrier Reef World Heritage Area (GBRWHA) has reported that the 'outwelling' of mangrove material is of limited importance in the coastal zone of the GBRWHA (Cappo *et al*. 1998). Little material, relative to the total tree production and standing biomass of the habitats, is exported and it generally does not move more than a few kilometres from mangrove estuaries.
This carbon is thought to have a significant impact on sedimentary nutrient cycles, but it does not translate into a significant dietary subsidy for coastal macro-organisms such as fish and prawns found outside of the mangrove forests. This is despite the fact that juveniles of some penaeid prawns do feed on mangrove detritus (Cappo *et al*. 1998).

Current understanding of these ecosystems is that organic matter export is limited in both quality (leaves and detritus, low in nutrients and high in tannins) and spatial extent (Lee 1999). Some systems are also thought to import organic matter (Alongi *et al*. 1998; Mueller and Ayukai 1998; Wolanski, Spagnol and Ayukai 1998). Further evidence supporting these conclusions has come from studies using stable isotopes. Much of the stable isotope evidence has recorded little resemblance between consumers in surrounding environments and mangrove signatures (Loneragan, Bunn and Kellaway 1998; Connolly and Guest 2004; Connolly, Gorman and Hindell 2005).

Although this outwelling of nutrients in near-shore environments may not be as important as initially thought, there is still sufficient evidence from biological surveys (which generally indicate a high level of biodiversity and abundance of fish and crustaceans around mangrove areas) to suggest that mangroves are important to fish stocks (Lee 1999). The role of mangroves in fisheries production is discussed further in Estuarine wetlands (see page 6). Cappo and Kelley (2001) developed a conceptual model of a chain of habitats in the GBRWHA, with all coastal and near-shore habitats being important to the integrity and health of the system. The connectivity of areas in the coastal and near-shore region is not well understood in terms of nutrient movement through sediment, water, or the movement of organisms (Appendix 1).

Given many studies indicate that mangroves do not export large amounts of material, the question remains: Where does the carbon produced by mangroves go? It is now thought that invertebrates consume much of this carbon and it is predominantly recycled within the mangrove forest (Connolly and Guest 2004). A study in Missionary Bay, Queensland, found that in terms of carbon only 2 percent is lost via tidal exchange, and this tends to be mostly in the form of larger particles such as roots, leaves and wood (Cappo *et al*. 1998). A review of the role of grapsid crabs in mangrove ecosystems found that these organisms play a significant role in the ecological functioning of tropical mangrove ecosystems (Lee 1998). The main functions include:

- Through the feeding activities of the crabs, large proportions of organic matter production, for example mangrove leaves, are recycled within the forest (Robertson 1986; Lee 1998).
- Crab-processed organic matter could also form the basis of a detrital food chain or be re-exported as micro-particles (Lee 1998). Further research found that leaf litter processed by crabs undergoes enrichment, which would be of benefit to both benthic and pelagic estuarine consumers and may provide a contribution to near-shore secondary production in this way (Werry and Lee 2005).

- Differential consumption of mangrove propagules by crabs reduces the relative abundance of species that prefer propagules as a food source (Lee 1998).
- Bioturbation by crabs is another important role as it results in changes in surface topography, particle size distribution and degree of aeration, and in this way reduces the concentration of phytotoxins in the substratum. These crab burrows are also thought to be important in surface groundwater interaction (Lee 1998).

Saltmarsh and salt flats

Saltmarshes are situated in the intertidal zone, below the level of highest astronomical tide but above the low tide level. Saltmarshes may be bare or vegetated (EPA 2005e). Vegetated saltmarshes fall into two categories: those dominated by samphires and those dominated by sparse to dense, low tussock grassland (EPA 2005e). As part of the continuum of saltmarshes on tropical coasts subjected to macro-tidal regimes and seasonal rainfall, the upper part of the intertidal zone may experience prolonged hypersaline conditions, which subsequently form expansive salt flats. These salt flats are characterised by sparse or absent vegetation, although microbial mats may be well developed (Adam 1998). Information on the distribution, conservation status and management of mangroves can be found in the EPA management profile on saltmarshes (EPA 2005e).

A review of Australian research into saltmarshes found that coastal saltmarsh was one of the least studied major vegetation types in Australia, with upper tidal flats (salt flats) being extremely poorly studied, although studies of saltmarshes globally are quite extensive (Adam 1998). Literature surveyed in the Aquatic Sciences and Fisheries Abstracts found that Australian saltmarsh studies make up only 3 percent of the global research into saltmarshes in the 44 years to 2004 (Lee and Choy 2004). In recent years, however, a number of studies have been conducted on Queensland saltmarshes (Ridd, Sandstrom and Wolanski 1988; Ridd *et al*. 1997; Thomas and Connolly 2001; Ridd and Stieglitz 2002; Lee and Choy 2004). Despite this increased research effort, information pertaining to saltmarsh is still scarce. This lack of direct study on Australian saltmarshes is compounded when considering the international literature on saltmarshes may not be broadly applicable to Australia. Adam (1998), Connolly *et al*. (1997) and Thomas and Connolly (2001) discuss these issues and concluded that:

- Many Australian marshes lack permanent deep creeks and pans.
- Saltmarshes tend to occupy the intertidal areas behind mangroves in Australia, whereas in the Northern Hemisphere, mangroves are generally lacking and saltmarshes extend down to the mid-intertidal zone. This change in landscape position means that Australian saltmarshes will have considerably shorter and less frequent periods of inundation.
- The vegetation structure and composition is significantly different from many Northern Hemisphere saltmarshes. In Australia short succulent bushes and salt couch grass dominate vegetation, whereas in North America much taller stands of cord grass is the usual vegetation.

In light of these issues the following discussion will focus on information pertinent to Australian saltmarshes. The important landscape functions that saltmarshes are thought to perform include feeding habitat for migratory birds, habitat for juvenile fishes, buffering and filtering system for sediments and nutrients, stabilisation of the substrate, and outwelling of material to near-shore environments (Adam 1998). The following sections discuss some of these functions in more detail.

Sediment and nutrient processes

Saltmarshes and mud flats have been observed to play a significant role in nutrient cycling due to factors such as the relatively large sediment to water ratio and the biogeochemically active nature of sediments (Cook, Butler and O'Grady 1999). Intertidal sediments have rapid temporal and spatial changes in redox status caused by inundation and immersion cycles especially when combined with other factors such as the presence of macrophytes, which can act to ventilate sediments (Reddy, Patrick and Lindau 1989; Cook, Butler and O'Grady 1999). The presence of aerobic and anaerobic interfaces is likely to increase processes such as nitrification and denitrification (Reddy and D'Angelo 1997). International literature is mixed on the role of saltmarshes as sinks or sources of nutrients, and while recent views have had a tendency to support the likelihood that saltmarshes have a role as transformers of nutrients, importing inorganic nitrogen and exporting organic nitrogen, the dominant saltmarsh process seems to be rapid internal cycling of nutrients (Cook, Butler and O'Grady 1999). Few Australian studies have measured nutrient cycling capacity of these ecosystems, although it is often listed as a function of saltmarshes.

Queensland-based research has investigated outwelling of nutrients from salt flats (Ridd, Sandstrom and Wolanski 1988; Ridd *et al*. 1997). Tidally averaged outwelling of salt, phosphates and silicate during spring tides, especially high tides, in the Norman River in the southern Gulf of Carpentaria was considerable at 90 g of salt per m^2 per tidal cycle, 1.0 mmol silicate/m^2/tidal cycle and 3×10^{-2} mmol orthophosphate/m^2/tidal cycle (Ridd, Sandstrom and Wolanski 1988). Outwelling occurred only during spring tides in summer and virtually not at all in winter in this region. This inundation pattern is unrepresentative of the typical tidal conditions in Queensland salt flats, as in the southern Gulf the mean sea level is approximately 1 m lower in winter due to wind (Ridd *et al*. 1997). A study on salt flats at Cocoa Creek, Townsville, which was deemed a more representative site, also found outwelling of salt, silicate and phosphates in spring tides which occur in this area throughout the year (Ridd *et al*. 1997).

In general the research indicates that tropical tidal salt flats are the source of large quantities of nutrients to the near-shore zone. Given the extensive area of salt flats in north Queensland and the discharge of nutrients throughout the year, as opposed to rivers in the area which discharge only for a few months a year, they may be a very important source of nutrients to river estuaries and near-shore environments (Ridd *et al*. 1997).

Water regulation and storm buffering

Saltmarshes and salt flats play a role in both the regulation of floodwater and in the protection of the coastal environs from storm damage. Little Australian literature exists on these functions. Observational reports of large expanses of salt flats, which after rain had been inundated with freshwater in north Queensland, gives some indication that these areas are capable of storing considerable amounts of water after rainfall (Cappo 2004). A general discussion of these functions can be found in Water regulation and shoreline protection (see page 50).

Habitat

It is thought that saltmarshes are sites of high faunal richness and productivity because of their proximity to both land and shallow seas (e.g. an ecotone between terrestrial and aquatic habitats). Saltmarshes in Australia are in general, and particularly in the tropics, relatively low in plant species diversity (Adam 1998). Saltmarsh fauna and flora are dependent upon freshwater and land-derived nutrients and trace elements as well as tidal water and also provide habitat at different times for many terrestrial and marine organisms. Saltmarshes in Queensland provide an important feeding habitat for some species of waterbirds and because saltmarshes are not inundated at all times they provide grazing opportunities for terrestrial fauna such as macropods. Salt flats support microbial mats, which little is currently known about (Adam 1998; EPA 2005e).

Fish use has been a focus of study in Queensland saltmarshes (Connolly 1999; Thomas and Connolly 2001; Connolly and Guest 2004). Studies that investigate saltmarshes as ecosystems rather than focusing on individual components are needed. Other areas where further investigation is required to better manage these ecosystems are saltmarsh faunas, productivity and energy and nutrient flows, and the effects of pollution, vehicle tracks and insecticides on marshes (Adam 1998; Dale and Knight 2005).

Productivity export

Recent reviews of international literature indicate that while most saltmarshes export some material, many others do not (Cappo *et al*. 1998). Stable isotope studies on saltmarshes show a possible contribution of saltmarsh grass to the food chains of some near-shore areas, for example mud flats (Connolly and Guest 2004). However, it may have been a spurious result, reflecting the similarity in isotope values of saltmarsh grass to seagrass (Connolly and Guest 2004). A study of saltmarshes in Jervis Bay, in southern New South Wales, found that the upper marsh had higher organic matter and nutrients compared to the lower saltmarsh and mangroves (Clarke and Jacoby 1994). The authors speculated that, given these results, saltmarshes may be a potential source of nutrients for mangroves, but highlighted the need for further studies on nutrient cycling and mechanisms of export and import in estuarine systems.

A number of other factors will influence the material exchanges apart from those associated with primary and secondary production (Cappo *et al*. 1998). These characteristics include:

- tidal range
- ratio of wetland to watershed area
- water circulation
- total wetland area
- frequency of storms and rainfall
- volume of water exchanged.

Physical characteristics, such as the geomorphology, are also important. With such a range of factors effecting material exchange, saltmarshes are likely to vary greatly in terms of these exchanges (Cappo *et al*. 1998).

Research needs for estuarine wetlands

Marked differences exist in our understanding of estuarine wetlands. The ecology and processes occurring in mangrove forests are relatively well understood, although there are still some areas where further research could provide better understanding of mangrove ecosystems. Saltmarshes and salt flats on the other hand are poorly studied, and interactions and processes occurring within saltmarshes and salt flats are not well understood, nor are the interactions with the wider landscape.

Table 2.2: Research needs for estuarine wetlands

Knowledge gap	Wetland type(s)
A better understanding of system interdependencies between estuarine wetlands, and other aquatic and terrestrial ecosystems	Mangroves Saltmarshes and flats
Quantification of nutrient cycling (Lukacs and Ludescher 1998)	Mangroves Saltmarshes and flats
A better understanding of long-term geomorphologic and hydrodynamic processes (Duke 1997)	Mangroves Saltmarshes and flats
Abetter understanding of patterns of micro-habitat use and dependence on different, adjacent habitat types during tidal ebb and flood (Cappo 2004)	Mangroves Saltmarshes and flats
Human impacts, such as the long-term effects of human pollution and modification (Lukacs and Ludescher 1998; Dale and Knight 2005)	Mangroves Saltmarshes and flats
Information on saltmarsh biota (Dale and Knight 2005)	Saltmarshes and flats
Productivity and energy and nutrient flow links with fisheries (Dale and Knight 2005)	Saltmarshes and flats
A better understanding of salt flat ecosystems (Cappo *et al*. 1998; EPA 2005e; Appendix 3)	Saltmarshes and flats

2

Riverine wetlands

The only group of wetlands that will be studied within this wetland group are in-stream waterholes in arid and semi-arid areas as recent research has shown that for a large proportion the time these systems function as lentic water bodies.

In-stream waterholes in arid and semi-arid areas

In-channel waterholes occur in most of the rivers of the arid and semi-arid zones of inland Australia. Arid and semi-arid rivers can convey large volumes of water, but for the most part exist as a network of ephemeral channels and waterholes. Waterholes are a distinctive geomorphological feature of the Channel Country region. For example, more than 300 permanent waterholes have been recorded in the lower reaches of Cooper Creek between Windorah and Nappa Merrie (Knighton and Nanson 1994b). Waterholes also occur in all other western catchments and in the seasonal streams of the dry tropics and Gulf catchments (Hogan and Vallance 2002; Burrows 2004).

Ecological functions of waterholes include their role as refugia for aquatic organisms. In this context waterholes represent the only permanent habitat for aquatic biota during periods of extended no flow. The role as physical refugia is twofold. Firstly, refugia support organisms not able to live elsewhere in the landscape and secondly, during extreme conditions refugia are when and where the negative effects of disturbance are reduced (Nekola 1999; Davis *et al*. 2002). Depending on their life history traits, individual organisms able to endure the extreme conditions are subsequently important in re-establishing populations when conditions become more favourable, that is, they act as a source for dispersal (Burrows 2004; Arthington *et al*. 2005; Marshall *et al*. 2006).

Waterholes are also important as watering points for stock and other terrestrial animals and as a water source for local communities, and have recreational and cultural heritage values. Waterholes and other aquatic environments in the more undisturbed western catchments also represent unique habitats and aquatic ecosystems, in that many are still functioning naturally as a result of the absence of water resource development (Kingsford, Curtin and Porter 1999).

A number of recent studies have quantified the refugia value of waterholes in the semi-arid and arid zones. These studies include:

- In the dry tropics, research on grazing pressure and other management issues in regard to waterholes has been undertaken by the Australian Centre for Tropical Freshwater Research (ACTFR).
- A preliminary study of fish biodiversity in the southern Gulf catchments has been undertaken by the Department of Primary Industries and Fisheries, which sampled some waterholes.
- The dryland refugia project, which studied waterholes on the Cooper, Warrego and Border Rivers, was undertaken by the Cooperative Research Centre for Freshwater Ecology (CRCFE).
- The ARIDFLO project had a few sites in Queensland, including the Diamantina River and the Thomson River (in the Cooper Creek catchment).
- Brian Timms and associates at the University of Newcastle, New South Wales, and Richard Kingsford of the University of New South Wales, have studied the Paroo catchment, mostly in terms of the invertebrate and bird populations respectively. These studies have been focused more on other wetland types.

The following section includes some discussion on these studies.

The Dry Tropics

ACTFR has undertaken a significant proportion of the research on waterholes in the dry tropics. This work has focused on the system conditions and the consequences of degradation. This research focus reflects the developed nature of areas in the dry tropics, in particular, the Burdekin catchment, where much of the work has been completed.

Aquatic ecosystems in the upper Burdekin rangelands are characterised by long periods of disconnection where the aquatic habitats are concentrated into permanent waterholes (Burrows 2004). The long period of disconnected habitats (lentic phase as opposed to a lotic phase) is characterised by increased potential for changes in contaminant concentrations, which subsequently impact on aquatic biota.

2. Wetland ecosystems

Long-term records indicate the Burdekin area is dominated by seasonal rainfall; however, flows are related to individual rainfall events, and biota are adapted to the occurrence of disturbance from high-intensity rainfall (Burrows 2004). The condition of aquatic habitats can be affected by:

- major rainfall events
- the intensity and frequency of rains during the wet season
- the occurrence of dry-season rain
- the effects of rainfall patterns in previous years
- the effects of extended droughts
- the geomorphology of streams.

Conceptual models of flow in the Burdekin catchment identify three seasonal stages: wet season, late wet/early dry season, and dry season (Burrows and Butler 2001). These stages are characterised below.

- In the *wet season*, the water quality is usually good, with spates of high-intensity flow in which much of the in-stream aquatic habitat may be washed away. As a result of this disturbance, invertebrate density and apparent diversity are reduced. A short high-intensity event will have more impact than lower-intensity longer duration flows. While high flows can transport high levels of sediment and nutrients, the short duration of these flows means that in-stream biota may not show a response to this change in water quality.
- In the *late wet/early dry season*, invertebrate populations recover quickly with the cessation of disturbance. Streams are flowing and water quality is at its best. Higher water levels allow access to habitats not generally available.
- In the *dry season*, flow ceases and this begins a successional period during which different sites exhibit different trends, a characteristic also noted in studies of the Lake Eyre basin waterholes. Physical characteristics and the size and permanency of the waterhole govern these differences. Water quality declines as the dry season progresses and may become a limiting factor for some species (Burrows and Butler 2001).

Other factors that should be considered include:

- The pattern and occurrence of wet-season rains is important. A good wet season flush can remove many potential contaminants. Rain in the dry season can have a good effect on aquatic habitats; however, in some cases it can create water quality problems if the event washes contaminants such as faecal material from livestock and nutrients from paddock into the waterhole, but it does not initiate stream flow. This can cause a rapid decline in water quality, in particular dissolved oxygen due to increased biological oxygen demand.
- Carry-over effects from previous years can be important. Drought can deplete base flow and this can take a number of years of normal rainfall to replenish (Burrows 2004).
- Geomorphology and groundwater influences are important. In some areas wet-season flows can change waterhole size and shape, especially in channels composed of sand. Soil porosity and the evaporation rate (to some degree affected by morphology) will affect the rate at which waterholes dry up. In the wet season surface water is dominant, but in the dry season base flow or groundwater becomes an important driver of water quality and vulnerability to impact. (Burrows and Butler 2001; Burrows 2004)

Research undertaken in the Townsville Field Training Area investigating the effects of grazing on aquatic ecosystems analysed water quality and aquatic invertebrate data and identified hydrological conditions such as rainfall intensity and the duration of base flow exerted the strongest influence on water quality and aquatic habitats (Burrows and Butler 2001). Their interpretation of ecosystem condition included the development of several multimetric indices. The final index developed was termed vulnerability, which attempts to determine how susceptible a waterhole is to disturbance by combining information on waterhole size, available dilution, base flow characteristics and local catchment condition.

The authors demonstrated that as the vulnerability status of waterholes increased, the frequency of poor water quality conditions also increased (Burrows and Butler 2001).

The occurrence of livestock presence in streams tended to be associated with the frequency of poor water quality regardless of the measure of vulnerability. The level of livestock activity associated with a negative impact was difficult to quantify as separation of the causal factors (vulnerability of a waterhole at any given time is a dominant factor) was limited.

In light of this research the following criteria for assessing the tolerance to grazing were recommended (Burrows and Butler 2001):

- waterhole size (in general larger waterholes are less vulnerable than small ones, except where flow conditions are different)
- degree and frequency of flushing
- level of shading
- soil types (a clay substrate reduces water clarity, whereas a rocky substrate may be clearer, but this may increase algae or nutrient problems)
- ground cover
- seasonal impacts (more impacts occur in the dry season and in drier years).

Another potential indirect effect of grazing and land management on these waterholes is alteration of hydrologic conditions resulting from changes in land use. Changes in hydrology can alter the persistence of wetland habitats, especially in the dry season, by reducing the potential base flow emanating from degraded soils. Another related issue raised in the workshops was associated with changes in the topography brought about by cultivation. In particular, laser levelling for sugar cane increases run-off and reduces infiltration into the soil, which may also reduce dry season recharge via base flow into waterholes (Appendix 1).

Gulf of Carpentaria

Studies of hydrology and ecology of waterholes in the Gulf of Carpentaria catchments are limited and this has been identified in other reviews (e.g. Douglas, Bunn and Davies (2005)). An assessment of fish habitats in southern Gulf catchments documented some waterholes (Hogan and Vallance 2002). Waterholes in this region were described as being large deep permanent water bodies that provided habitat and refuge areas for wildlife. These waterholes appeared to be in good condition, based on fish biodiversity; however, it was noted that there was bank slumping, and a study was recommended to gain a better understanding of the geomorphology of the rivers and the role of flow in maintaining these waterholes (Hogan and Vallance 2002). Further study of the wetlands in the Gulf region is warranted. As these catchments currently have little development, it may be possible to gain an understanding of the natural processes to assess future impacts if they occur, but also possible to apply some of the learnings from undisturbed catchments to improve management of other more impacted areas (Kingsford 2000).

Lake Eyre Basin

Hydrology is thought to be the most important driver of the health and persistence of freshwater aquatic ecosystems. Research in the waterholes of the Lake Eyre Basin in particular has investigated the role of hydrology in driving their persistence in the landscape, which in turn is therefore vital for maintaining their value as refugia (Knighton and Nanson 1994b; Knighton and Nanson 2000; Hamilton *et al*. 2005). However, while surface water is important to the Lake Eyre ecosystems, the importance of groundwater input into waterholes in the region is not significant (Knighton and Nanson 1994b; Gibling, Nanson and Maroulis 1998; Hamilton *et al*. 2005). The research on groundwater inputs presents several lines of evidence. One line of evidence comes from the stratigraphy of the area, as most waterholes lie over several metres of fine clay, and coring of the floodplain indicates that the sand lens within this clay layer was dry (Knighton and Nanson 1994b; Gibling, Nanson and Maroulis 1998). High turbidity of the water is evidence of high clay content, which would be likely to seal the bottom (Knighton and Nanson 1994b). Despite these studies, until recently the Cooper Creek system was still classified as a groundwater dependent ecosystem (Hatton and Evans 1998). Hamilton *et al*. (2005) used changes in the stable isotopes of water to determine the source of water in a suite of waterholes in Cooper Creek. In all but possibly one case, no evidence was found for groundwater inputs. This finding concurs with other studies of the hydrology of waterholes in arid catchments, which also found that systems were likely to be surface water driven, based on evaporative concentrations of solutes (Townsend 2002; Costelloe *et al*. 2005).

Hamilton *et al*. (2005) stressed the importance of occasional, irregular in-channel flow pulses for sustaining refugia in dry years. This is an important finding, as often in dryland rivers floods are highlighted as being of critical importance to the biota and geomorphology of the region, but this study illustrates that small in-channel flows are also very important. These flows are more likely to be affected by local human disturbance, such as small impoundments, raised roads and upstream water harvesting. In anabranching systems, small changes in the topography, such as those caused by these human disturbances, have the potential to significantly alter the relative amounts of water flowing through the various channels. Although a number of studies have found that some waterholes in Cooper Creek are surface water systems, Hamilton *et al*. (2005) cautions against the extrapolation of these findings to all waterholes in Cooper Creek, because if waterholes with groundwater inputs do exist these would be very important as refugia. It is recommended further survey work on persistence and sources of water of waterholes in the Cooper Creek system be undertaken to confirm the widespread applicability of previous findings and that these surveys could also be widened to include waterholes across the semi-arid and arid zones of Queensland.

In the waterholes of Cooper Creek, food webs appear to be driven by high productivity within the waterhole. Using stable isotope studies, algae in the shallow littoral zone of the waterholes were found to be the main source of energy for aquatic consumers (Bunn and Davies 1999; Bunn *et al*. 2003).

Others have documented the importance of hydrological connectivity on the fauna of the Cooper system. The structure and abundance of fish, based on a study of five species, was related to the extent of floodplain inundation in last flood, the interconnectedness of waterholes and waterhole habitat structure (Arthington *et al*. 2005). Temporal variation in macro-invertebrates was larger than spatial variation (Marshall *et al*. 2006). Temporal assemblage patterns were best explained by the connectivity potential of waterholes, which was defined as the position of individual waterholes within the broader channel network and long-term connectivity relationships rather than the actual time since hydrological connection. These results are supported by the work of Sheldon, Boulton and Puckridge (2002), who found that there was a complex influence on macro-invertebrate assemblage composition by hydrology and connectivity in dryland rivers. Studies of other organisms from arid zone areas have also found patterns that reflect the influence of hydrology, for example Roshier *et al*. (2001b).

By contrast to the studies of fauna discussed above, algae of waterholes in the Cooper and Warrego catchments were not related connectivity (McGregor, Marshall and Thoms 2006). Algal assemblages were instead associated to broad environmental factors, for example geology or land use and associated nutrient and light regimes. Within the two catchments, waterholes positioned close to each other within the landscape were no more likely to have similar algal communities than those further away.

Implications for management in the Lake Eyre Basin include:

- the need to account for temporal variability as well as spatial variability when estimating diversity or monitoring using macro-invertebrates (Marshall *et al*. 2006)
- to maintain macro-invertebrate biodiversity, conservation of a range of waterhole types across regional landscapes will be needed (Marshall *et al*. 2006)
- the magnitude, timing and frequency of floodplain inundation and subsequent variations in waterhole volumes must be maintained to sustain distinctive habitats and fish assemblages (Arthington *et al*. 2005)
- importance of maintenance of in-channel flows (Costelloe *et al*. 2005; Hamilton *et al*. 2005).

Murray-Darling Basin

The western rivers of the Queensland Murray-Darling Basin have in-stream waterholes that fulfil similar roles as refugia for other dryland rivers (as discussed above). While research has been undertaken on the lakes and ephemeral wetlands in the Paroo catchment, much of the ecological function of waterholes has been derived from studies of other western rivers. The Queensland Water Resource Plan (WRP) process prepared a scientific forum on the Moonie, Warrego, Paroo, Bulloo and Nebine River basins that summarised information on the processes which are thought to operate (Cottingham 1999).

The Cooperative Research Centre for Freshwater Research (CRCFE) dryland refugia project surveyed waterholes in the Warrego as well as Cooper Creek, but apart from McGregor, Marshall and Thoms (2006), the Warrego component of this project has not been published to date. Waterholes of these western rivers are thought to be similar to Cooper Creek in that they have a band of intense productivity by algae around the littoral margins (Cottingham 1999).

A number of studies have found that waterholes of the western Murray-Darling Basin are important to fauna such as invertebrates and fish, which tend to have different species assemblages than other wetlands in the same area (Cottingham 1999; Timms 1999).

While Queensland Murray-Darling western rivers are assumed to be similar to systems in the Lake Eyre Basin such as Cooper Creek, it is important this assumption is validated, particularly since aquatic systems in arid and semi-arid zones are governed by high variability and uniqueness (Cottingham 1999). A few current studies may help to further elucidate the functioning of waterholes in the western region of the Murray-Darling Basin. For example:

- Surveying of waterholes was undertaken as part of the dryland refugia project in the Warrego catchment, most of which is yet to be published.
- The Department of Natural Resources and Water currently has a project under way investigating the function of waterholes as refugia. The project aims to investigate waterhole attributes that influence their function as refugia, and examine how flow management can potentially influence these properties within a conceptual framework. The conceptual models developed will have statewide relevance and will be tested through application in the Moonie catchment (Department of Natural Resources and Water, Sharon Marshall, pers. comm., 6 December 2005).

Research needs for riverine wetlands

In-stream waterholes have, in some areas, been the focus of comprehensive studies while in other areas these wetlands remain largely undocumented. Cooper Creek, in the Lake Eyre Basin, has been the focus of a number of studies and most arid systems are assumed to operate in a similar way (Cottingham 1999). Given the highly variable nature of arid zone hydrology and variability in these systems, further investigation should be undertaken to ensure that these assumptions are valid (Timms and Boulton 2001; Jenkins, Boulton and Ryder 2005). Other knowledge gaps have been highlighted in the literature and from workshops undertaken as part of this review:

- Many catchments are unsurveyed, for example the Bulloo.
- Information on the location and persistence of waterholes is required, including their connectivity and temporal variability related to current and predicted flow-regimes.
- Hydrological knowledge is lacking, due to a lack of flow data and groundwater surveys.
- Information on the roles of flow in maintaining the geomorphology of waterholes and other wetlands is needed in some areas, for example the southern Gulf catchments (Hogan and Vallance 2002).

2. Wetland ecosystems

Lacustrine wetlands

Lakes are not common in Queensland; however, some significant groups of lakes exist. Large artificial lakes and impoundments have not been reviewed. Other lake types such as crater lakes where little information has been found are briefly discussed under Other inland lakes (see page 24). Coastal lakes have been reviewed as a single section, whereas inland lakes have been divided into terminal and subterminal lakes, which also include large shallow ephemeral lakes on floodplains, and billabongs, lagoons and pools.

Coastal dune lakes

The sand islands and dune fields of coastal Queensland often contain freshwater lakes. South-east Queensland contains the greatest concentration of them, in particular Fraser Island, which contains over half the world's known perched lakes (Fraser Island World Heritage Area Scientific Advisory Committee 2004; Hadwen and Bunn 2005). These lakes are valued for uniqueness, aesthetic value and recreational value as well as providing habitat for fauna and flora that have limited distributions (Centre for Coastal Management 1989; Fraser Island World Heritage Area Scientific Advisory Committee 2004).

Most of the natural freshwater lakes occur within sandy coastal dune areas of south-east Queensland, notably of Fraser, Moreton and North Stradbroke Islands, within the Cooloola sand mass (Bowling 1988), and in the siliceous dunefields of Cape Flattery in tropical north Queensland (Timms 1986; Hawkins *et al*. 1988). Typically, these lakes are small in comparison to man-made reservoirs, are acidic, are of low conductivity dominated by sodium and chloride ions, vary from optically clear to strongly humic-stained, and are generally oligotrophic, that is, low nutrient systems (Bayly 1964; Bayly and Williams 1973; Timms 1986; Bowling 1988; Hadwen, Arthington and Mosisch 2003).

Oligotrophic ecosystems are potentially highly sensitive to increases in nutrients, a topic that researchers at Griffith University have dealt with in some detail (Hadwen 2002; Hadwen, Arthington and Mosisch 2003; Hadwen and Bunn 2004; Hadwen and Bunn 2005). Lakes in contact with regional groundwater may have more nutrient rich waters, as the source of these waters is not necessarily local.

Information on the distribution, conservation status and management of dune lakes can be found in EPA 2006b. Compared to many types of wetlands found in Queensland, the lakes on Fraser Island, in particular, are comparatively well studied, with studies focused on the limnology of dune lakes and the impacts of tourism and nutrient additions to these lakes. Large areas of swampy ground and fens are associated with the margins of these lakes and dune environments; however, studies of these environments are lacking.

South-east Queensland

Hydrology and water quality

Timms (1982) provided a classification of dune lakes in non-tropical eastern Australia, dividing these lakes into six types:

- water bodies perched in leached dunes
- lowland water bodies on leached dunes, which lie in gutters and swales close to sea level and are typically associated with extensive swamps
- watertable window lakes, the lake basin in a drowned valley or interdune space, which intercepts the watertable
- dune-contact water bodies, lakes and swamps on solid substrates, but at least one shore is a coastal dune
- freshwater lakes with marine contact
- ponds in frontal dunes.

An explanation of some of the properties of each lake type is contained in Table 2.3.

Watertable window lakes, marine contact lakes and perched lakes are the most common forms of dune lakes encountered along the east coast of Australia (Timms 1982). Perched lakes are particularly abundant on the sand islands off the coast of south-east Queensland. Most research in Queensland has been undertaken on perched lakes and watertable window lakes and these two are described in greater detail below.

Table 2.3: Dune lakes according to the classification of Timms (1982)

Lake traits	Type 1: Perched lakes on leached dunes	Type 2: Lowland lakes on leached dunes	Type 3: Watertable window lakes	Type 4: Dune-contact lakes	Type 5: Freshwater lakes with marine contact	Type 6: Ponds in frontal dunes
Water clarity	Opaque from humic flow-off	Opaque, from humic substances from the local watershed	Clear groundwater	If deep, clear groundwater; if shallow, opaque	Depends on the hydrology. Like dune-contact lakes	Clear groundwater
Total dissolved solids (TDS)	High TDS due to leached organic acids	High TDS due to leached organic acids	Low TDS	Low TDS	High TDS from seawater	Low TDS
Water chemistry	Dominated by Na^+ and Cl^-	Dominated by Na^+ and Cl^-	Dominated by Na^+ and Cl^-	Dominated by Na^+ and Cl^-	Depends on the degree of freshwater-saltwater mixing	Dominated by Na^+ and Cl^-
pH	4.5-4.7 (acidic)	5.5 (acidic)	6.0 (acidic)	5.5 (acidic)	Depends on the degree of fresh-saltwater mixing	8.0 (alkaline)
Littoral vegetation	Lepironia articulate dominates	*Typha* sp., *Phragmites* australis, Cladium procerum, Leptocarpus tenax and Scirpus litoralis	*Typha* sp., *Phragmites* australis, Cladium procerum, Leptocarpus tenax and Scirpus litoralis	Lepironia articulate dominates	*Typha* sp., *Phragmites* australis, Cladium procerum, Leptocarpus tenax and Scirpus litoralis	Little or no littoral vegetation, generally terrestrial vegetation
Invertebrates	Calamoecia tasmanica (a calanoid copepod) dominates zooplankton	Calamoecia tasmanica dominates zooplankton. Sporadic appearance of ostracods and molluscs	Calamoecia tasmanica joined or replaced by cyclopoid zooplankton	Regular presence of ostracods, molluscs, leeches and a diverse zooplankton with cyclopoids and/or cladocerans	Ostracods and molluscs and species with marine affinities dominate. Calamoecia tasmanica is absent.	Calamoecia tasmanica, shrimps, ostracods and molluscs common. Conchostracans and notostracans also.

Source: from Hadwen 2002

2. Wetland ecosystems

Perched lakes are formed by cemented organic matter, aluminium and sand (coffee rock), which effectively cuts off any connection with regional groundwater (Timms 1982). These systems are essentially closed and rainwater-fed, which results in fluctuating water levels, although the perched lakes on Fraser Island are nearly all permanent, perched watertables that can contribute to their sustained levels. Longmore (1986; 1997) estimated that some lakes have a continuous history in excess of 300,000 years. Perched lakes are characterised by acidic waters, low conductivity and low nutrient status. The water can be stained by dissolved humic acids leached from swamps, peat bogs and podzolised B horizons (Timms 1982; Arthington 1988; Hadwen, Arthington and Mosisch 2003) and the colour of lakes ranges from clear to 'black water'.

Watertable window lakes: These lakes have differing properties due to the input of groundwater. Watertable window lakes on Fraser Island have higher pH, conductivity, and transparency and nutrient status than perched lakes. The water in these systems is likely to be clear or lightly stained with dissolved humic acids, which reflects the groundwater source. Some have creeks which flow out to the sea or into other aquatic ecosystems. Watertable lakes sampled by Hadwen, Arthington and Mosisch (2003) were found to have total phosphorous concentrations approaching those typical of mesotrophic conditions. Arthington *et al*. (1986) found a greater number of fish species in watertable window lakes than would normally be found in perched lakes.

Ecology

Coastal lakes in Queensland are generally unproductive systems. Faunal composition is spatially variable and species richness is low in these lakes. Some lakes have no resident fish species, while others can have several (Arthington *et al*. 1986). Freshwater turtles also occur in these lakes. Food sources for coastal dune lake–dwelling organisms may be either allochthonous or autochthonous. Three food webs were described by the Centre for Coastal Management (1989) for these lakes: a grazing food chain involving phytoplankton, a detrital food chain in which dissolved humic acids from leaves and other organic matter provide nutrients for bacteria which are grazed by zooplankton, and a terrestrial organic food chain where allochthonous food sources such as pollen or insects provide food for fish and turtles directly.

Given the acidic water of perched lakes, only acid tolerant species can live in these lakes. Significant populations of some vulnerable and rare fish species such as the Honey Blue Eye (*Pseudomugil mellis*) and the Oxleylan Pygmy Perch (*Nannoperca oxleyana*) occur in coastal lakes in south-east Queensland. Acid frogs such as the Wallum Froglet (*Crinia tinnula*) and Wallum Sedge Frog (*Litoria olongburensis*) among others also occur in these lakes (EPA 2006b). These species are geographically rare and restricted to acidic waters (Lewis and Goldingay 2005).

Recent research on Fraser Island lake ecosystems has concentrated on investigating the effects of increased nutrient additions resulting from tourism activities (Hadwen 2002; Hadwen, Arthington and Mosisch 2003; Hadwen and Bunn 2004; Hadwen and Bunn 2005). Dune lakes typically have low inputs of nutrients, and therefore are at risk of a significant change in the functioning of these ecosystems even with small increases in nutrients, especially given the algal flora of these oligotrophic systems are able to respond to nutrient addition (Outridge *et al*. 1989). This research concluded:

- A trend towards higher periphyton contributions in lakes identified at key tourist locations was evident, indicating that increased visitation may increase the contribution of periphyton to littoral food webs.
- Nutrient additions from tourism may lead to increases in periphyton biomass, with the degree of increase proposed as detrimental likely to be dependent on water level fluctuations and the consumptive capacity of grazers.
- A recommendation for a regular periphyton monitoring program for dune lakes will enable the early detection of impacts from excessive tourist use (Hadwen 2002; Hadwen, Arthington and Mosisch 2003; Hadwen and Bunn 2004; Hadwen and Bunn 2005).

Cape York

Studies of Cape York dune lakes are dominated by descriptive limnological studies on the formation, and flora and fauna, of the lakes.

Timms (1986) and Hawkins *et al*. (1988) demonstrated that Cape York lakes are not perched and are in contact with the regional watertable. One study of nine lakes showed that almost all macrophytes, littoral invertebrates, fish and limnetic zooplankton were common tropical species, and only a few species were shared with lakes further south (Timms 1986). The other study found a greater diversity of species than that of lakes on Fraser Island (Hawkins *et al*. 1988). Water chemistry, however, was found to be similar to dune lakes in south-east Queensland characterised by high acidity, low to very low conductivity and variable staining by humic acids. Ionic composition of the water was dominated by Na^+ and Cl^-, but also had appreciable amounts of Ca^{2+}, Mg^{2+} and HCO^-_3 proposed as resulting from groundwater inputs from bedrock. The lakes at Cape Flattery were found to be consistent in terms of chemistry and biota (Hawkins *et al*. 1988).

Since both articles cited for these dune systems lakes in Cape York are around 20 years old, it would appear that further more up-to-date study of these systems is warranted.

Terminal and subterminal lakes

In the arid and sub-arid areas of Australia, some inland river systems discharge into shallow lakes and wetlands, which can be at the end of the hydrological system, or receive overflow and backflow waters from flooded rivers, and are often referred to as terminal or subterminal lakes. A terminal lake is at the end of an essentially closed system, whereas in a subterminal lake water can flow through the system in high volumes. These wetland systems can be very complex, with the lakes being a mosaic of varying habitat conditions temporally and spatially (Timms 1999; EPA 2005a).

Information on the distribution, conservation status and management of terminal and subterminal zone lakes can be found in the EPA management profiles 'Arid zone lakes' (EPA 2005a) and 'Inland non-arid lakes' (EPA 2006d).

The predominant value of arid zone lake areas is their significance in maintaining the aquatic ecology of the region, in particular the distinctive 'boom and bust ecology'. The more permanent water bodies act as refugia for organisms in dry times and are part of the spatial and temporal mosaic of habitats significant as feeding and breeding areas for waterbirds (Kingsford and Porter 1994; Kingsford, Curtin and Porter 1999; Roshier *et al*. 2001a; Timms 2001a).

Permanency and the chemistry of lakes in arid regions depend on the climate, position in the landscape and the frequency, timing and duration of hydrological input. For example lakes in the Paroo catchment are relatively more permanent than other arid areas, as the Paroo has flows a few times per year on average and has a moderate flood flow during most years (Timms 1997).

Lakes in very arid areas, such as Lakes Koolivoe and Mipia on the fringe of the Simpson Desert, some of the Coongie Lakes and Lakes Wyara and Numalla, have been shown to hold surface water for similar time periods as water bodies with water regimes modified by damming (Roshier *et al*. 2001b). This illustrates how important these lakes can be for aquatic organisms. Lakes that are less permanent can also fulfil a very important role for aquatic organisms (Roshier *et al*. 2001a; Roshier *et al*. 2001b; Roshier and Rumbachs 2004). If considering the arid zone of Australia as a whole, it would be unlikely for all lakes to be dry at the same time; hence a mosaic of filled, semi-filled and empty lakes is likely to be the prevailing condition. This is supported by evidence that there was no period longer than 12 months in the last 95 years where potential for wetland filling in the arid zone did not occur (Roshier *et al*. 2001b). While this scale of connectivity and habitat distribution is not important for many organisms, it is essential to the life histories of waterbirds. At smaller catchment scales similar mosaic patterns of connectivity may exist, for example in the Paroo it is rare for all lakes to dry simultaneously so there is nearly always some habitat (Timms 2001a).

While most lakes in the arid zone exhibit a wide range of salinities throughout a wet and dry cycle (i.e. from being full of water, with fresh low salinity water, to higher salinities as evaporation concentrates salts in the remaining water), some lakes consistently exhibit much higher salinities than others. These lakes characterised by higher salinity measures tend to have different floral and faunal assemblages, indicated by research focused on waterbirds and invertebrates (Timms 1987; Kingsford and Porter 1994; Kingsford 1999a; Kingsford, Curtin and Porter 1999; Kingsford and Porter 1999; Timms 1999; Timms and Boulton 2001; Kingsford and Auld 2005). A significant geomorphic parameter that influences salinity is whether the lake is terminal or subterminal. Subterminal lakes will occasionally be flushed of salts whereas in terminal lakes the salt is trapped (Timms 2001).

2. Wetland ecosystems

A relatively well-studied example of differences that can occur between lakes based on hydrology and geomorphology is the difference between Lake Wyara and Lake Numalla in the Currawinya National Park (Timms 1999). These two lakes, which are not separated by great distance, exhibit differences based on their position in the landscape. Lake Wyara originated by earth movements, unlike others in Currawinya National Park. The basin is almost closed, meaning inflows are dominated by its own localised catchment, but water from the Paroo River reaches it in very large events, and these waters also flow back into the Paroo as water levels recede. Salinity in Lake Wyara can range from almost fresh to brine. Lake Numulla is the largest freshwater lake in the park and salinity fluctuations can place it at the extreme range for a lake classified as freshwater. Timms (1999) reports a salinity range of 4600-200,000 uS^{-1} cm for saline lakes and for Lakes Numulla and Yumerarra 100-56,000 uS^{-1} cm). While Lake Numulla fluctuates greatly in terms of salinity, it remains less saline than Lake Wyara. Lake Numulla has frequent inflows of water from both the Paroo and the lakes catchment (Timms 1999). These differences in the salinity of the lakes correspond to differences in the utilisation of these lakes by waterbirds. Approximately 10 times as many waterbirds have been recorded on Lake Wyara than on Lake Numalla (Kingsford and Porter 1994). The species composition of birds was also different with mainly herbivorous species such as ducks and small wading birds on the salt lake and mainly piscivores, large wading birds, on the freshwater lake, reflecting the differences in the type of organisms and therefore trophic ecology found in the lakes. This demonstrates the importance of maintaining a mosaic of lake and wetland types for maintenance of the functions attributed to wetlands at a regional scale.

Organisms use different lake habitats due to differing conditions that occur in these habitats and of major importance is that these habitats change both temporally and spatially. Turbidity, salinity and relative permanence of lakes are major factors affecting community assemblage structure; however, occurrence of flooding events has an influence on the abundance of invertebrates, indicating that a relatively intact hydrological regime is important to the health of these ecosystems (Timms and Boulton 2001). Hydrological regime is discussed for waterholes in flat environments in the section on Lake Eyre Basin (see page 15), and explains that water diversions are not the only important alterations to the hydrology. Flow patterns can be complicated and even small structures such as roads can alter the flow between channels, which in the context of the lake differences in the examples above can be a potentially important influence on salinity dilution and moisture persistence. Changes in hydrology therefore may lead to complex shifts in the ecology of lakes (Timms 1999; Thoms *et al*. 2002).

Research currently underway on a terminal lake system is the Narran Lakes Project run by Dr Martin Thoms and associates as part of the CRCFE. Although the Narran Lakes are in New South Wales this study has relevance, as the findings will be applicable to terminal and subterminal lake systems in southern Queensland, given the similarities in climate, landscape and land use. This project has released an initial scoping study (Thoms *et al*. 2002) and a preliminary report on the hydrology of the lakes (CRC for Freshwater Ecology 2004). Conceptual models of how the system operates were developed from scoping relevant literature. The main components of these models were:

- that water, nutrients, carbon and living organisms are transported from upstream via the river and floodplain and enter the floodplain system
- the amount and type of transported material is transformed during interactions with the floodplain
- because the system is predominantly ephemeral, much of the biota colonises the wetlands from the river or elsewhere soon after water arrives
- a major component of the biota will be permanently associated with the wetland and have mechanisms to cope with flooding and periods of drying
- the major export of carbon from the system during the aquatic phase is through waterbirds
- the major export of carbon from the system in the terrestrial phase is grazing on vegetation
- a key characteristic of the wetland system is spatial and temporal variability, where biotic and abiotic features will be in a constant state of flux (Thoms *et al*. 2002).

A preliminary study on the hydrology of the system (CRC for Freshwater Ecology 2004) concluded that inundation patterns of the Narran Lakes are highly complex due to the high temporal variability of river flows, the morphological diversity of landforms and the complex pattern of water movement between different parts of the system. Similar landforms in different areas are inundated at different times during flooding, which increases the diversity of habitat and prolongs habitat availability. This finding ties in well with studies from the Paroo lakes where a similar spatial and temporal mosaic of habitats is thought to be important for the biota of the system.

Billabongs, lagoons and ponds

The term billabong is used to describe standing water bodies associated with floodplain rivers. These water bodies fall into one of two systems: 'palustrine' if they are relatively small in area and 'lacustrine' if they are large lakes. However, since the literature rarely has enough information to discriminate between these two systems, they are considered as one group here. The terms billabong and lagoon are generally used for lotic waters associated with the floodplain. Billabongs and off-channel lagoons can be cut-off meanders, but can also be subsidence depressions, flood scours, or deep holes in beds of temporary anabranch streams (Hillman 1998). In general, the ecological functions attributed to billabongs include refugia, as sites of high productivity and biodiversity, productivity export to rivers and flow regulation.

In Queensland these wetland features appear to be quite poorly understood in terms of function. Much of the study on these systems has taken place in the southern states, particular the southern Murray-Darling Basin, and while this does not preclude it from having relevance to Queensland systems, it has not been validated and inconsistencies between climate and land use highlight the need for conclusions from southern areas to be tested in Queensland. In particular, validation in tropical areas is essential, where characteristics include year-round equable temperature, a seasonal or highly seasonal rainfall, enormous short-term variability in flow regimes, high frequency of fire in drier systems and often low availability of nutrients (Pearson and Connolly 2001).

In terms of hydrology, billabongs are generally thought to be surface water systems (Hillman 1998). However, physicochemical processes can be different to other water bodies within a riverine system. For example, rates of sediment accretion, including organic matter can be low in billabongs (Ogden 1996; Hillman 1998). A study on the sedimentology of two floodplain wetland complexes in New South Wales showed that long-term wetlands are a temporary store of sediments and pollutants (such as trace metals), which has resulted from exchange of materials between the river channel and bordering environments over a variety of time scales (Thoms 1998). This illustrates that while wetlands are depositional environments, patterns of deposition and erosion can change through time.

Primary and secondary production

In general terms billabongs are diverse, productive and highly variable ecosystems, being rich in plant nutrients and not nutrient limited for significant periods (Ogden 1996; Hillman 1998). These two factors combined mean that billabong ecosystems have the potential to support substantial fauna (Hillman 1998). Billabongs have complex food webs, with most of the biomass, diversity and heterotrophic activity occurring at the level of microscopic organisms (Hillman 1998). The presence of large and diverse microbial decomposers supports large and diverse bacteriavore communities, making these assemblages the main sinks of carbon within billabong food webs. The large bacteriavore community is one of the biggest differences between billabongs and other riverine ecosystems. Future research continuing to build an understanding of the trophic functioning in billabongs would be beneficial (Hillman 1998).

Research has been conducted on the effects of flooding and changes to the hydrology of wetlands brought about by river regulation using macro-invertebrate assemblages in some permanent and temporary wetlands of the southern Murray-Darling Basin (Quinn, Hillman and Cook 2000; Hillman and Quinn 2002). These studies found that:

- Consistently different species assemblages existed in temporary and permanent wetlands.
- A mosaic of wetland habitats needs to be maintained to keep floodplain biodiversity and this mosaic is dependent on hydrological patterns.

Stable carbon isotope analysis was used in an attempt to trace carbon through the food web of several billabongs in south-east Australia (Bunn and Boon 1993). The technique was found to be unable to discriminate between potential sources of fringing, emergent or floating vegetation or benthic detritus. The authors speculated that methane released from billabong sediments could provide a possible source that is reintroduced into metazoan food webs via the consumption of methanotrophic bacteria or alternatively, food webs in these water bodies are largely driven by an unknown and inconspicuous ^{13}C-depleted primary producer, such as planktonic Chlorophyta.

Billabong and floodplain lakes are generally thought to be valuable habitats for fish, and in particular billabongs and floodplain lakes on the coastal plains of the catchments discharging into the Great Barrier Reef Lagoon are thought to be a valuable habitat and nursery ground for some fish species (Vietch and Sawynok 2005) (for further discussion, see Freshwater wetlands, from page 57). In billabong wetlands in the Burdekin catchment an important component of wetland water quality for biota is dissolved oxygen (DO) (Perna and Burrows 2005). Both agricultural run-off and floating weed mats have the potential to reduce DO levels in these wetlands, by increasing oxygen consumption in the water column. While the authors cite that DO has the capacity to reach low levels overnight in even undisturbed wetlands, weed mats can dramatically increase diurnal fluctuations, leading to fish kills and conditions that favour the release of nitrogen and phosphorus into the water column. Results from harvesting and removal of water hyacinth mats show an improvement in DO levels (Perna and Burrows 2005).

Studies in Queensland have also surveyed the fauna and flora of some lagoons and billabongs. This sampling has often been conducted as part of studies looking at a range of other wetland types. These studies document aspects of the biota and potential for high rates of productivity (e.g. Mackey 1991; Nolen 2001; Venz, Mathieson and Schulz 2002). Further research, which looks at a more holistic view of these ecosystems and investigates the linkages between billabongs and other aquatic ecosystems, is needed.

Other inland lakes

Lake types reviewed by Arthington (1988) include those mentioned in Lacustrine wetland (see page 18) and other less common types such as:

- lakes associated with lava flows. These lakes tend to occur in high rainfall areas and are often permanent. Some examples occur in association with the Great Basalt wall
- crater lakes or marrs, which occur on the Atherton Tableland, for example Lake Eacham and Lake Barrine. Information on the distribution, conservation status and management of crater lakes can be found in the EPA management profile Crater Lakes (EPA 2005c)
- other isolated lakes, such as Lake Broadwater on the Darling Downs, which is thought to have once been part of the Condamine River floodplain (EPA 2006d).

Limited information on the physical and chemical properties and the benthic communities of these lakes is available but not described in detail here. See Arthington (1988), Scott (1988), Walker (1999) and Burrows and Butler (2003).

Research needs for lacustrine wetlands

Lacustrine wetlands cover a range of climatic and landscape settings, and there are differences in the amount of research that has been undertaken on them in Queensland. Research tends to be geographically patchy. The coastal dune lakes of south-east Queensland and the arid zones lakes in the Paroo catchment have been the focus of most research undertaken in Queensland on lacustrine wetlands, whereas some of the lakes in the northern parts of the state lack information on ecosystem processes, hydrology and ecology. Billabongs and lagoons in particular need further investigation to validate research undertaken on these ecosystems in south-east Australia.

Palustrine wetlands

Palustrine wetlands are a diverse group. Classification of types of palustrine wetlands is difficult due to the lack of documented evidence which would allow us to understand their ecological character and determine functions and variability among these wetland types. Gathering information on palustrine wetlands as a group generally makes interpretation difficult and ambiguous because it may not apply to all types.

In an attempt to overcome this ambiguity palustrine wetlands in this document have been divided into groups based on broad vegetation classes. The groups include:

- forests and woodland wetlands
- wetlands dominated by shrubs
- wet heaths and fens
- wetlands dominated by grass/sedge/reed/rush
- claypans
- spring wetlands.

While distinct similarities exist between some of the groups, for example spring wetlands could be a subset of any other grouping, the classifications adopted here appear to be supported by the literature and are appropriate for this review. Where possible, discussion is divided further into geographical regions or based on a plant species or genus found in a wetland, although this is not always possible. In some cases only one wetland type is discussed under a grouping. This is not necessarily due to there being only one type of wetland under this heading, but is based on the available information relevant to the subjects covered in this review.

Table 2.4: Research needs for lacustrine wetlands

Knowledge gap	Wetland type(s)
Basic scientific studies to better understand processes occurring with lakes (e.g. Timms and Boulton 2001)	Dune lakes (in particular Cape York) Terminal and subterminal lakes Billabongs, lagoon and ponds Crater lakes
Groundwater interactions in arid zone lakes (e.g. Fensham and Fairfax 2005)	Terminal and subterminal lakes Billabongs, lagoon and ponds
Longer-term studies to better understand temporal variability (Timms and Boulton 2001)	Dune lakes Terminal and subterminal lakes Billabongs, lagoon and ponds Crater lakes
A better understanding of the hydrology, flow patterns and connectivity between wetlands and rivers, which cause different wetlands to connect and fill (Timms and Boulton 2001)	Terminal and subterminal lakes Billabongs, lagoon and ponds
The ecology of flood events (Timms and Boulton 2001)	Terminal and subterminal lakes
Trophic dynamics (Pearson and Connolly 2001)	Billabongs, lagoon and ponds (particularly northern Queensland)
The strength of linkages between floodplain wetlands and main channel habitats (Pearson and Connolly 2001)	Billabongs, lagoon and ponds
Quantification of the impacts of barriers to fish movement on aquatic food webs (Douglas, Bunn and Davies 2005)	Billabongs, lagoon and ponds Terminal and subterminal lakes

Forest and woodland wetlands (Melaleuca wetlands)

A number of types of forested wetlands have been identified in Queensland, both in arid zones (EPA 1999) and in coastal areas, for example Palm Swamps (EPA 2006g); however, research into the ecological functions and ecosystem processes is too limited to review, so only *Melaleuca* wetlands have been reviewed in this report.

Melaleuca wetlands are non-tidal, wooded wetlands, and floristically they are dominated by *Melaleuca spp*. These wetlands are inundated on a temporary basis, and this can be for three to six months of the year (EPA 2005b). *Melaleuca* swamps occur in freshwater coastal or near coastal floodplain and riparian areas of Queensland. Landscape position affects the species composition and the ecological functioning of these communities (Zoete 2001). *Melaleuca* swamps are often found in conjunction with other wetland types such as *Casuarina* forested areas, wet heath communities and ephemeral grassy wetlands, and are often positioned on the landward edges of saltmarsh and mangroves (Greenway and Kordas 1994; Anorov 2004). An important feature of many *Melaleuca* wetlands due to their coastal nature is that they are associated with soils having potential for acidification when disturbed by land clearing. Modifications to the hydrological regimes of these systems can also result in the development of acid sulfate soils (Anorov 2004), a process discussed further in the section on Acid sulfate soils (see page 64). Information on the distribution, conservation status and management of *Melaleuca* wetlands can also be found in the EPA management profile 'Coastal *Melaleuca* swamp wetlands' (EPA 2005b).

Melaleuca wetlands are recognised as threatened natural ecosystems in south-east Queensland because being located in the coastal zone or riparian areas they have often been removed for agricultural or urban purposes (EPA 2005b). Between 22 percent and 77 percent of the *Melaleuca quinquenervia* wetlands of south-east Queensland had been converted to farming or urban areas during the 15 years from about 1972 to 1987 (Davie 1991). Up to 95 percent of the Brisbane region originally covered in *Melaleuca quinquenervia* wetlands was lost by 1991 (Catterall and Kingston 1993).

Like most wetland information grey literature dominates as a source with fewer than a dozen significant references relating to the ecological character of these ecosystems (Zoete and Davie 2000). However, while being the most comprehensively studied of all palustrine wetlands reviewed in this document, most literature was focused on research of *M. quinquenervia* as a pest species in Florida, United States, with others based on south-east Queensland and Northern Territory ecosystems.

Functions of *Melaleuca* wetlands listed in the literature include:

- water quality filtering
- protective buffer zone between shorelines, estuaries and river systems
- protecting waterways from salination, nutrient run-off and erosion
- flood mitigation
- groundwater recharge
- nutrient sinks
- sites of high productivity
- productivity export in floods
- temporary and permanent habitats for flora and fauna
- refuges for wildlife during drought periods
- social values such as aesthetics and education (Greenway 1998).

Water quality filtering and nutrient sinks

Margaret Greenway and associates at Griffith University have conducted a number of studies on the filtering capacity of *Melaleuca* wetlands.

Investigations of the feasibility for using *Melaleuca* in constructed wetlands for the purpose of wastewater treatment may not be completely applicable to natural wetlands or those wetlands constructed for water improvement in agriculture areas due to the unpredictability of flow, depth of inundation and residence time of water within natural systems. However, some findings are applicable (Raisin and Mitchell 1996). *Melaleuca* trees can survive in permanently waterlogged conditions and under conditions comparable with nutrient enrichment by sewage (although in the enriched phosphorus treatment there was an indication of toxic response, but this was at higher levels than most secondary treated effluent) and therefore can be a considerable store of nutrients (Bolton and Greenway 1999a). *Melaleuca* plants can also be important for transferring nutrients from one nutrient sink (plant) to another (sediment), as senescent leaf fall is a significant contributor to the long-term sediment sink in *Melaleuca* wetlands (Bolton and Greenway 1997). Added incentives for using *Melaleuca spp*. in constructed wetlands are their ability to be harvested (in particular *Melaleuca alternfolia*) and their ability to tolerate extreme environmental conditions such as salinity, acidity and high metal concentrations (Bolton and Greenway 1997).

Comparisons and research on natural *Melaleuca* wetlands in south-east Queensland, including the Carbrook Wetlands in Logan City and Black Swamp and Egret Swamp wetlands in Redlands Shire, showed that *Melaleuca* wetlands perform vital ecosystem functions (Daniel and Greenway 1995; Greenway and Daniel 1997; Daniel 2002). The two main functions demonstrated were the wetland role as buffers for downstream areas by filtering out sediments and nutrients, and a high flow retention capacity, which assists in minimising floods and preventing excessive freshwater run-off into tidal waterways (Greenway and Daniel 1997).

Research into Black Swamp and the Carbrook Wetlands found larger *Melaleuca* areas perform these two vital functions more effectively. The Carbrook Wetlands (large in extent) function as a nutrient sink in non-flood times and in most flood events, with the exception of major and prolonged flooding when they become a source of total organic carbon (TOC), orthophosphate and ammonium (Greenway and Daniel 1997). By contrast the smaller sized Black Swamp is a source of nutrients. However, a confounding factor highlighted was the difference in the level of disturbance between the two catchments. The Carbrook Wetland catchment is relatively undisturbed, compared to the Black Swamp catchment, which is highly urbanised.

The role of landscape disturbance as an influence on source or sink was indicated in comparative investigations of two wetlands of similar area in size, Black Swamp and Egret Swamp. Black Swamp was found to be acting as a source of nutrients and suspended solids during the period of study, which resulted from nutrient enrichment within the supplying catchment and guano inputs within the wetland itself (also causing eutrophication within the ecosystem) (Daniel and Greenway 1995). By contrast, the Egret swamp wetland with a relatively undisturbed catchment was functioning as a nutrient sink. However, there were some other differences in the two wetlands which were of significance. The Egret Swamp wetland was thought to be predominantly fed by subsurface flow with surface water flowing through only during heavy rains, whereas Black Swamp received large amounts of water from stormwater drains and a permanent stream.

This study is one of few found from Queensland that directly investigates the ability of natural wetlands to improve downstream water quality and as explained above confounding factors of size and hydrological processes have reduced the capacity for conclusive results.

While *Melaleuca* trees are quite tolerant to higher nutrient loads, it is often assumed that *Melaleuca* wetlands have similar properties. Thus, releasing waters with elevated nutrients and other pollutants into these ecosystems reduces the potential impacts in receiving waters without harm to the wetland ecosystem. This assumption needs to be tested, as there are some indications that this is not the case. An assessment of sewage effluent impacts on coastal wetlands in Tin Can Bay found that continued discharge of contaminants into natural coastal wetlands resulted in vegetation change (Hillier 1997), including forest dieback of trees, and weeds and freshwater macrophytes had invaded the understorey within the zone of the effluent plume. Zoete and Davie (2000) argue that in ecosystems dominated by one or two tree species, the lower vegetation strata may be a better indicator of environmental perturbation. In a survey of *Melaleuca* wetland vegetation in south-east Queensland, tree layers contained a total of 18 species while the ground stratum contained a total of 236 species, representing 10 percent of all species occurring in the Moreton region. Monitoring and assessment protocols suggest that community indicators with the potential for more variability are often better at discerning an impact (Karr and Chu 1999), supporting the arguments of Zoete and Davie (2000).

Water storage

Water storage capacity was also investigated in the Carbrook and Black Swamp *Melaleuca* wetlands (Daniel 2002). This study found that both the Carbrook and Black Swamp wetlands were important water storage areas. During flooding the wetlands acted as a flood detention basin, and considerable drawdown of water levels occurred during low flow periods. As expected the smaller wetland areas had a more limited capacity to store water, which highlights the effect that fragmentation and reduction of wetland area will have on this function.

Primary and secondary productivity

Comparisons of leaf litter fall between *Melaleuca* forests and other Australian forest types indicated that production in *Melaleuca* forests is high (Finlayson, Cowie and Bailey 1993; Greenway 1994). Annual leaf litter fall within the Carbrook *Melaleuca* forest was among the highest recorded (at time of paper) for Australian temperate/subtropical sclerophyll forests and rainforests (Greenway 1994).

Greenway (1994) concluded that the *Melaleuca quinquenervia*–dominated leaf litter in the Carbrook Wetlands was an important nutrient sink due to the high carbon, nitrogen and phosphorus ratios (indicative of slow decomposition rates), and the high nitrogen and phosphorus concentrations of the small litter size fractions. It was also noted that a flood occurrence during the study period created leaching of soluble organics, but not nitrogen or phosphorus. Physical removal of fresh litter by increased levels of flowing water and litter in the riparian zone will move laterally into associated creeks, providing further allochthonous organic material to the stream. Northern Territory *Melaleuca* forests have been found to have leaf litter on the floodplain that contained 10 times more nitrogen and five times more phosphorus than the water entering the floodplain during one year (Finlayson, Cowie and Bailey 1993). This was taken as an indication that the role of litter in this ecosystem might be substantial.

Fauna surveys on the Carbrook Wetlands and other *Melaleuca* wetlands have found a considerable array of birdlife, bats, insects and other fauna (Greenway and Kordas 1994), indicating these are valuable habitat and feeding areas. The potential is also that many of these organisms will transport nutrients gained here to other parts of the terrestrial or estuarine landscape (i.e. an allochthonous nutrient source).

Wetlands dominated by shrubs

Arid zone

Swamps dominated by shrubs, in particular lignum (*Muehlenbeckia florulenta*), are common in the semi-arid and arid zones of Queensland. Lignum swamps can occur in channels, basins or flats on deep cracking clays. Lignum swamps can be dry for many months or years, when wet water is normally fresh and turbid (EPA 1999). The distinction between intermittent lakes, pans, and shrubby swamps, such as those dominated by lignum, and shrub species, such as river cooba, is somewhat arbitrary, as there is a high degree of overlap in the characteristics of these systems. Although lignum swamps are sometimes grouped, either with freshwater lakes or with pans and depressions in typologies, lignum swamps are distinct from claypans in terms of waterbirds. Waterbirds in the Cuttaburra Creek system favour small black box and lignum swamps for breeding as lignum is often used for nesting (Kingsford and Porter 1999).

Arid shrub swamps are valued for their significance in maintaining the aquatic ecology of the region, in particular the distinctive ‘boom and bust cycles’ are significant feeding and breeding areas for waterbirds and are grazing habitat essential for sustaining terrestrial wildlife and livestock. Information on the distribution, conservation status and management of shrubby swamps in the arid zone can also be found in the EPA management profile on Arid-zone Swamp Wetlands (EPA 2006a)

Lignum swamp hydrology is dominated by channel or overland flow (Timms 1999). Lignum survives across a range of flooding regimes, and at natural sites water can be ponded for some time and flow durations are as important as flood frequency (Roberts and Marston 2000). Some work has been done on estimating the changes to the flooding frequency in the Murray-Darling Basin. For example in the Cuttaburra Basin, lignum swamps flood 1 in 3 years and these systems retain water for as long as six months. On the Chowilla floodplain lignum swamps naturally had a flooding frequency of 2–4 years with inundation lasting 3–4 months; however, now these systems flood every 3–10 years and floods now last

2–3 months. While flooding is important, lignum is intolerant of sustained flooding durations (Roberts and Marston 2000).

Lignum ecosystems and associated wetlands in the arid zone have very little recorded information on their ecology (EPA 1999; Roberts and Marston 2000). The fauna of these areas appears to be similar to claypans (Timms 1999) except for the regular presence of riverine species.

Coastal wet heath and patterned fens

Heaths are plant communities dominated by low shrubs and various other ground

flora. Wet heath is found in lowland, often coastal situations (EPA2006f). In Queensland most heath is found along the coast. Patterned fens are areas that contain vegetation which is peat forming in fens water, and nutrients are received from the surrounding catchment through the watertable. Patterned fens normally occur in high latitude areas; however, in Queensland these features are found on the Cooloola Coast and on Fraser Island, which makes them unusual (Fraser Island World Heritage Area Scientific Advisory Committee 2004).

Wet heath and the fens are noted for their role in maintaining unique flora and fauna, as core areas for a number of species that are adapted to acid waters, and as habitat for threatened and rare species (Fraser Island World Heritage Area Scientific Advisory Committee 2004). It is surprising that information on the hydrology, food webs and ecosystem function is lacking, given that the area of wet heath in Queensland is found in a number of coastal lowland situations and across three widely dispersed bioregions—south-east Queensland, central Queensland coast and Cape York Peninsula (EPA 2005f). Some additional distributions may also be found in the Gulf plains. Information on the distribution, conservation status and management can also be found in the EPA management profile on ‘Coastal wet heath/sedgelands’ (EPA 2006f).

Heath flora has evolved in soils with low nutrient status. Seasonal waterlogging is also a dominant feature of these wetlands, with some heaths waterlogged for up to six months a year. Studies have recorded significant changes in heath lands with the application of nutrients (Heddle and Specht 1975; Specht, Conner and Clifford 1977; Specht 1979). These changes included:

- Phosphorus application speeds up the life cycle of heath plants causing them to have shorter life spans.
- Spring-growing herbaceous species were able to compete successfully with heath plants, leading to floristic changes in plant species composition.

These results illustrate the sensitivity of oligotrophic ecosystems to changes in species composition and abundance with the addition of nutrients, a finding also illustrated in studies of coastal dune lakes (Hadwen 2002) (see under South-east Queensland, page 18 & Appendix page 99).

The focus of information pertaining to wet heath is biased towards vegetation characteristics, the ecology of individual faunal species (e.g. the Wallum sedge frog (*Litoria olongburensis*) (Lewis and Goldingay 2005), the ornate rainbowfish (*Rhadinocentrus ornatus*) (Page, Sharma and Hughes 2004) and the ground parrot (*Pezoporus wallicus*) (McFarland 1991). Less information is available on the function and importance of these wetlands to the surrounding ecosystems and ecological interactions within these ecosystems.

The patterned fens that exist on Fraser Island and at Cooloola are unique and of great scientific interest as they are the only known examples of subtropical patterned fens in the world (Fraser Island World Heritage Area Scientific Advisory Committee 2004). These ecosystems have a range of other unique features, which include:

- the presence of fish, as fish are not known to inhabit fens anywhere else
- the high number of rare and threatened species
- the occurrence of earthworms and crayfish in acidic environments
- they are the only known examples of patterned fens flowing into tidal wetlands in the world.

Apart from some discussion in Fraser Island World Heritage Area Scientific Advisory Committee (2004) this review has found no research or literature pertaining to these features.

Wetlands dominated by grass, sedge, reed or rush

These wetlands are valued for a range of functions including as habitat for a range of flora and fauna including waterbirds, grazing reserves for livestock and terrestrial fauna, and it is thought that shallow vegetated wetlands are especially good for improving downstream water quality (Fisher and Acreman 2004).

The extent of some wetland areas of this type is quite large. For example Driscoll (1995) documented subcoastal sedgelands that extended inland along river floodplains on the Cape York Peninsula for many kilometres. Information on the distribution, conservation status and management can also be found in the EPA management profiles on Inland non-arid Swamp Wetlands' (EPA 2006e), Arid-zone Swamp Wetlands (EPA 2006a) and Coastal Grass/sedge Wetlands (2006c).

Information on this type of wetland is often incorporated into studies of floodplains and other wetland types, as these wetlands often occur as patches at the margins of lakes and deeper water habitats and within other wetland types such as saltmarsh and *Melaleuca* wetlands. Nolen (2001) sampled riverine, billabong and 'swamp wetlands', and found that the swamps and billabongs had a higher diversity and abundance of macro-invertebrates, which would be expected in lotic sites when compared to lentic.

The water regime for a number of plant species that occur in these wetlands has been summarised for the Murray-Darling Basin by Roberts and Marston (2000); however, this review may be of limited relevance to subtropical and tropical areas.

Ponded pastures represent a highly modified form of this wetland type (Hyland 2002). Modification of wetlands for the purposes of cattle fodder production is considered a threat to the biodiversity of wetlands in Queensland (EPA 2006h). However, Pittaway and Chapman (1996) argued that ponded pastures have value in reducing nutrient and sediment loads from grazing areas if appropriately sited. This is likely to be the case and constitutes an example of where the values of high nutrient retention are not necessarily complementary to the ecological health or biodiversity of a system.

In addition to modification of wetlands for ponded pastures, exotic grasses have also invaded other areas, in particular adjacent coastal wetlands, as a result of their use as pasture grasses. A study that documented the effects of the invasion of ponded pasture species on the function of seasonally inundated wetlands has been conducted on the Magella floodplain, Kakadu National Park, Northern Territory (Douglas *et al*. 2001). While the study found that para grass does have implications for biodiversity (further discussed in Weeds and feral animals, page 110) it had little effect on the aquatic food web, which was largely driven by epiphytic algae. Also fish and aquatic invertebrates appeared to be insensitive to changes in grass composition, presumably due to the aquatic food web being driven by algae. However, the authors documented two limitations, in that only a subset of flora and fauna was sampled, and para grass invasion was patchy and the results may not apply to larger-scale infestations. Para grass has also been recorded in Queensland spring wetlands where in some situations exotic grasses have invaded the wetland to the detriment of much of the native wetland flora (Fensham and Fairfax 2003).

A number of studies exist on ponded pastures (Pittaway and Chapman 1996; Hyland 2002); however, information on natural wetlands is less available. In 'fact sheets' describing the natural wetlands of south-west Queensland published by the Queensland Environmental Protection Agency a number of wetlands were identified, for example forb meadows on floodplains, sedge swamps, and freshwater lakes with couch grassland (EPA 1999). For all these wetland types, knowledge of hydrology, ecological processes and occurrence of wetland species was inadequate. Inland non-arid swamps are also poorly studied (EPA 2006e). Natural coastal wetlands of this type are sometimes discussed in the literature, but also have not been researched to any great extent in terms of subjects relating to the aims of this review.

Claypans (vegetation is generally sparse or absent)

Geldenhuys (1982) defines pans as 'natural, shallow depressions … which are flooded during the rainy season, have no outlets, and usually dry up seasonally mainly through loss of water due to evaporation'. Most Australian-based typologies recognise them as shallow, flat and hard-bottomed wetlands in heavy non-cracking clays, also characterised by very turbid water. Pans may lack vegetation, while others have cane grass communities and other species growing on the pan surface. Some pans have riparian vegetation such as black box (*Eucalyptus largiflorens*) or poplar box (*Eucalyptus populnea*) while others lack fringing vegetation (Timms 1999). A further recognised characteristic is that the majority of these pans are filled by local rainfall (Timms 1999).

In arid zones of Queensland (e.g. Murray-Darling Basin to Georgina Basin), shallow ephemeral claypans are a common wetland type (Timms 1999). Estimates within Currawinya National Park are that pans have a density possibly exceeding 7.4 pans per square kilometre, which gives some indication of the extent in area of the habitat they can provide after rainfall (Timms 1999).

Professor Brian Timms (University of Newcastle, New South Wales) and associates have been studying the invertebrates of the wetlands, including claypans, of the Paroo catchment for over a decade. Results of these studies indicate claypans have a unique fauna, dominated by phyllopod crustaceans having eggs resistant to desiccation, and opportunistic insects with dispersal mechanisms and life cycles evolved to cope with the ephemeral and unpredictable nature of arid habitats (Hancock and Timms 2002).

Timms and Boulton (2001) conducted a study on a number of wetland types in the Paroo catchment, investigating how existing wetland typologies match invertebrate assemblages. Their conclusions were that pans formed a core group of wetlands with highly similar invertebrate communities when compared to other wetland types. Pans with very high turbidity and those without fringing trees showed highest invertebrate similarities. It was also found that the invertebrate assemblage of wetlands, such as black box depressions and other vegetated depressions were distinct from claypan assemblages (Timms, 2001). Lignum swamps are sometimes characterised by freshwater lakes, or with pans and depressions; however, waterbirds have been identified as preferring lignum swamps for breeding, indicating that they are a distinct wetland type compared to claypans (Kingsford and Porter 1999) (see Arid zone, page 28).

Hancock and Timms (2002) studied a complete filling and drying cycle of five pans situated in the Paroo catchment in north-western New South Wales. These pans were characterised by:

- shallow depth
- high turbidity
- a short filling phase
- low conductivity
- moderate alkalinity
- generally low in nutrients, although during the early inundation phase nutrients can be relatively high
- persistence time between 30 and 120 days
- varying water temperatures
- a lack of riparian vegetation.

By contrast to the findings of Timms (2001), environmental variables were poorly correlated with macro-invertebrate community structure and zooplankton (Hancock and Timms 2002). Wide variation in environmental characteristics between filling events has been recorded (Meintijes 1996; Sanders 1999) and may explain this lack of association, although it has been suggested that community structure in these pans might be more influenced by the relative success of species in previous breeding, particularly for crustaceans, and the chance colonisation of mobile species such as insects than the prevailing environmental conditions (Hancock and Timms 2002). Succession was directional and continuous without distinct phases, but in longer-lived pans there was a tendency towards a stable assemblage of macro-invertebrates dominated by predatory insects and a simple zooplankton dominated by calanoid copepods.

Compared with other wetlands in the Paroo catchment, pans have low macro-invertebrate species richness with the exception of those on Bloodwood station where a richness of 75 species occurred in four pans (Hancock and Timms 2002). This is distinctly higher than the mean cumulative richness of 28 species from 19 pans recorded by Timms and Boulton (2001). Differences may be due to species turnover with temporally more numerous collections undertaken than in other studies (Hancock and Timms 2002). This has implications for the study of pans and other wetlands as it highlights the large variability of many systems, in particular arid systems (characterised by the traditional isolated waterholes and the 'boom and bust' cycling of many arid ecosystems). An understanding of temporal variation in these systems is lacking, and this study illustrates that single sampling or sampling that does not capture all hydrological stages may underestimate the species richness of intermittent and episodic wetlands.

Food webs in claypans

Stable isotope ratios of benthic ooze from claypans of the Cooper Creek floodplain indicated that sources of carbon were largely from algal origins rather than riparian vegetation (Bunn and Davies 1999). Shield shrimps, conchostracans and snails also clearly obtained all of their biomass carbon from this algal source and not from terrestrial carbon. Hancock and Timms (2002) noticed a bathtub ring of algae in pans studied from the Paroo catchment, from which it was assumed that these pans may be operating in a similar way to the Cooper Creek system, and that the algae was the dominant carbon source, despite high turbidity and abundant detrital matter. However, further validation of this using isotope analyses was not undertaken.

Spring wetlands

Spring wetlands are groundwater wetlands normally located where aquifers are shallow or fractured by a fault and where water escapes to the surface (EPA 2005d). Most research relating to spring wetlands in Queensland has been conducted on the wetlands of the Great Artesian Basin (GAB). Information on the distribution, conservation status and management of GAB spring wetlands can also be found in the EPA management profile on Great Artesian Basin Spring Wetlands (EPA 2005d). The Queensland Herbarium has undertaken a number of research projects in recent years on the GAB wetlands in Queensland and while some limited biological surveys in the Queensland section of the GAB have been attempted (including the recharge springs of Cape York), information from other areas is lacking (Fensham and Fairfax 2005).

The values attributed to these wetland types include:

- a unique environment and habitat for organisms that have high endemicity
- as a refugia and habitat for aquatic organisms in an arid landscape
- as a water source for terrestrial fauna, such as birds, native mammals and livestock (EPA 2005d; Fensham and Fairfax 2005).

GAB wetlands naturally occur in a range of landscape settings or a combination of them. These include:

- recharge areas where water exudes from the outcropping sandstone sediments that form the head of the basin when inflow exceeds through-flow
- where the water bearing sediments approach the ground surface near the margins of the basin or are relatively shallow
- where water flows through faults or unconformities in the overlying sediments
- where a conduit is provided at the contact between the confining sediments and the outcropping of bedrock (for example granite) (Habermehl 2001).

Artificial spring wetlands also exist in Queensland, in the form of bore pools, bore drains and other watering points. Investment in Queensland through the GAB Sustainability Initiative to cap bores and pipe bore drains has seen a reduction in these artificial wetlands with the aim of eventually capping and piping all bores and bore drains (Department of Natural Resources and Mines 2005). Between 1989 and 2005, 498 bores were capped and 4600 km of drains were piped (EPA 2005d).

In general an important distinction in the GAB is the difference between recharge springs and discharge springs. Recharge springs normally occur where the sandstone aquifer is at the surface or buried under porous sand layers, allowing water to be absorbed and discharged again locally in a relatively short period. These springs are not necessarily situated directly in the sandstone, but are in the vicinity of it and water residence times are short (Fensham, Fairfax and Sharpe 2004). Recharge wetlands can be the source of large watercourses that exist for tens of kilometres (Fensham and Fairfax 2003). In Queensland main recharge areas and therefore recharge springs are found in the northern and eastern margins of the GAB.

Discharge springs are found down-gradient of recharge areas, where water escapes to the surface through faults in the rock or where the aquifer comes to the surface. As well as water permanence, these systems are characterised by high levels of environmental constancy with respect to water physicochemical attributes, including temperature, pH and ionic composition. Consequently, they are highly significant ecosystems, providing critical habitat for many endemic taxa including flora, fauna and microbial communities (Department of Natural Resources and Water, G. McGregor, pers. comm., 2 September 2005). Discharge springs tend to range in size from 100 cm^3 to 3 ha.

Habitat for endemics

There has been limited biological survey of the Queensland section of the GAB, but what is known suggests they are highly specialised ecosystems with high endemicity due to isolation from other aquatic habitats. The best-known faunal groups to date include macro-invertebrates (hydrobiid and planorbid snails, atyid shrimps) and fish. Three freshwater fish, four species of crustacea, 23 snails and several other invertebrates are found only in discharge springs (Fensham and Fairfax 2005). In Queensland there are nine species of plants endemic to discharge springs and three restricted to the recharge springs (Fensham and Fairfax 2005). Prolific microbial mats, most of which have not been characterised from a structural or functional perspective, are also associated with artesian wetlands and these contribute to the high productivity of these wetlands (Department of Natural Resources and Water, G. McGregor, pers. comm., 2 September 2005). Spring wetlands also have vegetation communities that are highly unusual. For example, spring wetlands (Boggomosses) of the Dawson catchment have sandy substrates with vegetative elements having origins in terrestrial and wetland coastal habitats and mound springs from western Queensland rather than floral elements more typical of the terrestrial and wetland habitats of the region. The resulting plant community is thought to be unique, as nothing similar has been described in the literature (Fensham and Wilson 1997).

The non-GAB arid zone spring wetlands (found in the North-west Highlands, Gulf Plains, Mitchell Grass Downs, Channel Country, Mulga Lands, Einasleigh Uplands, Desert Uplands and Brigalow Belt) have high value as habitat for endemic species. Fensham, Fairfax and Sharpe (2004) identified endemic species in the sandstone springs in the North-west Highlands of Queensland and the Northern Territory and in springs associated with basalt in the Einasleigh Uplands.

While endemic species have been recorded in artificial spring wetlands, for example species of fish and the specialised plant *Myriophyllum artesian* have been found in bore drains, it seems that few endemic species exploit these artificial habitats (Fensham and Fairfax 2003). However, a study of the southern Gulf of Carpentaria catchments identified what might be an undescribed species of fish, which appears to have a distribution range limited to bore drains (Hogan and Vallance 2002). On the basis of this find it has been recommended that individual bores should be assessed before capping and that a fish and wildlife study of bore drains in the southern Gulf area is urgently required (Hogan and Vallance 2002).

2. Wetland ecosystems

Habitat for generalist aquatic species

In arid and semi-arid regions of Queensland, GAB-fed natural spring wetlands and bore drain wetlands are a distinctive aquatic ecosystem. They represent some of the few permanent surface water habitats in an otherwise ephemeral landscape. Over 300 native vascular plant species in GAB spring wetlands outside of Cape York and another 300 native vascular plant species associated with the spring-fed forests of Cape York have been identified (Fensham, Fairfax and Sharpe 2004). These figures highlight the role of springs as habitat for flora and fauna.

Recorded occurrences in springs of a large number of native species (approximately 60 species) are hundreds of kilometres (250-500 km) from the nearest known occurrence (Fensham, Fairfax and Sharpe 2004). In the non-GAB spring wetlands of the Einasleigh Uplands, springs from Tertiary sandstone aquifers in the Mulga Lands and springs of the North-west Highlands have populations of non-endemic native plant species isolated by more than 500 km from the other populations (Fensham, Fairfax and Sharpe 2004).

Some concerns have been raised during workshops and discussions with experts that as many of the natural spring wetlands have dried or contracted, much of the natural habitat in Queensland may have been lost. Some expressed concern that the wetlands associated with free-running bores may represent critical refugia and that there is a pressing need to consider the importance of constructed GAB wetlands in this context before the bores associated with them are capped (Appendix 3). This subject requires further research to validate if this is an important consideration in GAB restoration works.

Water source for terrestrial fauna

Natural springs provide a source of water for terrestrial animals, including livestock, which prior to the advent and utilisation of artificial watering points and the increase in the impoundment of rivers, were potentially essential in maintaining many species' population in the region. These artificial watering points include bore pools, bore drains and troughs containing groundwater. However, artificial watering points are currently widespread over grazed arid and semi-arid zones (with estimates of average distance between points at less than 10 km), and therefore natural springs have become less critical habitats (Landsberg *et al*. 1997).

Research needs for palustrine wetlands

Information on the ecology, hydrology and functions of palustrine wetlands is poorly documented. The main exception to this was *Melaleuca* and spring wetlands, although an understanding of the trophic interactions and ecosystems function is lacking. Palustrine wetland types occur in Queensland that have not been discussed by this review due to a lack of literature pertaining to the scope of this document, for example arid zone forested wetlands and palm swamps.

Given the limited nature of research on these wetland types we recommend that investment is urgently needed into developing an understanding of these shallow vegetated wetland types, including their hydrology, ecology and functions.

Table 2.5: Research needs for palustrine wetlands

Knowledge gap	Wetland type(s)
Studies that focus on how the ecosystem as a whole is functioning	All palustrine
Surveys of wetlands and their biophysical processes and functions (Fensham and Fairfax 2005)	All palustrine
A better understanding of the hydrologic requirements of these wetlands, including assessments of filling patterns and commence to flow levels (Cottingham 1999; Finlayson *et al*. 2004)	All palustrine
Quantification of the processes occurring in these wetlands that provide ecosystem services (Appendices A1 and A2)	All palustrine
Appropriate management regimes wetlands, such as the effects of burning	All palustrine
Development of a better understanding of the connectivity between these wetlands and other aquatic and terrestrial ecosystems in terms of: species may be dependent on these features for part or all of their life cycle; and carbon and nutrient movement (Pearson and Connolly 2001; Appendices A1, A2 and A3)	All palustrine
Information on the formation and persistence of ecosystems, to assist in appropriate management (Fraser Island World Heritage Area Scientific Advisory Committee 2004)	Patterned fens
Optimum fire frequencies to sustain peat formations and the fauna they support (Fraser Island World Heritage Area Scientific Advisory Committee 2004)	Patterned fens
The effects of capping on biota/assessment of ecological significance of bore pools and drains (Hogan and Vallance 2002)	Spring wetlands
Studies on micro-habitat patterning (Fensham and Fairfax 2005)	Spring wetlands
Improved knowledge of hydrogeology as it relates to springs (Fensham and Fairfax 2005)	Spring wetlands

3. Functions attributed to wetlands

Introduction

Discussion of the functions and values of wetlands as a whole can be difficult given the variety of ecosystems that are classified as wetlands (see Chapter 1). This is further confounded by information sources that do not detail the wetland type studied. However, while classification can be used to reduce variability for interpretation purposes, it needs to be noted that differences such as position within the landscape, the extent of a wetland, and changes to its ecological character from human pressures are unique events acting in a unique environment. The extent to which it is utilised by fauna will also affect the type of functions a wetland will provide, so even two wetlands that may appear similar may be unique (Mitsch and Gosselink 2000b).

Mitsch and Gosselink (2000a) considered a number of landscape and scale phenomena which make generalisations about wetland values and functions difficult, in particular:

- the *scale principle*: Wetland values are different, accrue to different stakeholders and probably have different importance depending on the spatial scale on which estimations are based. For example at a small scale landowners may value a wetland on their property because it maintains a population of a species that they value, in a recreational, commercial or existence sense. At a global scale wetlands as a whole are valued as having a role in global carbon cycles, and significance to global climate patterns. In this example the value of wetlands in areas such as boreal regions where the majority of peatlands are found will be important to the world's population
- the *marginal value paradox*: Fewer wetlands do not necessarily imply greater value in situations where human populations have overwhelmed the functions of the last remaining wetlands. For example, faunal value can be lost with increasing fragmentation of wetlands as size becomes smaller and connectivity is reduced. Wetlands when overloaded with nutrient and pollutant sinks can also cease to be effective in this role (Bailey, Boon and Morris 2002)
- the *hydrogeomorphic principle*: Wetland values depend on the location in which they are found and the linkages to other aquatic ecosystems. For example, a wetland close to a river may be of more value in retaining floodwaters than an isolated wetland
- the *ecosystem substitution paradox*: If different ecosystems are ascribed different values in a given landscape, recommending the substitution of more valuable types for less valuable ones may appear to seem logical and beneficial. For example, wetlands have been valued as 64 times more valuable than rangelands and grasslands (Costanza *et al*. 1997). This does not, however, mean that we should replace these ecosystems with wetlands. At a small scale this type of substitution has been attempted in the United States to meet regulatory requirements of wetland migration. Many of these created systems do not function in the same way as natural wetland systems and so are not as 'valuable' as the original ecosystems that were lost to create them (Mitsch and Gosselink 2000a).

Given these considerations, the following sections describe the major ecological functions ascribed to wetlands based on existing literature and discussions with relevant experts. The functions are discussed under the following categories:

- water quality processes
- water regulation and shoreline stabilisation
- groundwater interactions
- biodiversity
- production export
- carbon sequestration
- prevention of acidity in the riverine and near-shore environments.

While an attempt has been made to discuss the processes occurring in terms of different wetland types, information is not always available to do this and to make assumptions may result in the undervaluation of a wetland type that little is known about.

Water quality processes

When discussing wetlands in the context of water quality improvement, most authors use the definition of Mitsch and Gosselink (2000b): *Wetlands are lands transitional between terrestrial and aquatic systems where the watertable is usually at or near the surface or the land is covered by shallow water … Wetlands must have one or more of … undrained hydric soils, support predominantly hydrophytes, or are saturated or flooded at some time during the growing season of each year*. While this definition is quite narrow, the literature discussing 'wetlands' as water quality filters is normally referring to relatively shallow and vegetated ecosystems, which have fluctuating water levels and waterlogged soils for at least some of the time. This is an important distinction from the very broad definition of wetlands described under the Queensland Wetlands Programme, which includes rivers, lakes and shallow marine ecosystems, which are not reviewed as part of this section.

Many planning and discussion papers on wetlands cite the values and functions of wetlands as one entity when it may be that different wetland types function differently in terms of water quality. Within the one wetland type there will be considerable variation in function depending on environmental factors. Even within individual wetland there may be zones with different functional attributes (i.e. reed beds, open water). A single wetland can act as a source, sink and transformer of nutrients across temporal scales (Mitsch and Gosselink 2000b). A wetland is termed a 'sink' if it has a net retention of an element or specific form of that element (e.g. organic or inorganic). If a wetland exports more of an element or specific form of that element to a downstream or adjacent ecosystem than would occur without a wetland, it is considered a 'source'. If a wetland transforms a chemical form (e.g. from a dissolved to a particulate form) but does not change the amount going into or out of the wetland, it is considered a 'transformer' (Mitsch and Gosselink 2000b). In general terms it is thought that many wetlands act as sinks for particular inorganic nutrients (phosphorus and nitrogen will be discussed here) and many wetlands are a source of organic material, in particular carbon for downstream or adjacent ecosystems.

As well as the effectiveness of wetlands to remove nutrients, there are also the possible effects of poor water quality inflows on natural wetlands to consider. A brief review of some of the different types of wetlands in Queensland included as part of this report illustrates that wetlands vary greatly in their capacity to tolerate increased nutrients (e.g. Hillier 1997; Hadwen 2002).

Nutrient cycling in wetlands

The understanding of nutrient cycling in wetlands is important to the understanding of many functions attributed to wetlands. In this section only carbon, phosphorus and nitrogen will be discussed. Carbon is generally discussed in the context of production export, and phosphorus and nitrogen are the two nutrients most commonly discussed in terms of enrichment associated with agricultural processes and wastewater. The general physical, chemical and biological processes occurring in wetlands are very well summarised in a number of texts, for example Reddy and D'Angelo (1997), Boulton and Brock (1999)and Mitsch and Gosselink (2000b).

Carbon

Organic carbon in wetlands is contained in living biomass and dead organic material. Wetlands are normally sinks for carbon, that is, typically there is accretion of organic matter (Reddy and D'Angelo 1997). Net accumulation of carbon in wetlands is a balance between primary production and respiration, although carbon can also be added from sources external to the wetland (Reddy and D'Angelo 1997) and released from the wetland via downstream transport and released into the atmosphere. Organic matter that is deposited (normally seasonally) on the soil surface can be added to the soil layer and over time buried, which provides a long-term store of carbon (Reddy and D'Angelo 1997). The major processes of carbon transformation occur under aerobic and anaerobic conditions (Mitsch and Gosselink 2000b). Photosynthesis and respiration occur in aerobic horizons.

The two major processes in anaerobic conditions are fermentation and methanogenesis. Fermentation occurs via anaerobic respiration by micro-organisms and forms low molecular weight acids, alcohols and carbon dioxide. It represents the major way that high molecular weight carbohydrates are broken down to low molecular weight organic compounds, usually as dissolved organic carbon, which becomes available to other microbes. Methanogenesis occurs when bacteria (methanogens) use carbon dioxide or a low molecular weight organic compound for the production of gaseous methane (CH_4). Methane can then be released into the atmosphere if disturbed (Mitsch and Gosselink 2000b).

Phosphorus

The cycle of phosphorus in wetlands involves transformations between organic and inorganic phosphorus, which exist in soluble and insoluble forms. Phytoplankton, benthic algae and macrophytes can use only soluble phosphate for growth and it is continually cycled by other organisms and bacteria. Phosphorus is also rapidly taken up by water plants and micro-organisms. It is thought that no significant loss of phosphorus to the atmosphere occurs, so accretion in the bottom sediments or uptake via plants removes the most phosphorus from the water column (Faithful 1997). Phosphorus bound to particles settles rapidly (Boulton and Brock 1999). Phosphorus is made relatively unavailable to plants and micro-consumers by:

- precipitation of insoluble phosphates with ferric iron, calcium or aluminium
- the adsorption of phosphate onto clay, organic peat and ferric and aluminium hydroxides and oxides
- the binding of phosphorus in organic matter as a result of its incorporation into the living biomass (Boulton and Brock 1999).

Phosphorus can be released from these forms if the pH and redox conditions are favourable. For example inorganic phosphorus can be released from sediments after 4–6 weeks of inundation (Greenway 2004). In the past, this process has been considered to be an abiotic one, but Baldwin, Mitchell and Rees (1997) documented the role of bacteria in the release of phosphorus in anaerobic conditions. The authors also found that this release is influenced by the availability of electron donors (e.g. acetate) and electron acceptors (e.g. sulfate).

In the literature on constructed wetlands, a common problem with removal of phosphorus is that the age of a wetland will affect the rate of removal, with efficiency decreasing with age (Faithful 1997; Fisher and Acreman 2004). However, in some natural wetlands this is not the case (Patruno and Russell 1994).

Nitrogen

Nitrogen reactions in wetlands are best discussed in terms of redox states (Boulton and Brock 1999). Nitrogen occurs in a number of oxidation states in wetlands. Ammonium ion is the primary form of mineralised nitrogen in waterlogged soils, although nitrogen is also tied up in organic forms in highly organic soils. In the anaerobic conditions with which ammonium is formed it can be:

- absorbed by plants, algae or anaerobic bacteria
- immobilised through ion exchange onto clay particles
- or if pH is high (above 9), it can be converted to ammonia and released to the atmosphere (Boulton and Brock 1999).

Under aerobic conditions, ammonium can be oxidised through nitrification and converted to nitrate, which is mobile in solution. Nitrate also can take a number of pathways: it can be assimilated by plants, algae and microbes; lost to groundwater; or lost to the atmosphere via denitrification, which is carried out by micro-organisms under anaerobic conditions. Wetlands can also gain nitrogen from the atmosphere by nitrogen fixation of nitrogen gas by bacteria and cyanobacteria. Carbon is important to denitrification processes, so for the cycling of nitrogen, vegetation is important indirectly (Fisher and Acreman 2004).

Wetting and drying cycles

Flooding and drying of wetlands, especially in the subtropics, tropics and arid regions, is a natural occurrence and is necessary to maintain wetland vegetation and maximise nutrient cycling (Greenway 2004). McComb and Qiu (1998) reviewed the effects on wetland sediments from drying and reflooding and found that effects are dependent on a number of factors and that in some shallow wetlands drying of sediment decreased phosphorus concentration at refilling, but in other cases it increased phosphorus concentrations. They suggested that sediment composition might be the dominant factor determining differences in responses to drying and reflooding. Waterlogging can enhance the ability of soils with charged colloids to retain nutrients (e.g. NH_4 and PO_4) and heavy metals through increases in cation exchange capacity and phosphorus sorption capacity (Phillips and Greenway 1998).

Soils in wetlands with organic matter produce large increases in cation exchange capacity with increasing pH. However, pH in wetlands can decline with processes such as nitrification, organic carbon decomposition and oxidation of FeS_2 sediments (Phillips and Greenway 1998). The principal benefit of a drying cycle appears to be to allow oxidisation of NH_4 to NO_3, which would then be lost through denitrification under subsequent waterlogged conditions (Phillips and Greenway 1998). In temporary freshwater wetlands in western New South Wales that were dried for several months and reflooded, total loads of iron, phosphate, nitrate and sulphate increased as wetlands reflooded.

Nitrate and phosphorus concentrations also peaked under these conditions (Briggs, Maher and Carpenter 1985). The release of nutrients from wetland soils on reflooding is thought to be a cause for the boom in productivity experienced by many wetlands, in particular ephemeral arid zone wetlands (Timms 1999). Wetlands with altered flow regimes that have increased durations of inundation may have changed productivity levels and suffered reductions in breeding and habitat use by waterbirds (Kingsford 2000).

Although wetting and drying cycles are thought to increase nutrients, as a pulse on reflooding, repeated wetting and redrying is thought to convert iron oxides and absorbed phosphorus to progressively less available forms (Greenway 2004). It is also reported that pastures with a cyclical flood regime have alternate oxic and anoxic soil conditions that could remove phosphorus on a sustainable basis by the incorporation of three steps: sorption onto soil particles, assimilation by pasture grass and removal by grazers or harvesting (Faithful 1997).

The role of wetlands in improving downstream water quality

The literature relating to wetlands as downstream water filters from Australia and elsewhere largely relates to constructed wetlands, and in particular those used in sewage and stormwater treatment. Wetlands constructed to treat sewage and wastewaters are used widely. The general roles of constructed wetlands are shown in Table 3.2. There are major differences that make results from the studies of wetlands used to treat sewage inapplicable for diffuse pollutants, although some of the processes that occur may be similar.

Important wetland characteristics for nutrient removal are:

- the concentration of the influent pollutant
- the depth, velocity and water retention time
- the size of the wetland
- the presence, species composition and growth habitat (i.e. submerged, floating) of macrophytes (Greenway 2004).

While control of these factors is possible in wetlands targeted for use as wastewater treatments, in stormwater and diffuse agricultural settings it is not possible to control all these factors as efficiently (Raisin and Mitchell 1996). Intermittent hydraulic loading and the lack of a significant organic load and high sediment loads in agricultural wetlands are the main differences between them and domestic wastewater wetlands (Higgins *et al*. 1993). The study of wetlands for the treatment of sewage is not comprehensively reviewed here; however, as the issue is the major source of literature in Australia on water quality improvement by wetlands, some of the principles and findings of this research will be included where relevant.

3. Functions attributed to wetlands

Table 3.1: Summary of constructed wetlands' roles in improving water quality

Pollutant	Role of wetland
Suspended solids and BOD	The vegetation facilitates sedimentation. Finer particles adhere to the biofilm surfaces of the vegetation or the gravel substrate. Microbial degradation of organic particulates.
Nutrients	Direct uptake by plants and micro-organisms. Inorganic nutrients converted to organic biomass. Microbial processes facilitate the removal and transformation of nutrients, especially nitrogen removal.
Metals	Plant uptake and bioaccumulation. Microbial bioremediation. Immobilisation by adsorption onto sediments or by precipitation.
Hydrocarbons	Microbial hydrocarbon degradation.
Pathogens	Natural UV disinfection. Natural biocontrol by microbial predators in the wetland ecosystem. Adsorption to fine particles and sedimentation. Natural death and decay.

Source: from Greenway, 2004

In the literature on constructed wetlands for diffuse water quality control, wetlands do not tend to be described in adequate detail in terms of their construction. Two types of wetland are usually discussed: shallow vegetated wetlands and riparian areas. The former is dealt with in some detail in this report. Riparian areas are not within the scope of this project; however, since the issue of water quality improvement is central to this review, the literature that exists in regard to riparian zones in Queensland will be included.

The key water quality improvement issues addressed in this section are:

- effectiveness of wetlands in reducing diffuse agricultural pollutants
- design characteristics to maximise effectiveness
- designing wetlands for multiple objectives
- potential impacts of nutrient enrichment on wetland ecosystems.

Effectiveness of wetlands in reducing diffuse agricultural pollutants

Few Australian studies have looked at the performance of natural wetlands in removing nutrients, and those that do present views that the effectiveness of these processes, while they do occur, is temporally variable and anthropogenic processes can lead to changes in chemical cycling (e.g. Raisin and Mitchell 1995; Greenway and Daniel 1997). There is more literature on this topic from the US and Europe, but results from many of these studies are conflicting (Fisher and Acreman 2004). A review of global literature on wetlands constructed for the treatment of non-point source pollutants highlighted the dramatic effect that storms have on treatment efficiency (Mitsch and Gosselink 2000b). Another review examined data from 57 studies on natural wetlands from around the world to investigate the effect of wetlands on the nutrient loading of waters draining through them. Fisher and Acreman (2004) found:

- The majority of wetlands reduced nutrient loadings.
- Some wetlands did increase nutrient loadings by the release of soluble nitrogen and phosphorus.
- Studies conducted over a period of a year or more or those that involved frequent sampling of high flow events were more likely to indicate that a wetland increased nutrient loadings.
- There was little difference in the proportion of wetlands that reduced phosphorus to those that reduced nitrogen.
- Swamps (off-stream wetlands) tended to be slightly more effective than riparian zones.

Fisher and Acreman's (2004) review does show that natural wetlands can have a role in nutrient cycling within the landscape; however, there are important confounding factors and considerations to their effectiveness.

Constructed wetlands in agricultural settings have been developed for the purpose of downstream water quality improvement and other objectives such as provision of habitat for fish and other aquatic biota (Lukacs and Pearson 1995). Investigations of the effectiveness of constructed wetlands developed for these roles are limited and long-term monitoring is nearly non-existent. Similarly, in the United States, there are few thorough studies of the effects of treatment of wetlands on agricultural non-point sources (Mitsch and Gosselink 2000b).

Several Australian reviews have examined the role of wetlands in water quality improvement. Water quality issues relating specifically to the Sugar Industry were reviewed by Bjornsson *et al*. (2002), and the role of wetlands and riparian zones in water quality processes summarised by Hunter and Hairsine (2001). Faithful (1997) provides a detailed synthesis of available information on wetland phosphorus dynamics. The key issues identified by Faithful (1997), which are relevant to our discussion are:

- Natural and constructed wetlands can efficiently remove phosphorus, but these wetlands experienced loads lower than those typically encountered in wastewater.
- The literature contains many examples of wetlands that are able to effectively remove solids, biological oxygen demand (BOD) and in some cases nitrogen, but not many remove phosphorus effectively. This may be a problem with design.
- Different types of wetlands have different abilities in removing phosphorus. Reed beds, for example, are not especially efficient at removing phosphorus, while vertical subsurface flow wetlands and cyclic flooded grazed pastures are better.
- Most authors suggest that consistent and sustainable removal of phosphorus in free surface water and horizontal subsurface flow wetlands requires low loading rates and long residence time.
- Much of the literature pertaining to phosphorus removal capabilities is confusing. Often authors do not address variables that are important for phosphorus removal, and as a result similar wetland types report a large variability in performance.
- Macrophytes are generally considered to have a valuable role in the functioning of wetlands. This role is governed by biomass, productivity and reproductive stress. Indications from the literature are that macrophytes are relatively more important in tropical climates due to higher growth rates.
- Most constructed wetlands use monocultures of *Typha* and *Phragmites*. Phosphorus cycling and partitioning characteristics vary tremendously between species.
- None of the single stage wetlands appears to effectively remove phosphorus on a sustainable basis, although performance is improved if substrates with high phosphorus sorption capacity are used.
- Multiple stage wetlands currently offer the best prospect for consistent reliable phosphorus removal in Queensland conditions. Such systems should comprise settling ponds, reed beds and cyclically flooded pastures and/or submerged macrophyte ponds.

A general conclusion of the review was that while natural wetland processes can result in long-term removal of phosphorus, the removal mechanisms are strongly influenced by local factors, and therefore it is unlikely that wetlands are capable of sustainable phosphorus removal in all situations.

A review of the performance of wetland and riparian buffers as sediment and nutrient sinks listed the following main findings (Hunter and Hairsine 2001):

- Performance in terms of nutrient removal is dependent on factors such as the composition and flow rate of the incoming water and interactions with riparian and wetland environments.
- The conditions under which wetlands are more likely to act as sediment and nutrient sinks are not clear.

- Not all riparian zones and wetlands function as sinks; they can also be sources. For example erosion, anoxic conditions which release phosphorus, and elevated nitrogen levels by nitrogen fixing riparian vegetation all may cause the release of nutrients.
- A lack of research exists that clearly demonstrates significant and sustained enhancement of downstream water quality following riparian and wetland restoration.
- Although natural wetlands can act as both sinks and sources of nutrients even where there is no net retention of nutrients, the water discharged tends to be higher in organic forms of nutrients and lower in inorganic forms than inflowing water.
- Exploitation of natural wetlands for protection of downstream water quality requires care to avoid over-stressing their inherent resilience, which puts other wetland functions and values at risk.
- Performance in terms of nutrient removal of constructed wetlands can be highly variable. Design is critical to performance. Location and landscape setting are also important considerations. Constructed wetlands need regular monitoring linked to an adaptive management program.

A number of the findings from Hunter and Hairsine (2001) were also reflected in the workshops undertaken as part of this project (see Appendix).

These two reviews conclude that wetland performance in removing nutrients from water is variable and dependent on several factors. Detailed research focusing on aspects of nutrient removal by wetlands is lacking, and this is especially the case when non-point source pollutants are considered in an Australian or Queensland context.

Research projects previously undertaken in Queensland have looked at aspects of nutrient control, including the creation of wetlands to control water quality (Hunter and Lukacs 2000), the use of riparian buffers (McKergow *et al*. 2004b) and other methods to improve the nutrient removal capacity of drainage systems (Willett, Erler and Knibb 2002). In addition to these studies, other projects have created on-farm wetlands for control of nutrients and sediment, as well as providing habitat for wildlife (Lukacs and Pearson 1995; Digman 1998). Information on the benefits and design of these wetlands has been difficult to find; however, two Sugar Industry Infrastructure Package (SIIP) projects on the Tully-Murray and the Herbert catchments are in the process of being finalised, which may have more information.

Investigation of the potential for using constructed wetlands to improve the quality of irrigation drainage in the Burdekin River Irrigation Area (Hunter and Lukacs (2000) found:

- wetlands removed 60–70 percent of suspended solid load (as compared to a control bay without vegetation)
- a net increase in total phosphorus loads and concentration at the outlet
- changes in nitrogen loads were relatively small and variable and inlet concentrations were not significantly different to outlets
- vegetated wetlands were effective in removing around 40 percent of atrazine and diuron and 52 percent of bromide tracers all added at the inlets.

Information from other climatic zones was reviewed as part of the study and also reported that the ability of wetlands to reduce nutrient loads was variable and that constructed wetlands can act as a nutrient source and sink (Hunter and Lukacs 2000).

It has been demonstrated that managed riparian buffers are useful for nutrient transfer from terrestrial environs to watercourses. However, riparian buffers also have limitations and are not a replacement for land managers working to limit sediment and nutrient delivery from hillslopes (McKergow *et al*. 2004b). Investigations into riparian buffers in north Queensland concluded:

- On planar slopes, even with high soil loss, grass buffer strips were able to trap more than 80 percent of the incoming bedload.
- Total nitrogen, total phosphorus and suspended sediment loads were reduced between 25 percent and 65 percent by the planar slope grass buffer and within the first 15 m of the moderately convergent grass buffer.
- Loads leaving the moderately convergent buffer were often higher than those delivered from the crop, due to seepage after prolonged or high

frequency rainfall. Under these conditions the buffer's main function is to prevent erosion rather than trap sediment and nutrients.

- Results from a highly convergent 5 ha hillslope suggest that for buffers to be more effective in such topography, they should also be placed at the end of the crop rows, where contributing areas are smaller.
- A remnant rainforest buffer, receiving run-off from a planar slope, acted as a temporary store of sediment and nutrients that were reworked during subsequent events (McKergow *et al*. 2004b).

A joint project between the former Cooperative Research Centre for Catchment Hydrology and the Coastal CRC titled 'Modelling and managing nitrogen in riparian zones to improve water quality' investigated riparian zones as important in buffering stream nitrogen levels by removing nitrate (a form of dissolved nitrogen) from shallow groundwater flows through denitrification.

Riparian areas with root zones that intercept shallow watertables contaminated with nitrate have great potential for denitrification and can therefore be important for improving stream water quality. A model called the 'Riparian Nitrogen Model (RNM)' has been developed as a tool for managers as it identifies these riparian zones that have high potential for denitrification (Rassam, Pagendam and Hunter 2005).

A pilot study investigating the influence of native fish on water quality and weed growth in irrigation channels found that:

- Naturally occurring aquatic weeds (mostly filamentous algae) removed more than 50 percent of nitrogen and phosphorus from incoming source water.
- Without fish in the experimental tanks, aquatic weed growth was prolific through the water column and on the water surface, which would lead to self-shading death and re-release of nutrients.
- With fish in the experimental tanks, growth of weed was restricted to artificial substrates in the tanks and there was no surface or bottom fouling.
- Reduced weed growth in the experimental tanks with fish precipitated a phytoplankton bloom and increased overall suspended solids concentrations in the water column towards the end of the trial. Therefore, to further improve nutrient recovery a greater range of species for inclusion into the system may need to be considered (Willett, Erler and Knibb 2002).

Additional to the various conclusions in different studies regarding nutrient removal by wetlands there is a broad scepticism in literature (Bramley and Johnson 1995; Roth *et al*. 2001), and communicated in personal discussions held as part of this review, on the ability of small wetlands to achieve useful water quality outcomes especially those situated in monsoonal regions. Furthermore, a lack of monitoring by wetland creation projects has meant little evidence of their effectiveness or whether intended goals have been achieved (Roth *et al*. 2001).

Spatial and temporal considerations

In many countries there is recognition of the importance of landscape planning issues associated with using wetlands for water quality improvement. This issue has been analysed using field studies and modelling techniques.

In the United States and in Europe the landscape issue of How many wetlands? has been investigated. This question is fundamental for landscape restoration activities and for considering the use of wetlands as water quality improvement structures. Estimates from some countries are listed below; however, estimates do not exist for any catchments in Australia:

- Around 15 percent of a watershed would need to be restored to accomplish the water quality functions over the landscape that small wetlands in a temperate region were providing at a local scale (extrapolated from results of 10 ha of experimental wetlands in the United States) (Hey and Philippi 1995).
- An estimated 3.4 percent to 8.8 percent of the Mississippi River basin would have to be converted to wetland and riparian forest to reduce nitrogen loads to the Gulf of Mexico by 2040 percent (Mitsch and Gosselink 2000b).

3. Functions attributed to wetlands

- Modelled scenarios based on 40 potential wetlands that make up 0.4 percent of a catchment in southern Sweden indicated that these wetlands would reduce nitrogen transport to the coast by 6 percent (Arheimer and Wittgren 2002).
- Modelling a suite of scenarios designed to reduce nitrogen loading to the sea from a catchment in southern Sweden, Arheimer, Torstensson and Wittgren (2004) found that changes in agricultural practices could reduce the nitrogen load to the sea by up to 30 percent, while the modelled wetland construction reduced the original load by approximately 5 percent. The cost for agricultural practices to reduce load by 86 t per year was 1.0 million SEK (Swedish krona), while constructed wetlands reduced load 14 t per year at cost of 1.7 million SEK.

Based on these examples as well as studies from China, Verhoeven *et al*. (2006) argue that as a general rule wetlands contribute significantly (about 30 percent removal of nitrogen and phosphorus) to water-quality improvement at the catchment level if they account for at least 27 percent of the catchment area. These figures may be applicable to Australian catchment; however, further study is required to validate if this is the case. In particular, the percentage of the catchment may need to be greater in tropical areas, whereas another study indicates that wetlands must be greater in area to accommodate higher flow volumes (Faithful 1997). Estimates such as these illustrate that wetlands must cover relatively large areas and/or be combined with other measures to achieve a substantial reduction of nitrogen fluxes to downstream or coastal waters.

Landscape placement of wetlands has been the focus of some study in Australia, for example Raisin, Mitchell and Croome (1997). In the US it is thought that wetlands lower in the catchment are more important for water quality from a catchment export perspective, for example Detenbeck, Johnston and Niemi (1993). This view is not universal, however, as indications of no relationship between phosphorus retention and landscape position have been observed and conclusions have been made that possibly only in small coastal catchments are the longitudinal differences found and that most wetlands may perform total phosphorus retention (Greiner and Hershner 1998).

Temporal variation is a known factor in a wetland's ability to remove nutrients (Mitsch and Gosselink 2000b; Fisher and Acreman 2004). Studies of the sedimentology of two floodplain wetland complexes in New South Wales illustrate that in the long term, wetlands can be a temporary store of sediments and pollutants (such as trace metals), as there is exchange of materials between the river channel and bordering environments over a variety of time scales (Thoms 1998). The temporal storage ability of wetlands may be important as it changes the rate, concentration and timing of nutrient delivery to downstream areas. For example if a wetland stores nutrients throughout the dry season that are then released in high flows, this may potentially increase the impact on some coastal ecosystems, for example the inner reefs of the Great Barrier Reef. However, the same wetlands may be of use for medium and small run-off events. This can be a useful objective as these events have been associated with a decline in water quality and fish kills in the Herbert floodplain (Roth *et al*. 2001). While this is only speculation, the example highlights the need for clear goals and an understanding of longer-term processes when considering the use of wetlands.

The CSIRO is currently undertaking research in Townsville on the importance of nutrient filtering by wetlands. The study, titled *The filter function of wetlands in Tully-Murray Catchment* may help to clarify this issue. However, it should be highlighted that if constructed wetlands are intended to be designed and used for nutrient retention then long-term monitoring of selected wetlands is needed to account for variations across climatic zones.

Wetland design

Design criteria to maximise nutrient removal

The design of wetlands constructed to improve water quality is the most important determinant in the success of a treatment wetland. However, a number of technical and institutional considerations have to be considered before any treatment wetland is designed and built (Mitsch and Gosselink 2000b). The following considerations may be relevant when constructing wetlands for water quality improvement in Australia:

- The values of wetlands such as wildlife habitat should be considered in any treatment in wetland development.

- Acceptable pollutant and hydrologic loading must be determined for the use of wetlands in wastewater management. This will determine the size of the wetland. Overloading a constructed wetland is worse than not building it at all.
- Existing characteristics of local wetlands, such as vegetation, geomorphology, hydrology and water quality, should be well understood so that constructed wetlands can be as similar to natural wetlands as possible.
- Care should be taken in wetland design to address mosquito control and protection of groundwater resources.
- Potential conflict over the protection and use of wetlands can arise among different agencies and stakeholders.
- Constructed wetlands can serve multiple purposes (e.g. water quality, wildlife, flood control), although the construction of treatment wetlands cannot mitigate for the loss of natural wetlands due to their high pollutant loadings (especially the case with wastewater wetlands). Wetland restoration is preferable.

A review of wetlands for the sugar industry concluded that although the concept of constructing artificial lagoons was becoming more popular, it was doubtful that the design criteria necessary to achieve the objectives of these lagoons were understood (Bjornsson *et al*. 2002). While it concluded that science and logic were incorporated into designs, they were yet to be rigorously tested. The review also listed several research opportunities existing within this area. These were:

- development of a best practice model or design criteria for these features
- review and evaluate whether current recommendations actually fulfil the role they set out to achieve (e.g. Do constructed wetlands adequately trap silt and nutrients? Are they being located in the optimal location?) (Bjornsson *et al*. 2002).

While some of these questions may be in part addressed by the research conducted by the State Implementation Plan (SIP) lagoons project on the Tully-Murray and Herbert catchments and the project by the CSIRO in the Wet Tropics, many questions around the best design of wetlands to improve water quality still remain unanswered. A lack of monitoring of construction projects for water quality objectives as well as biological ones makes evaluation and adaptation of design criteria difficult.

Review of the use of wetlands in the sugar industry identified the types of lagoons or detention basins that might be used by landholders (Bjornsson *et al*. 2002). These structures include:

- detention basins to capture and moderate agricultural land run-off rates
- retention basins to slow run-off velocity and allow the settling of nutrient-laden silt
- constructed wetlands for wildlife habitat.

In workshops and interviews conducted as part of this review, design criteria were discussed and while many felt that appropriate design criteria and guidelines were lacking, those more experienced in wetland management did have practical advice. Margaret Greenway from Griffith University commented that wetlands should be shallow (approximately 20 cm), with other sections deeper (>1 m) to allow for flood control. Ideally, wetlands should contain variable depths to accommodate a range of processes that can occur. Also important is the presence of plants which had to be planted in the appropriate depth zone to ensure their health and viability (Mitsch and Gosselink 2000b).

Wong *et al*. (1998), in a study of constructed wetlands for management of urban stormwater, defined wetlands as shallow (<2 m) and having fluctuating water levels and a regular to very erratic drying cycle. While wetlands may have patches of deeper water, their characteristic feature is the presence of emergent macrophytes and epiphytes that are often associated with macrophytes.

In a longitudinal study that designed and tested constructed wetlands for water quality control, Higgins *et al*. (1993) used a system that consisted of:

- a sedimentation basin
- a grass filter strip
- a constructed wetland
- a retention pond.

Results of two years' monitoring in these systems illustrated that the wetland system functioned well although seasonal variations occurred (Higgins *et al*. 1993). Of particular interest is that the sedimentation basin provided half the total sediment removal. The sedimentation basin is also important in constructed wetlands as without it the high sediment loads might overwhelm many wetlands and this could affect their capacity to treat run-off (Higgins *et al*. 1993). They stressed that constructed wetlands are not a replacement for conservation practices used when cropping, but rather a supplement that may further reduce nutrients entering downstream environments.

Constructed stormwater wetlands have similarities to wetlands collecting diffuse run-off from agricultural areas, as both need to be designed to cope with erratic run-off patterns. Wong *et al*. (1998) recommended that constructed stormwater wetlands should include the following design features:

- a minimum of two cells – an open water inlet zone and a macrophyte zone, with a high flow bypass system for the macrophyte zone.
- a macrophyte zone should be allowed to fill and drain regularly in response to run-off.
- an outlet should be located to create a permanent pool equal to 10–15 percent of the total storage volume.
- a length to width ratio exceeding 3 to 1, unless features such as islands are incorporated to promote uniform flow patterns.
- vegetation and basin depth should be banded perpendicular to flow.
- an outlet structure should provide for manual control of water level (Wong *et al*. 1998).

While construction of stormwater wetlands tends to be more complex than one which is designed for a property, it will have similar design elements to the agricultural design described by Higgins *et al*. (1993). This design is based around the objective of providing the retention of water to facilitate the settling of coarse and medium particles, while also providing a vegetated zone for the removal of fine particles and the establishment of biofilms for maximum nutrient transformation (Wong *et al*. 1998).

The size of the wetland area is another important factor in design that may impact on the ability of wetlands to filter water quality in agricultural areas. This is especially important in areas that have rainfall that is not evenly distributed throughout the year (Wong *et al*. 1998). For example even though Auckland has slightly higher rainfall than Brisbane, a stormwater wetland in Auckland would need to be only 40 percent of the area than one in Brisbane, because in Auckland rain, and therefore run-off, is evenly distributed throughout the year (Wong *et al*. 1998). Queensland generally has highly seasonal or episodic rainfall patterns; in particular, wetlands in tropical regions need to be able to accommodate higher flow rates, and therefore wetlands may not be as effective in climates where seasonal rainfall generates high volumes of run-off over short periods of time (Faithful 1997).

Designing wetlands for multiple objectives

Although the literature shows that while there are processes in wetlands that are effective in reducing nutrients, these processes can be affected in an agricultural setting by:

- climate and seasonality of rainfall
- velocity and depth of water passing through the wetlands
- the pollutant loading
- geochemical conditions within the wetlands
- substrate
- biological activity
- the presence of macrophytes
- wetland size
- temperature
- a number of other conditions (Higgins *et al*. 1993; Mitsch and Gosselink 2000b; Greenway 2004).

While this may in some cases make the construction of wetlands for non-point source pollutants seem ineffectual, other functions may also be met from constructed wetlands. For example, farm dams have been shown to support a similar richness of frog species to natural ponds, although species composition was different (Hazell *et al*. 2004). Many inland water storages and dams have become an important habitat for waterbirds and fish (Burrows 2004). However, a question is whether these other functions are compatible with water quality improvement. In addition, while there is a general concern about nutrients, it is important to take into account other factors relating to the health of the overall systems; otherwise, there is the risk that they may be improving water quality in some aspects and degrading it in others. For example, aquatic weeds will be very effective in removing nutrients from water; however, they may lead to a host of other water quality and biodiversity issues (Perna and Burrows 2005). The invasion of ponded pasture species into natural wetlands has illustrated that weeds overrun systems quickly and can eventually lead to a reduction in dissolved oxygen and in the diversity of plant species of wetlands (Douglas *et al*. 2001). Therefore, their use could not be recommended in constructed wetlands, even though they might be efficient at removing nutrients.

Research on restoration ecology indicates that wetlands used for water quality will be eutrophic and these wetlands tend not to have high species diversity (Zedler 2000). A study on wetland design for multiple objectives has been conducted in Sweden (Hansson *et al*. 2005). The aims of this Swedish study were to increase the knowledge on how to improve the design of a wetland for nutrient retention and biodiversity. The conclusions were that a combination of shallow depth, large surface area and high shoreline complexity would provide for the high retention levels of nitrogen, and a high biodiversity of birds, benthic invertebrates and macrophytes, while small deep wetlands are likely to be more efficient in phosphorus retention but less valuable in terms of biodiversity (Hansson *et al*. 2005). It was also concluded that it is possible in some cases to design wetlands for both functions; however, not all functions may be achieved.

There is some debate in north Queensland (see Appendix 1) over the best types of wetlands to construct, so there is a need to establish design criteria for specific objectives. One theory is that shallow weedy wetlands are better for water quality improvement whereas deeper waterholes are better fish habitat. To address both objectives the creation or restoration of a mosaic of wetlands within the landscape is a beneficial alternative to multiple objectives for single wetlands. Others claim this theory needs to be quantified; otherwise, shallow wetlands are potentially building up sediment, which will be scoured and transported downstream in the wet season. They also argue that if wetlands are deep enough they can possibly function as a downstream water quality improver, a place for flood detention, a zone for groundwater recharge, and a fish habitat area, and the shallow areas can act as refuges.

Many of the wetlands constructed in Queensland have been constructed to achieve multiple functions, often have design features that incorporate structures for fish use, and are thought to improve downstream water quality. Some of the researchers and departmental staff who participated in workshops or were interviewed as part of this project felt that it was possible to incorporate more than one function into wetlands, while others were unconvinced (Appendix 1). Studies such as Willett, Erler and Knibb (2002) illustrate that the presence of biota can improve a systems ability to remove nutrients, through grazing of macrophytes and algae. In some cases biota can also impair the function of wastewater treatment wetlands. Anecdotal reports from Queensland suggest that turbidity and suspended solid level in wastewater treatment wetlands can be elevated by the action of ducks and geese (Greenway and Simpson 1996).

While wetlands may be constructed for multiple uses, a hierarchy of functions needs to be taken into account when designing a wetland. The design will depend on an evaluation of the relative importance of these functions. In an agricultural setting where a large percentage of wetlands have been drained and filled, the community and other stakeholders may feel that water quality improvement and providing habitat for aquatic species is of similar value; however, in a situation such as that reported in Greenway and Simpson (1996), the polishing of wastewater is the most important function of sewage treatment wetlands and other values can be incorporated if they are not at the expense of the primary function.

Management of constructed wetlands

Wetlands constructed in agricultural landscapes need management to remove sediment and control weeds (Wetzel 2001). In nearly all discussions with researchers and managers in Queensland weeds were considered a critical issue for wetlands. Wetlands are depositional environments and with time they fill up with sediment and may need cleaning out (Higgins *et al*. 1993).

3. Functions attributed to wetlands

Harvesting of macrophytes in wetlands has been discussed as a way to remove the nutrients from wastewater treatment wetlands (Mitsch and Gosselink 2000b). Harvesting of plants may lead to:

- removal of nutrients from the system, if harvesting occurs a number of times over the growing season
- increased net growth
- control of mosquitoes
- reduced congestion in the water
- a change in the residence time of the basin
- greater plant diversity
- weed control (Mitsch and Gosselink 2000b; Perna and Burrows 2005).

Boulton and Greenway (1999b) proposed the use of *Melaleuca* trees in artificial wetlands, which could be used for water quality improvement but also harvested for tea tree oil production.

Potential impacts on wetland ecosystems with nutrient enrichment

Natural wetlands are highly threatened aquatic ecosystems in Australia and throughout the world. Wetland losses in some catchments of Queensland have been estimated at up to 80 percent (Johnson, Murray and Ebert 1999). Overall it is estimated that 50 percent of Australia's wetlands have been significantly diminished through degradation or loss (Environment Australia 1998). Given the threatened status and importance of wetlands to the landscape, the effects of nutrient enrichment should be a topic of further research for most wetland types in Queensland. Potentially, constructed and natural wetlands can be used for water quality improvement, although the pollutant loads in natural wetlands need to be sized to meet ecological goals (Keenan and Lowe 2001).

It is a common misconception that all wetlands are highly productive nutrient-rich systems (Mitsch and Gosselink 2000b). The effects of nutrient addition on wetlands will depend largely on the wetland type, with some being sensitive to changes in nutrient status and others being capable of attenuating pollutants (Reddy and D'Angelo 1997). While some wetlands are naturally high nutrient systems (eutrophic), for example many floodplain wetlands (Hillman 1998), others will be naturally low in nutrients (oligotrophic), such as dune lakes and wet heath (Arthington *et al*. 1986; Hadwen, Arthington and Mosisch 2003). Other types of wetlands are also thought to be nutrient-limited. For example saltmarshes are thought to be nitrogen-limited and increases in available nitrogen are thought to change patterns of productivity and species production (Adam 2002). For example, the spread of reeds and sedges into saltmarshes of urbanised catchments is thought to be associated with lowering of salinity and increased nutrients from stormwater (Zedler, Paling and McComb 1990).

Many examples appear in the literature that document changes in wetland ecosystems that occur as a result of eutrophication. Examples of the effects of excess nutrients on wetlands are:

- changes to the patterns of productivity and species distribution in wetlands (Hadwen and Bunn 2004)
- algal blooms(Boon and Bailey 1998)
- weed encroachment (Perna and Burrows 2005)
- vegetation dieback (Hillier 1997)
- a reduction in water quality (Perna and Burrows 2005)
- a change in trophic status and resulting long-term changes in species composition (Keenan and Lowe 2001)
- changes in meta-stable states (see Pollutants, page 71)
- loss of nutrient-absorbing capacity (Bailey, Boon and Morris 2002).

An assessment of the sewage effluent in coastal wetlands of Tin Can Bay found that continued discharge of effluent into adjacent and downstream natural coastal wetlands has resulted in vegetation change (Hillier 1997). Within the effluent plume, the *Melaleuca* forest had areas of dieback and local weeds, and freshwater macrophytes had invaded the understorey. In the intertidal zone, which is normally largely unvegetated, apart from halophytic vegetation, freshwater macrophytes were now present. The *Melaleuca* community was not able to absorb all nutrients contained in the sewage, and it was concluded that this may be a result of dieback and poor landscape management or that the carrying capacity had been reached for this community (Hillier 1997).

In a study that examined two *Melaleuca* wetlands of similar area, Daniel and Greenway (1995) found that nutrient enrichment in the catchment coupled with guano input eutrophication had occurred in one wetland. The swamp was acting as a source of nutrients and suspended solids in the period of study.

While these are only a few examples, they illustrate that wetlands can be sensitive to nutrient enrichment. Despite little information from Australia or other tropical and subtropical areas, it appears that wetlands in the landscape context do have a role in trapping and cycling nutrients. The processes within natural wetlands that are responsible seem to function well within a range of concentrations that are not much elevated over the natural state (Bailey, Boon and Morris 2002). Eutrophication is as much of a threat to wetlands as it is for other aquatic ecosystems when nutrient loads are elevated (Boulton and Brock 1999). Although this will vary, with oligotrophic wetland types potentially being at a greater risk to changes in trophic status, others may be more resilient (Verhoeven *et al*. 2006). However, it appears that this is only up to a point and if the pollutant loading is relatively low (Mitsch and Gosselink 2000a; Mitsch and Gosselink 2000b; Bailey, Boon and Morris 2002). If a wetland's threshold to a pollutant is exceeded, it may no longer function as a sink (Wetzel 2001) and the resulting degradation may lead to release of nutrients out of the system (Daniel and Greenway 1995). Conservation of the ecological health of natural wetlands will need to look at ways to prevent excess nutrients entering these systems.

Verhoeven *et al*. (2006) discusses the concept of a critical load of a nutrient, which is defined as the loading rate below which the system remains all but unchanged, but beyond which it exhibits sudden dramatic changes, and this can include major shifts in structure and function of the wetland, including an increase in nutrient exported from the wetland. The critical load of a nutrient will depend on the wetland type, in particular the natural trophic status of a wetland (i.e. if it is a naturally high or low nutrient system). The critical load of nutrients, especially nitrogen and phosphorus, for different wetland types in Queensland requires further investigation, in particular in settings where the wetland receives high inputs of agricultural, urban or industrial run-off.

Conclusions

The natural processes that occur in natural and constructed wetlands can result in the retention or removal of significant amounts of nutrients; however, not enough studies have looked at the value of using constructed wetlands for water quality control in agricultural areas, and those that have, have found variable results. A study currently being undertaken by the CSIRO on the filter functions of tropical wetlands may further refine our expectations around the use of wetlands for water quality improvement in agricultural areas. It is likely that design criteria will be important, but the general lack of any monitoring of these systems once they have been created makes these criteria hard to refine. The use of constructed wetlands may also have value for other functions such as for biodiversity in areas where a large percentage of wetlands have been filled or drained. The findings of a current study into the creation of wetlands in the Tully-Murray and Herbert catchments as part of the SIIP package may further add to assessments of the value of created wetlands for biodiversity. More focus should be given to the adoption of improved farming practices which may include, along with measures to reduce nutrients and sediments leaving the paddock, the creation of sediment traps and artificial wetlands. This strategy will help protect coastal waters and freshwater aquatic ecosystems.

Recommendations

- There is a risk involved in using natural wetlands to ameliorate water quality, particularly in the light of widespread wetland loss and degradation in Queensland. The critical load of nutrients for different wetland types in Queensland requires further investigation, in particular in settings where a wetland receives high inputs of agricultural, urban or industrial run-off. If it is possible, guidelines should be developed.
- Not enough information exists at this time to make a recommendation about the use of constructed wetlands for water quality improvement in agricultural areas, as there has not been enough study, especially in tropical and subtropical areas. To this end, any relevant findings of the CSIRO project in the Tully-Murray should be incorporated into design guidelines and recommendations for the future use of constructed wetlands.

3. Functions attributed to wetlands

- A better understanding of the ability of wetlands to retain nutrients and the types of anthropogenic threats that impact on this ability is needed before causal relationships between wetlands, high-risk agricultural activities, and Reef water quality can be determined.
- Guidelines for the construction and restoration of artificial wetlands in an agricultural setting should be developed. These design guidelines should also incorporate, where possible, design features that would also enhance the habitat value of these wetlands. Any relevant findings of the SIIP wetlands project in the Tully-Murray and Herbert catchments should be incorporated into design guidelines and recommendations for the future use of constructed wetlands.
- It appears that water quality improvement has not been monitored in many wetlands. If wetlands are to be used for the purposes of water quality improvement then it would be beneficial to monitor the water entering and leaving these systems.
- No attempt appears to have been made into looking at the area or number, diversity, and landscape position of wetlands in individual catchments that would need to be retained or created to maximise the full suite of ecosystem functions that wetlands provide. If wetlands are to be properly valued and restored this type of information is very important and further study is needed.

Water regulation and shoreline protection

While the role of wetlands of all types in regulating water and in stabilising shorelines is widely acknowledged as an important function, not a great deal of study has been undertaken on these roles.

Regulating water

One of the important landscape functions of wetlands is the regulation of water. During flood and high-flow events, wetlands that fill with water either from local rainfall and run-off, overbank flooding or as a result of connections to the river via channels that occur only in large flows will store this water, which reduces the volume of water continuing downstream and transfers stored water back to the river system via base flow in non-flood conditions. This water also provides valuable wetland habitat. An example of the amount of floodwater that can potentially be stored in natural floodplain and wetland systems is illustrated in the Cooper Creek catchment, where in the area between Currareva and Nappa Merrie transmission loses can be up to 75 percent (Knighton and Nanson 1994a).

Wetlands are very important for flood control. Studies from the United States have found that in catchments with wetlands the flood peak was 50 percent of that of catchments with no wetlands (Mitsch and Gosselink 2000b). Wetlands became more important in reducing flooding with:

- an increase in the area of the wetland
- the distance of the wetland downstream
- the size of the flood
- the closeness of a wetland to another upstream wetland
- the lack of upstream storages such as dams (Ogawa and Male 1986).

Quantification of the value of wetlands in the role of flood control becomes important if a restoration of wetlands is to have a positive impact on downstream flooding. Much of the discussion of the importance of scale (see Spatial and temporal considerations, page 43) is also important when discussing the capacity of wetlands for flood retention. Small-scale restoration and creation projects may improve the situation at a local or farm scale, while in order to use wetlands to improve flooding at a catchment level the area and placement of wetlands in the landscape will need to be considered. It is estimated that the restoration of approximately 5.3 million ha in the upper Mississippi and Missouri Basins would have provided enough floodwater storage (about 1 m deep) to accommodate the excess river flow from the large 1993 flood in mid-western United States (Hey and Philippi 1995). Restoring an even greater amount of wetlands to 7 percent of the watershed would be enough to deal with an extreme event flood on a large scale. Estimations were that before European settlement 9-11 percent of this basin was wetland (Hey and Philippi 1995).

A recent study investigated a method to evaluate wetland flow functions using stream flow records and flow duration curves to evaluate how flows of different magnitude are affected by wetlands (Smakhtin and Batchelor 2005). They found that a reliable reference condition was very important in order to make quantitative conclusions about wetland functions; however, defining this reference condition may represent a problem in itself. They recommended a greater use of flow duration curves to better understand the hydrological functions of wetlands. Methods such as the one used by Smakhtin and Batchelor (2005) provide a mechanism to better understand the role of wetlands in regulating water.

From the review of literature it appears that little study of the water regulation functions of wetlands has been undertaken in Queensland. One exception was as part of a study conducted by Daniel (2002), which looked at water storage capacity as part of a larger study of *Melaleuca* wetlands in south-east Queensland. The study found that the Carbrook and Black Swamp wetlands were acting as water storage areas as they were a flood detention basins, but also because of the drawdown of water in low-flow periods. As expected the smaller wetland areas had a more limited capacity to store water, which highlights the effect that fragmentation and reduction of wetland area will have on this function (Greenway and Daniel 1997).

In a review of wetlands in the sugar industry, Bjornsson *et al*. (2002) cited an opportunity for research into:

- the role of constructed wetlands as flood regulation structures and, if they are sufficient, water detention/retention basins to minimise the risk of additional flood damage downstream
- the effect that drainage systems and artificial lagoons are having on the moisture levels of cultivated areas.

The role of wetlands in shoreline stabilisation

Coastal wetlands are thought to be very important in stabilising coastlines and acting as buffers from storms (Mitsch and Gosselink 2000b). Riparian areas are also often cited as being important in preventing stream bank erosion and trapping sediments originating from upslope (e.g. Werren 2003; McKergow *et al*. 2004a). The role of vegetation in stabilising soils and preventing erosion is well documented and this function is applicable to vegetated wetlands (McKergow *et al*. 2004a).

The wetland types that tend to be cited as shoreline stabilisers are mangroves, as they reduce the velocity of water and trap sediments with the roots, pneumatophores and trunks (Duke 1997). Because of this ability to trap sediment, river-borne nutrients and other pollutants are also likely to be trapped and recycled within mangroves (Wolanski, Spagnol and Lim 1997). Given the landscape position of mangroves, this may explain the discussion of them in terms of this value in particular, although coastal wetlands in general often are ascribed this value (Lugo and Brinson 1978; Duke 1997).

The role of wetlands in stabilising shorelines is a very important one, and coastal wetlands in particular are afforded a high level of protection under legislation, partly to ensure this role is maintained (EPA 2006f). In terms of further research needs, this area is a low priority given the widespread agreement on the ability of vegetation to stabilise shorelines and riverine environments and the lack of information on many other wetland functions.

Factors that reduce the ability of wetlands to regulate water and stabilise shorelines

Increasing fragmentation and sedimentation will affect wetlands' capacity to hold floodwater (Greenway and Daniel 1997). Barriers and other modifications to the hydrology of a catchment will also impact on this value, causing isolation of wetlands from channel or overbank flow (Mitsch and Gosselink 2000b). Excessive sedimentation within wetlands will result in a reduction of water-holding capacity (Higgins *et al*. 1993). Loss or degradation of vegetation in wetlands and the extent of wetlands along the coastal or riparian strip will impact on shoreline stabilisation (Mitsch and Gosselink 2000b).

Recommendations

The following areas need further research to better understand the value of natural and constructed wetlands:

- the importance of wetlands in regulating water in catchments in terms of flood control and in maintaining base flow throughout dry seasons
- the number and size of wetlands needed to provide sufficient water detention/retention to minimise the risk of flood damage downstream
- the effect that drainage systems and artificial lagoons are having on the moisture levels of cultivated areas (Bjornsson *et al*. 2002).

Groundwater interactions

Interaction of groundwater and surface water within wetlands is a significant knowledge gap for most wetland types (Hatton and Evans 1998). In some types such as dune lakes, spring wetlands and some arid zone waterholes, interactions are understood to some degree. A review of the literature on groundwater and discussions with experts in the field may yield further information; however, given the already broad scope of this report and the limited timeframe it was not possible to review the literature on groundwater where it was not directly related to wetlands. A special edition of the Australian Journal of Botany (2006, Volume 54: Number 2) on groundwater dependent ecosystems came after this study was completed, and due to the timeframe it has not been possible to review these articles. However, the edition contains a number of papers relating to the topics in this section.

Groundwater discharge

Groundwater that discharges into wetlands can be from regional or local sources. Base flow from the surrounding soils can be important in maintaining the persistence of water bodies in dry times. For example this issue is discussed in terms of waterholes in the Burdekin catchment (Burrows 2004) in the section on the Dry Tropics (see page 13).

Groundwater dependent ecosystems have been defined as:

- terrestrial ecosystems that rely seasonally or episodically on groundwater
- river base-flow systems, including aquatic, hyporheic and riparian systems that depend on groundwater, especially in dry periods
- aquifer and cave ecosystems
- wetlands depending on groundwater influx for all or part of the time
- estuarine and near-shore marine ecosystems that rely on groundwater recharge (Evans and Clifton 2001).

The following discussion will focus on wetlands (listed as the fourth point above), although some discussion of disconnected riverine systems and estuarine systems are included. A list of examples of wetlands in Australia that are thought to be groundwater dependent has been developed (Hatton and Evans 1998; Sinclair Knight Merz Pty Ltd 2001). The ones that are relevant to this review are:

- mesophyll palm vine forests
- paperbark swamp forests and woodlands
- swamp sclerophyll forests and woodlands
- swamp scrubs and heaths
- swamp shrublands
- sedgelands
- swamp grasslands
- swamp herblands
- mound spring ecosystems (these are termed ‘spring wetlands’ in other parts of this review)
- coastal lakes
- mangroves
- saltmarshes.

While this list was derived as part of an Australia-wide study, which acknowledged that there was ‘virtually no literature specific to the dependence of Australian Ecosystems on groundwater’ (Hatton and Evans 1998), it illustrates that a large number of wetlands may be, at least seasonally, dependent on groundwater. For most of the listed wetland types the review found no literature specific to groundwater interactions.

Wetland dependence on groundwater is documented for spring wetlands within the Great Artesian Basin (GAB) and from other aquifers outside of the GAB and for some dune lakes along the Queensland coast. Although the source of the water is known the hydrogeology is not well documented. For example although a significant body of work has been collated on spring wetlands in Queensland over the last few years, knowledge gaps still exist and further research is needed into the hydrogeology as it relates to springs (Fensham and Fairfax 2005). To accurately predict the impacts of groundwater extraction and pressure recovery on springs, information is needed on the aquifer that individual springs discharge from, and the pressure surface of the aquifer in relation to precise spring elevations (Fensham and Fairfax 2005). A discussion of spring wetlands can be found in the section on Spring wetlands (see page 32).

A project is under way to examine the groundwater discharge to wetlands of the lower Burdekin, using water samples from groundwater and wetlands and analysed for chemical similarity (Loy 2005).

Groundwater, from regional or local sources, is likely to be important for many ecosystems; however, it is not always as important as assumed, as a study of some of the waterholes in the Cooper Creek catchment revealed. The Cooper Creek system has been classified as a groundwater dependent ecosystem (Hatton and Evans 1998). However, a number of studies from the upper Cooper Creek catchment have all found that the groundwater input into the waterholes studied is not significant (Knighton and Nanson 1994a; Knighton and Nanson 1994b; Gibling, Nanson and Maroulis 1998; Hamilton *et al*. 2005). It is important to note, however, that the area these studies focused on was just outside the area defined by Hatton and Evans (1998) and if waterholes exist that rely on groundwater inputs in Cooper Creek they would be very important as refugia (Hamilton *et al*. 2005).

While the ecology of a wetland system may be dependent on groundwater, other biophysical processes may also be dependent on groundwater sources where it exists. This is the case with many coastal wetlands where waterlogging by groundwater discharge provides an environmental service, by preventing the oxidation of pyrite and the development of acid sulfate soils (ASS) (e.g. Anorov 2004).

Wetlands may also have a role in improving groundwater quality. Research currently being undertaken through the Coastal CRC titled 'Modelling and managing nitrogen in riparian zones to improve water quality' has shown that riparian zones can be important in removing nitrate from shallow groundwater flows through the process of denitrification in the root zone. Riparian areas with root zones that intercept shallow watertables contaminated with nitrate have great potential for denitrification and can therefore be important for improving stream water quality (Rassam, Pagendam and Hunter 2005).

Groundwater recharge

Wetlands are generally thought to store water in times of flood and to be important in dry times as they may return water to the fluvial system via base flow (Lukacs 1998). Changes in base flow have been cited as a potential threat to the persistence of in-stream waterholes in the dry tropics (Burrows 2004). The role of groundwater dynamics in wetlands needs further research to improve their management. An example given by a manager in the northern region of two land uses that might affect hydrological processes at a regional level, sand extraction and aquaculture (i.e. aquaculture groundwater effects, salinity, sand extraction, loss of dune adjacent to a wetland), found a lack of information on the possible impacts and this created difficulty in assessing these types of developments (Appendix 1).

Wetlands may be zones of recharge and discharge depending on the environmental conditions. Modelled storage from a Western Australian surface wetland to a subterranean cave system indicated the occurrence of subsurface flow when the surface wetland was receiving excess water (Krasnostein and Oldham 2004).

3. Functions attributed to wetlands

Threats to groundwater dependent ecosystems

A list of the key threatening processes for groundwater dependent ecosystems is:

- water resource development
- agricultural land use
- activation of acid sulphate soils
- urban and commercial development
- mining
- plantation forestry (Sinclair Knight Merz Pty Ltd 2001).

The following discussion of these impacts on groundwater resources has been summarised from Sinclair Knight Merz Pty Ltd (2001) and elsewhere.

Water resource development

Consumptive use of water resources poses a major threat to groundwater dependent ecosystems in many landscapes across Australia. These threats include:

- consumptive use of groundwater which results in lowering the localised watertable level or reduces the pressure of confined aquifers. Potential impacts on dependent ecosystems include reduced access to groundwater, reduced base flow in streams and loss of habitat (Sinclair Knight Merz Pty Ltd 2001)
- diversion and/or impoundment of surface waters may result in changes in the groundwater level, either higher or lower than pre-diversion levels (Sinclair Knight Merz Pty Ltd 2001)
- altered water quality, particularly within the aquifer itself. Abstraction may lead to water from other parts of an aquifer, or from nearby surface water features or the ocean, being drawn towards pumped zones (Sinclair Knight Merz Pty Ltd 2001). Water quality may change significantly because of this. In some coastal catchments in Queensland and elsewhere saline intrusion is a problem. A zone of mixing of saltwater and freshwater occurs in the coastal zone (Lait 2004). The location of this interface can be changed by natural and anthropogenic processes. For example if the head of freshwater is reduced by excessive pumping, low rainfall or displacement by saltwater, the interface will move inland. When this occurs freshwater ecosystems that have a dependence on the groundwater may become saline. Also, if too much freshwater enters the groundwater the interface will move seaward and other more saline ecosystems may be affected (Lait 2004).

Agricultural land use

Intensive agricultural land use leads to changes in vegetation cover and recharge-discharge relationships across catchments and groundwater basins (Sinclair Knight Merz Pty Ltd 2001). The nature of these changes varies with the physical character of the landscape (climate, soils, topography, geomorphology, hydrogeology), the degree of change in vegetation and the management of agricultural land. Salinity and increased waterlogging of land can be one result (Nielsen *et al*. 2003). Changes to base flow patterns may also occur.

There is also the potential for contamination of groundwater from the application of agricultural chemicals (fertilisers, herbicides, insecticides). Groundwater contaminants are most likely to pose a problem for ecosystems in wetlands, lakes or estuaries fed by groundwater discharge (Sinclair Knight Merz Pty Ltd 2001).

Acid sulfate soils

Acid sulfate soils (ASS) will be discussed in detail later (see Acid sulfate soils, page 64). Impacts of wetlands from acid soils may sometimes occur naturally in dry seasons when the watertable lowers (Anorov 2004). However, excavation and lowering of watertables may lead to the activation of ASS. Developments in coastal areas all have potential to activate ASS (Sinclair Knight Merz Pty Ltd 2001). These outbreaks will not only affect wetlands where they are still intact, but also downstream ecosystems and agricultural areas.

Urban and commercial development

Urban and commercial development has the potential to influence the groundwater through clearing, drainage and land reclamation. Possible impacts on groundwater attributes are listed below (after Sinclair Knight Merz Pty Ltd 2001):

- intensification in groundwater resource development, to support domestic garden, recreational or industrial uses
- drainage and construction of canals and marinas may also lower groundwater levels in coastal areas
- groundwater pumping associated with urban and commercial development may also reduce discharge fluxes in aquifers
- a reduction in groundwater quality.

Mining

The impacts of mining on groundwater dependent ecosystems varies with the type of mining, the need for and intensity of groundwater pumping and the proximity to groundwater dependent ecosystems. Mining-related industrial activities may affect groundwater levels and groundwater quality (Sinclair Knight Merz Pty Ltd 2001).

Plantation forestry

Plantation forestry development can reduce the level or pressure of groundwater (depending on whether the aquifer was confined or unconfined). This can arise from two processes:

- reduced recharge to the aquifer below the plantation, which can lower the watertable or cause a reduction in pressure
- reduced surface water flows from reafforested catchments, which may reduce recharge to riverine aquifers.

These processes could be beneficial to natural ecosystems that are affected by salinity or waterlogging resulting from elevated water levels, but may have negative impacts elsewhere (Sinclair Knight Merz Pty Ltd 2001).

Recommendations

Based on current research it is not possible to make broad generalisations on groundwater relationships in wetlands, as wetlands of a particular type may not have the same interactions with groundwater. Like Hatton and Evans (1998) this report recommends that any research, assessment or monitoring of individual wetlands should investigate possible groundwater influences, and a methodology should be developed and incorporated into procedures.

In addition, modelling of wetland hydrology such as the one presented in Krasnostein and Oldham (2004) may help to target sites for future field studies.

A better understanding of the effects of groundwater quality on aquatic ecosystems and the best way to manage these impacts is also required (Appendix 1).

Biodiversity functions

Previous sections have touched on various aspects of the importance of wetlands to flora and fauna. Many wetlands have an aquatic and terrestrial component, which makes these ecosystems potentially important not only to aquatic organisms but also terrestrial organisms. Maintaining biodiversity is the most discussed value ascribed to wetlands. Surprisingly little appears to be known about the trophic relationships and ecosystem functions of many wetlands in Queensland. Wetlands are often termed biodiversity hotspots due to the number of species that occur within them. Some wetlands are highly productive systems, although this is not always the case (Mitsch and Gosselink 2000b; Hadwen 2002). Different wetland types vary enormously in their biodiversity characteristics. The biodiversity functions of wetlands were not a priority topic in this review; however, the following topics will be briefly discussed.

- endemic biota
- migratory animals
- value to commercial fisheries
- refugia values
- the value of constructed wetlands for biodiversity.

3. Functions attributed to wetlands

Endemic biota

In Queensland a number of rare and endangered organisms reside in remnant wetland areas. A list of endangered and rare species in a number of wetland types has been included in management profiles recently published by the Queensland Environmental Protection Agency (EPA 2006h). A wetland can have a high degree of isolation from other aquatic ecosystems. Where this isolation occurs it can lead to the development of species that are found nowhere else (Fensham and Fairfax 2005). For example in spring wetlands in Queensland and elsewhere, a number of endemic species have been found, some occurring only within one group of springs (Fensham and Fairfax 2005). A longer discussion of these values can be found when looking at different wetland types in Chapter 2.

Migratory waterbirds

Wetlands are often valued in terms of their habitat for waterbirds. In particular, this value has been attributed to arid zone wetlands, saltmarshes and, in some cases, constructed wetlands in agricultural areas. The protection of migratory waterbirds has been a major driver in the global protection of wetlands, and Australia has international responsibilities for the preservation of habitat for many species, under various agreements, such as the Ramsar Wetland Convention, the Japan-Australia Migratory Bird Agreement (JAMBA) and the China-Australia Migratory Bird Agreement (CAMBA) (Department of Environment and Heritage, Australia, 2006b). While waterbirds were not a specific focus of this study, the following has been found as the result of reviewing literature on wetlands.

Waterbirds tend to occur in large densities and many breeding colonies exist in some of the wetlands of the arid and semi-arid zone (Kingsford and Porter 1994; Kingsford, Curtin and Porter 1999; Kingsford and Porter 1999; Roshier *et al*. 2001a; Roshier *et al*. 2001b; CRC for Freshwater Ecology 2004). This can be attributed to the availability of food resources due to large 'booms' in productivity after flooding in arid floodplains and lakes. The spatial and temporal mosaic of wetlands in these areas is also important as flood flows move down these river systems and fill wetlands that have a range of permanence (from a few days to permanent), salinity and turbidity, which provides habitat for a range of waterbirds for long periods (Roshier *et al*. 2001a; Roshier *et al*. 2001b; Timms 2001b).

While wetlands are known to be important in supporting waterbirds, a number of studies comment that birds are likely to have a role as significant exporters of carbon out of wetland systems to terrestrial systems and other aquatic environments (Roshier *et al*. 2001a; Thoms *et al*. 2002). The importance of this connectivity and production export has received little direct attention (Pearson and Connolly 2001). Given that large numbers of waterbirds often descend on individual wetlands their role as grazers and predators must have a large effect on the food webs of these systems.

Value for fisheries

In coastal areas, estuarine wetlands and coastal freshwater wetlands have been regarded as very important in the life cycle of a number of commercial species. 75 percent of commercial fish species in Queensland spend part of their life cycle in estuarine and wetland areas (Quinn 1992). Seventy-nine species within the Great Barrier Reef coast have been identified as using both freshwater and marine habitats in the last 15 years (Vietch and Sawynok 2005). In New South Wales a relationship was found between geomorphology of the estuary, wetland area and fish landings and crustaceans (Saintilan 2004).

Wetlands are often regarded as important for fisheries, in particular for feeding, for breeding and as nursery areas. Further information on the species of fish that utilise wetlands is needed to better manage Queensland fisheries (Appendix 1; Douglas, Bunn and Davies 2005). The influence of fish movement on the food web structure and dynamics of wetlands, and the effect of removing the ability of fish to move through habitats, are areas that are worthy of further investigation, in particular in tropical areas (Douglas, Bunn and Davies 2005).

Key features of productive inshore nursery habitats include:

- shallows
- fine sediments
- turbid conditions
- variable salinities
- sheltered, low (wave and tide) energy waters
- vegetated habitats (Cappo *et al*. 1998).

Wetlands tend to possess these features, which is why they are often cited as nursery areas for fish. A study currently being completed by Dr Marcus Sheaves and Associates, as part of the Coastal CRC, is looking at the role of fresh and brackish pools as nursery habitats for fish. This study has released some preliminary results, which indicate that:

- Not all pools fulfil a role as nursery areas for fish as many become isolated and predators such as large fish and birds can decimate stocks.
- Although the process of pool isolation will occur naturally, human impacts such as dams, weirs, ponded pastures and urban infrastructure can reduce the connectivity of some pools to such a degree that the capacity for fish movement to other aquatic ecosystems is lost.
- Different pools provide unique habitats and in some cases habitats for uncommon organisms.
- Once a pool becomes disconnected different pressures operate on different pools and they act quite independently of each other. This supports the opinions of other researchers who feel that once a wetland is disconnected from other aquatic habitats, it may show very different characteristics to other wetlands which may appear to be of a similar type (Appendix 1; Coastal CRC 2005a).

This study also highlights that it is not possible to generalise about all types of wetlands in terms of their functions.

Freshwater wetlands

Many freshwater wetlands are valued as recreational fisheries by the presence of preferred fish species, for example juvenile barramundi enter freshwater and brackish wetlands and can remain in these habitats for more than a year before returning to the estuary (Vietch and Sawynok 2005). The role of coastal freshwater lagoons and other wetlands in the productivity of coastal fisheries is the focus of reports and studies in Queensland, in particular the role these coastal freshwater wetlands play as part of a critical chain of habitats for some organisms in the near-shore environment and the Great Barrier Reef (Cappo and Kelley 2001). A recent review of the role of freshwater wetlands for fish has summarised available knowledge on this topic, with particular reference to the Great Barrier Reef catchments (Vietch and Sawynok 2005). The review concluded that while survey data is lacking in many locations and further research is needed in some areas, sufficient knowledge is available to rehabilitate and protect wetlands (Vietch and Sawynok 2005). The knowledge gaps found were:

- the relationship between habitat type and the extent and productivity of fisheries
- the impacts of sublethal effects on fish from poor water quality in tropical wetlands
- food chain relationships between freshwater and marine environments
- criteria for assessing wetland value to fisheries resource.

Estuarine wetlands

Surveys generally show a high level of biodiversity and abundance of fish and crustaceans around mangrove areas (Lee 1999). Within mangroves shelter and infauna and epiphytic algae on roots as food supply are thought to be important. Mangroves also play an important role as sites for reproduction (Sheaves 2005). Mangroves, mud flats and seagrass nursery areas in south-east Queensland were studied and mangroves were found to be important as the fish will recruit elsewhere, but they do not survive or grow as well (Laegdsgaard and Johnson 1995). In Moreton Bay, 27 of the 53 species recorded in the bay were exclusive to mud flat and mangrove areas (Laegdsgaard and Johnson 1995).

In a study of links between mangrove extent and coastal fisheries production it was found that:

- Links between mangrove extent and coastal fisheries production can be detected for some species at a broad regional scale (thousands of kilometres) on the east coast of Queensland.
- For the mangrove-related species, mangrove characteristics such as area and perimeter accounted for most of the variation.
- For the non-mangrove estuarine species, latitude was the dominant parameter but some mangrove characteristics also made significant contributions to the models.
- By contrast, for the offshore species, latitude was the dominant variable, with no contribution from mangrove characteristics (Manson *et al*. 2005).

Molony and Sheaves (2000) investigated the extent to which three fish species, *Epinephelus coioides, Epinephelus malabaricus* and *Lutjanus argentimaculatus* prey on sesarmid crabs, based on fish from three mangrove estuary systems on the north-east coast of tropical Australia. They found all three species fed extensively on sesarmid crabs. They highlighted three implications for the ecology of tropical mangrove systems based on these findings:

- Food webs are apparently more complex, and food chains leading from mangroves to top predators may be shorter than previously thought.
- A substantial part of the mangrove productivity sequestered by sesarmid crabs may be exported from mangrove ecosystems as a result of offshore migration by these fishes.
- The low incidence of piscivory (preying on fish) in these fishes support theories that reduced predation pressure may enhance the nursery ground value of tropical mangrove systems for fishes.

A review undertaken on fisheries habitat research by Cappo *et al*.(1998) documented a lack of study of the role of Australian saltmarsh as fisheries habitats apart from a few studies of fish in saltmarsh creeks (Russell and Garrett 1985; Morton, Pollock and Beumer 1987; Davis 1988) and a others that illustrated fish use saltmarsh ecosystems. (Ritchie and Laidlaw-Bell 1994; Connolly, Dalton and Bass 1997). Ritchie and Laidlaw-Bell (1994) also showed that fish may have an important role there as predators of mosquito larvae. Since the review undertaken by Cappo *et al*. (1998) there has been some Queensland-based research on fish use of saltmarshes (Thomas and Connolly 2001) as well as studies from temperate areas of Australia (Crinall and Hindell 2004). The study by Thomas and Connolly (2001) found widespread use of saltmarshes by fish on two subtropical saltmarshes in Queensland, despite the relatively low duration and frequency of inundation. They also found that fish occurred at all distances into the marsh and that there was no clear separation of vegetated and unvegetated habitats. Both marshes were dominated by estuarine species, and included some economically important species of fish. In addition to fish, saltmarsh may have a role as prawn habitat and studies are under way to determine this through Griffith University (Cappo 2004). Juvenile stages of mud crabs have also been recorded from the upper tidal limit area in salt flats of northern Queensland (Cappo 2004). These crab larvae have been found to be a food source for fish feeding on saltmarsh, and also this larvae is exported from saltmarshes on high tides (Hollingsworth and Connolly 2004; Mazumder, Saintilan and Williams 2005).

In terms of tropical salt flats, the authors cite that ephemeral water bodies on saltpans are known to provide temporary habitat for barramundi juveniles, but studies are lacking. This use of flooded habitats may be relatively short before drying occurs, but there may be abundant food there at times due to the presence of insect larvae in high densities (Cappo 2004). When inundation occurs above a 500 mm depth for long periods, large barramundi have been recorded traversing the flooded saltpans in large numbers in the Burdekin catchment (Cappo 2004).

A correlation exists between fish productivity and mangrove area in New South Wales, but a stronger correlation exists between fish productivity and combinations of wetland variables or water area (Saintilan and Rogers 2002). Data analysed from 1985 to 2001 from 37 countries, using the principal components regression approach, found that prawn catch in tropical near-shore environments was more dependent on the extent of intertidal areas and organic matter availability, as represented by tidal amplitude, than to relative mangrove abundance (Lee 2004). These findings combined seem to suggest that while mangroves are important to fisheries, a complex environment of many wetland types is also needed to ensure continued fisheries productivity.

Refugia

Wetlands can act as refugia for aquatic organisms in times of habitat contraction. The concept of refugia is of an environment that supports populations not able to live elsewhere and that have a role in times of adversity, where refugia are defined as places (or times) where the negative effects of disturbance are lower than in the surrounding area (or time) (Nekola 1999; Davis *et al*. 2002). During adverse conditions, organisms in refugia have a higher probability of survival. Organisms that survive play a very important role in re-establishing populations when conditions become more favourable (Burrows 2004; Arthington *et al*. 2005; Marshall *et al*. 2006). Earlier sections (see Chapter 2) have discussed the value of some types of wetlands as refugia, particularly in the arid zone, where some research on the role of wetlands as refugia has taken place. Most wetlands are likely to act as refugia for organisms at certain times.

The value of constructing and restoring wetlands for biodiversity

Constructed wetlands do appear to have some value as habitat for native animals (Hazell 2003), especially waterbirds and fish (Nichols and Mcintosh 1998; Burrows 2004), although there is a general acceptance that while constructed wetlands can have ecological benefits, their nutrient dynamics and the number and composition of existing species can be different. Therefore retaining natural wetlands is preferable (Verhoeven 1998; French, Robertson and O'Donnell 2004). In particular, construction and restoration has tended to lead to the construction of 'generic' ecosystems with a high number of generalist species. These ecosystems do not sustain regional biodiversity, although they may have benefits for waterbirds (Zedler 2000).

The recognition of the potential value of these wetlands for biodiversity has prompted some authors to encourage the incorporation of design elements that may be beneficial to wildlife into wetlands constructed for other purposes.

The following features were recommended in the construction of farm dams in grazing areas:

- a small island for wildlife
- a trickle pipe to take normal overflow from the dam back to the creek, so as not to interfere with normal flow and to minimise erosion
- a large expanse of edge effect where the water will recede over a wide area, for waterbirds and wetland plants
- a buffer zone planted with trees normally found in wetlands (Brouwer 1995).

For wetlands used in the sugar industry the following steps are recommended when constructing a lagoon in cane growing areas:

- soil tests should be taken prior to construction and the lagoon should be located elsewhere if there is a risk of activating acid sulphate soils
- lagoons should be constructed in low-lying areas
- avoid causing harm to any adjacent shallow but viable natural wetlands
- surface area as large as possible
- some areas that have a depth of at least 5 m during the driest period
- orientate lagoon in line with prevailing winds to improve oxygenation
- re-distribute the top soil layer after excavation is completed to improve plant establishment
- plant a buffer of trees along edges; depending on lagoon size, the windward side may remain untreed
- shallow, well-vegetated input drain that avoids watertable lowering
- broad entry points to reduce flow velocity and encourage silt to settle
- shallow basin margin vegetated with sedges, etc. to encourage deposition of suspended particles close to the edge for future excavation; also provides favoured habitat for many juvenile fish and waterbirds
- habitat island that provides predator-free nesting opportunities and silt deposition in lee of the island
- unrestrictive outflow to encourage fish entry (Bjornsson *et al*. 2002).

The steps that are outlined above may help improve the biodiversity of wetlands that are being used for other purposes, such as water supply.

If constructing or attempting to rehabilitate, restore or create wetlands for predominantly ecological reasons, more care needs to be taken to ensure that the wetlands will sustain at least some of the biodiversity of an area. Realistic goals are necessary as it is unlikely that creation or restoration of wetlands will end up with a wetland of a similar biodiversity value as a natural wetland, especially if the goal is to restore a wetland in an agricultural or urban setting back to a pristine state (Hilderbrand, Watts and Randle 2005). Poor design and a lack of understanding of important ecological factors impact on the success of these projects (Zedler 2000).

A review of the restoration of wetlands from the United States highlights 10 ecological principles that are largely ignored when restoring or constructing wetlands:

- Landscape context and position are crucial to wetland restoration. Poorly placed wetlands are unlikely to compensate for natural wetlands.
- Natural habitat types should be used as reference systems. Systems such as lagoons and ponds may be the easiest systems to build; however, there is a risk of creating or restoring wetlands that are too 'generic' to sustain regional biodiversity.
- The hydrological regime is crucial to restoring biodiversity and function. The regime will be different for different wetlands, so it is important to know what the regime was before modification, so that some of the important hydrological attributes can be reinstated.
- Ecosystem attributes develop at different paces. While plants and some fauna may recolonise relatively quickly, properties such as the development of organic soils will take much longer.
- Nutrient supply rates affect biodiversity recovery. It is difficult to establish some wetland flora when nutrient levels are high.
- Disturbance regimes can increase species richness.
- Not all species will reappear from seed banks and dispersal. Exotic plants are normally aggressive colonists.
- Environmental conditions and life history traits must be considered when restoring biodiversity. There is a need to understand which environmental conditions will favour the desired species assemblage.
- Succession theory is important in wetland restoration. Knowledge of population and community dynamics is needed to understand successional changes. Also exotic species often dominate and persist in wetlands.
- Genotypes influence ecosystem structure and function. It is suspected that genetic differences within species can affect restoration outcomes (Zedler 2000).

Recreating a wetland is a complex process and there is a risk of creating ecosystems that are dominated by a few generalist species, some of which may be undesirable weed species. As lack of detailed understanding of the ecological processes occurring in wetlands is a major problem in most areas of Australia, including Queensland; techniques such as adaptive management are required (Jensen 2002). One of the major components of any adaptive management framework is monitoring to assess change in ecosystems with management changes. Monitoring of projects is generally poor, with a study of wetland rehabilitation in Australia reporting that of the projects surveyed that undertook monitoring, under 25 percent monitored variables related to the project goals (Streever 1997). Additionally, in many cases monitoring is undertaken only for the length of the project, which is unlikely to be long enough for the ecosystem to stabilise (Streever 1997). For example monitoring of a mangrove rehabilitation project suggested that it takes at least 20 years for the recovery of original species and height composition (Quinn and Beumer 1984).

In addition to the technical difficulties of rehabilitating and restoring wetlands, costs are often high. Research into the costs of rehabilitation in comparison to protection should be undertaken in order to provide incentives for landholders (Appendices A1 and A4). The costs to protect a wetland, for example fencing, are easy to quantify; however, valuing the benefits gained from protection or rehabilitation of a wetland is difficult. The functions performed by wetlands are often assumed, but studies which quantify these biophysical and ecological processes occurring in wetlands that contribute to the value of a wetland, and the processes that impact on these processes, are lacking (Appendices A1, A2 and A4). The results of such studies could be of benefit when arguing the case for the protection of wetlands.

Threats to biodiversity

Finlayson (1999) cites some general threats to wetlands as changes to the water regime, physical modification of the habitat (drainage, filling, excavation etc), eutrophication and other pollution, and invasion by exotic pest species. Climate change is also an emerging threat, which has the capacity to alter the extent and types of wetlands found in Queensland. These threats are discussed in Chapter 4.

Recommendations

A number of knowledge gaps have been listed in sections of Chapter 2. It is important for management that the processes that lead to the transfer of energy and materials and food web interactions, as well as how these processes drive the normal system function, are understood (Pearson and Connolly 2001). For many wetland types more information is needed on:

- food web and ecosystem understanding
- whole-of-system research, as many studies focus on one aspect of wetland ecology
- the extent of modification to wetlands, for example changes to food webs brought about by barriers to migration (Pearson and Connolly 2001)
- longer-term ecological and biophysical studies
- appropriate methods for creating and restoring wetlands of different types, and guidelines for restoration.

Productivity export

Wetlands are often cited as being valuable in terms of productivity export to the river system and to terrestrial systems in terms of physical and biological transport (Lukacs 1998). Much of the research in this area in recent years, based on stable isotope data, has found a less than expected component of allochthonous carbon sources in rivers and near-shore food chains; however, both near-shore environments and rivers appear to exhibit changes in carbon dynamics and food chain structure when connections to wetlands and the floodplain are modified (Robertson *et al*. 1999; Manson *et al*. 2005).

In general, grazing and detrital food webs affect the flow of energy and nutrients (Boon and Bailey 1998). Many factors as well as primary and secondary production within the ecosystem may affect the degree to which production is exported to other ecosystems. As an example the factors that will influence the material exchanged in saltmarshes are listed below (Cappo *et al*. 1998). These types of factors will be relevant to other wetlands, and are:

- the rate of primary and secondary production
- tidal range (not relevant to non-estuarine wetlands; however, the timing, frequency, duration, variability, extent and depth of freshwater flow would be similar measures)
- ratio of wetland to watershed area
- water circulation
- total wetland area
- frequency of storms and rainfall
- volume of water exchange.

These factors vary between wetlands, and different combinations of these factors are likely to make each wetland system unique in its capacity to exchange material (Cappo *et al*. 1998).

Floodplain wetlands

Floodplain wetlands are generally highly productive, with the concentrations and biomass of dissolved and particulate carbon and the algal microbial and micro-faunal communities on average being one to three orders of magnitude greater than in the adjacent river channel (Robertson *et al*. 1999). However, increasing studies indicate that autochthonous carbon production in large rivers play a disproportionately important role in the aquatic food web (Douglas, Bunn and Davies 2005). While it is known that there is physical and biological transport between floodplain wetlands and the river, the direction and magnitude of this transport is not well documented.

Bunn and Boon (1993) found by stable isotope analysis that macrophytes contribute disproportionately small amounts of material to the food web in billabongs. Other authors (France 1995; Bunn and Davies 1999; Lewis *et al*. 2001; Bunn *et al*. 2003) have also found this for other wetland types and rivers. Osborne (2000) found that on tropical floodplain systems, the importance of downstream delivery of organic material was small in comparison with production and decomposition, with most material forming detritus (Pearson and Connolly 2001). These findings raise the question that the fate of much wetland primary production is not known, where fire is not a factor (Pearson and Connolly 2001).

Although studies in the Lake Eyre Basin have shown that autochthonous carbon sources dominate the food webs of some floodplain river systems (Bunn *et al*. 1999; 2003), both fish and macro-invertebrate species composition and abundance appear related to floodplain character as well as in channel attributes (Arthington *et al*. 2005; Marshall *et al*. 2006). It is also known that river systems that have suffered major alterations to catchment primary productivity through development have corresponding alterations in food web carbon dynamics (Robertson *et al*. 1999). Collectively this suggests that the role of allochthonous carbon sources in riverine ecosystems cannot be disregarded. Bunn and Davies (1999) speculated that other aspects of ecosystem function, such as the supply and mobilisation of nutrients, the provision of habitat and recruitment, and dynamics of populations of fish and invertebrates, might be some of the benefits of flooding and connection of the river system to the floodplain (and floodplain wetlands). In addition, a review of floodplain inundation and fish dynamics found that, despite a lack of research in the area, evidence exists that the status of a wide range of fish depends on the effects of flooding (Graham and Harris 2004).

Estuarine wetlands

Early overseas studies created the paradigm that mangrove forests were important in supporting near-shore secondary production via detrital-based food chains. As discussed earlier (see Primary and secondary productivity, page 9), the current understanding is that organic matter exported from mangroves is limited. Stable isotope studies show a contribution of saltmarsh grass in near-shore areas; however, the authors of that study view it as a spurious result, reflecting the similarity in isotope values to seagrass (Connolly and Guest 2004). Although seagrass is not within the scope of this study it should be noted that based on the stable isotope studies mentioned above, seagrass beds have been found to be very important sources of carbon in estuarine and near-shore areas, so it appears that these wetlands do export material (Connolly and Guest 2004; Melville and Connolly 2005).

While the literature seems to indicate that mangroves and saltmarshes are not as important as a carbon source for near-shore food webs as previously thought, significant movement of organisms may occur from these environments to marine environments. These wetlands have other important roles, such as habitat provision and as paths of connectivity between riverine, coastal and marine ecosystems, for example some of the studies reviewed in the section Value for fisheries (see page 56) document the importance of coastal wetlands to some fish species. Mangroves are thought to be part of a habitat mosaic (Sheaves 2005) or chain of habitats (Cappo and Kelley 2001) in which fish and other organisms utilise a number of connected habitats, and therefore degradation of any one of the habitats can affect species across the whole mosaic (Sheaves 2005). Connectivity of different parts of the coastal and near-shore region is not well understood in terms of nutrient movement, both sediment- and water-based, but also in terms of nutrients tied up in organisms (Appendix 1).

Terrestrial linkages

Little literature was found on this subject, although some information may be embedded in terrestrial ecosystems literature that was not identified as part of this review. Many wetlands such as ephemeral wetlands (Thoms *et al*. 2002) and saltmarshes (Adam 1998) are important to terrestrial grazers. Recently Ballinger and Lake (2006) published a review discussing the importance of energy and nutrient fluxes from rivers into terrestrial food webs.

An increase in non-aquatic bird density and diversity was associated with the presence of billabongs in the floodplain forests of the Ovens River (Parkinson 1996). Also, the role that waterbirds have in connecting wetlands and terrestrial areas across broad scales is one that a number of authors have noted (Roshier *et al*. 2001a; Thoms *et al*. 2002).

Threats

The greatest threat to the export of productivity from one ecosystem to another is physical and hydrological barriers, which are discussed in Chapter 4.

Recommendations

The research reviewed in this section highlights the need for a better understanding of how or if wetlands of different types export productivity. It appears that there is good evidence to suggest that some wetland types have an important role in maintaining the health of floodplain rivers and the near-shore marine environment. Further studies are needed to:

- better understand the connectivity of different parts of the coastal and near-shore region in terms of nutrient movement, both sediment- and water-based, but also in terms of nutrients tied up in organisms (Appendix 1)
- the magnitude and direction of the potential subsides within the freshwater aquatic ecosystem and in relation to terrestrial ecosystems warrants further investigation (Douglas, Bunn and Davies 2005)
- determine the fate of large amounts of wetland primary production (Pearson and Connolly 2001)
- further quantify the long-term impacts of altering or impeding connectivity between ecosystems and mechanisms to improve wetland connectivity.

Carbon sequestration

Wetlands are often cited as carbon sinks. Their role in carbon sequestration globally is significant, most being tied up in the peat deposits and in wetland soils (Mitsch and Gosselink 2000a). The carbon sequestration abilities of different wetlands were highlighted as a knowledge gap in workshops undertaken as part of this project (Appendixes 1 and 2). In Queensland a major study undertaken as a joint venture between the Australian Institute of Marine Science, the Kansai Electric Power Company Inc., and the Kansai Environmental Engineering Centre Co. Ltd. looked at the potential of mangrove ecosystems to fix and store carbon.

The study site was Hinchinbrook Channel, Queensland. Mangrove ecosystems were found to be highly productive (Clough 1998) and autotrophic, with carbon fixed greatly exceeding that respired and buried (Alongi *et al*. 1998). This suggests that these areas have the potential to export large amounts of carbon to coastal waters, although from studies it appears that transport does not occur only in one direction (Alongi *et al*. 1998). The sediments within the channel act as a large organic carbon reservoir (Matsui 1998). The overall conclusion was that mangroves are a manageable natural sink for atmospheric carbon dioxide (Ayukai *et al*. 1998).

While wetlands may have the capacity to store large amounts of carbon, many wetlands also release greenhouse gases, in particular methane. It has been estimated that in billabongs in the southern Murray-Darling Basin, between 30 percent and 50 percent of the total benthic carbon flux was accounted for by methane and that a major proportion of carbon fixed by plants leaves the wetland via this methane release (Boon and Mitchell 1995). Another study found that emission of methane was negligible in ephemeral floodplain wetlands in south-eastern Australia when flooded in autumn or winter; however, when flooded over the summer months these wetlands emitted a similar amount of methane as permanent wetlands (Boon, Mitchell and Lee 1997). It should be noted that for this part of southern Australia, water resource development has lead to a shift in the seasonality of flooding, from predominantly winter to summer flooding of wetlands.

Another study which examined the fluxes of the greenhouse gases methane and nitrous oxide in Queensland mangroves found that, as in many ecosystems in which anoxic conditions prevail, methane and nitrous oxides can be immediate or end products of microbial processes (Kreuzwieser *et al*. 2003). The main point of interest was that field sites with high substrate availability (sewerage works nearby) showed higher emissions than sites with poor nutrient supply. This finding has been supported by a recent international review by Barnard, Leadley and Hungate (2005), which found that nitrogen addition to natural ecosystems increased nitrous oxides emissions. These findings have some bearing on increasing the nutrient supply to wetlands.

Factors that hinder the ability of wetlands to store carbon

While many wetlands do have a potential to act as carbon sinks, they can also be the source of methane emissions to the atmosphere, although at a much smaller scale than anthropogenic processes such as burning fossil fuels (Mitsch and Gosselink 2000b). From the few examples cited, it appears the carbon balance in wetlands can be affected by human activities, such as:

- any process that releases the carbon store in wetlands, for example draining, which may allow for the oxidisation of peats where they exist, and fire
- processes such as a change in the hydrology of wetlands and eutrophication may have some impact on the carbon cycling of wetlands.

Recommendations

Wetlands do appear to have a valuable role in the global cycling of carbon. Although quantification of the role is not complete, it is a topic that is gaining increasing interest. While documenting the role of wetlands, in carbon sequestration may be important in supporting policy for the protection of wetlands, another important topic for investigation is the impact that human-induced changes are having on the capacity of wetlands to act as carbon sinks.

Acid sulfate soils

Coastal wetlands have a role in the mediating acidity found in some coastal soils. A number of authors have investigated this topic and the following discussion is largely based on a review by Anorov (2004).

Acid sulfate soils (ASS) are coastal wetland soils whose formation is dependent on marine-influenced processes such as fluctuations in sea level, tidal regime and estuarine sedimentation (White *et al*. 1997). Wetlands such as mangroves, saltmarshes and coastal back swamps and floodplains are often underlain by acid sulfate soils (Anorov 2004; Powell and Martens 2005). The artificial drainage and disturbance associated with various coastal land uses can produce large volumes of sulphuric acid, with the subsequent release of toxic levels of iron, aluminium, manganese and other toxic heavy metals. This reaction releases acid and removes dissolved oxygen from the waterways (Ahern and McElnea, 2000), which has severe consequences for aquatic ecosystems (Sammut and Callinan, 2000). Soluble iron is thought to stimulate marine algal blooms (Powell and Martens 2005).

Coastal swamps occupy the lowest land on the floodplain and are prone to waterlogging. In Queensland remnant *Melaleuca* wetlands tend to occupy the freshwater coastal swamps. These swamps are subject to seasonal flooding and may be inundated for up to six months a year, followed by periods of drought.

Under natural conditions, small amounts of acid may be generated and released in drought periods. In this case the acid leachate is largely confined to the wetlands and the contamination of other waterways by acid leachate from undisturbed coastal swamps is considered to be minor. The artificial drainage of coastal swamps and lowlands, however, has led to adverse environmental and structural impacts, such as the exposure of ASS scalds, the acidification of waterways and the corrosion of infrastructure. Most natural swamps pond water for up to 100 days, with much of the ponded water evaporating, whereas artificial drains were designed to remove water from floodplains and swamps within five days so that crops could be successfully grown (White *et al*. 1997). The rapid removal of water into streams means that increased sediment, nutrients and pollutant loads are also exported (Powell and Martens 2005). The design of drainage systems for agriculture and other uses has led to the acidification of sulphidic soils (White *et al*. 1997; Cook *et al*. 2000).

Maintaining wetland areas which have ASS will prevent further damage to downstream aquatic ecosystems. White *et al*. (1997) recommend that in low lying areas (<1 m Australian Height Datum; AHD) or where the sulphidic layer is within 0.5 m of the surface, soils should remain in a waterlogged state.

Threats

The drainage and loss of coastal wetlands is one of the main drivers of ASS in coastal areas. Acidity from the activation of ASS has the potential for changes in water quality in the remaining wetlands and can cause changes in chemical conditions, which can result in changes to nutrient storage and cycling, and poor health and death of aquatic organisms.

Recommendations

The protection of remaining wetlands is a priority to maintaining acid bearing soils in their natural state. Knowledge gaps highlighted in discussions with experts in this area are:

- More information is needed in areas that are undergoing intensive development pressure.
- Inland forms associated with salinity are unknown in Queensland, but may occur.
- Management strategies and guidelines need further refining (See Appendix 2).

4. Threats to wetland ecosystems

Introduction

While it was not one of the aims of this project to review threats specifically, it is not possible to review wetland processes and functions without some discussion of them. A number of well-documented threats exist for most wetland types, although the exact nature of the change to the ecosystem brought about by these threats is not as well documented.

There are primary drivers and proximate drivers for the continuing loss and degradation of wetlands (Finlayson and Lukacs 2001). Primary drivers are mainly social and institutional, such as:

- a lack of public awareness of wetland values
- bureaucratic obstacles
- over-centralised planning processes
- historical legacies of land tenure and use
- weakly and poorly resourced conservation institutions
- sectoral organisation of decision making and alliances that promote policies and studies rather than action
- economic development in wetlands (Hollis 1992; Finlayson and Rea 1999).

These primary drivers lead to changes in proximate drivers (Finlayson and Lukacs 2001) or direct drivers (Finlayson, Grazia Bellio and Lowry 2005). In northern Australia, as an example, proximate drivers include changes to hydrologic regime, invasive species, clearance and drainage, over-harvesting and pollution (Finlayson and Lukacs 2001). A table of direct and indirect threats to wetlands is included in Bunn, Davies and Kellaway (1997) and McComb and Lake (1988).

While threats to wetlands appear to be relatively well known and some research has quantified the impacts of some threats, these threats will often remain if the underlying causes cannot be removed. Therefore research is needed into the best way to manage wetlands to reduce the impact of these threats. Based on comments made as part of the workshop component of this project and interviews with people involved in wetland research in Queensland, management information on wetlands of different types can be difficult to find. The EPA 'wetland management profiles' have scoped available management information for a number of wetland types, and limited discussion of this information will be entered into here. The outputs from the wetland management profiles are available on the EPA website (www.epa.qld.gov.au).

Threats are often interrelated and the effects of a number of impacts will need to be managed in a wetland. For the purposes of this review, threats will be discussed under the following headings, which were listed as the priority issues in the National Wetlands Research and Development Scoping Review (Bunn *et al*. (eds) 1997):

- changes in water regime
- habitat modification
- pollutants
- weeds and feral animals.

Climate change will also be discussed, as it is an issue that has the potential to significantly change the diversity and extent of wetland areas in Queensland and elsewhere (Hughes 2003).

Changes to water regime

It is widely agreed that hydrology is central to the ecology of wetlands; in particular it has profound effects on the reproduction, growth and distribution of plant and animal species (Boulton and Brock 1999). The hydrological regime of a wetland can also affect the decay of organic matter, nutrient cycling and the provision of ecosystems services generally. Wetlands have water sources from precipitation, surface water inflow, flooding and groundwater. Most wetlands may get water at different times from all of these sources, although this is not always the case, for example spring wetlands and perched lakes. This potential reliance on water from multiple sources for the maintenance of the ecosystem means that changes to the quantity or quality of any of these sources may have an impact (Bunn *et al*. (eds) 1997).

The impact of hydrological modification on the filter function, habitat provision, primary productivity, biological function, connectivity, water quality and spatial extent has been cited as a research priority in a recent wetlands workshop held by the Coastal CRC (Coastal CRC 2005a). A number of reviews and studies have documented the ecological processes that can be impacted with changes in water regimes (for example Boon, Mitchell and Lee 1997; Boulton and Jenkins 1998; Brock, Smith and Jarman 1999; Kingsford 2000; Leslie 2001; Bunn and Arthington 2002; Scholz *et al*. 2002; Thrupp and Moffatt 2002; Graham and Harris 2004; Staunton-Smith *et al*. 2004; Brock, Crosslé and Nielsen 2005).

Changes to the hydrology of a wetland occur with changes to the timing, duration, frequency and magnitude of surface or groundwater to wetlands (Boulton and Brock 1999). Most often cited in Australia-wide literature are the effects of large-scale water resource development. Other types of hydrological modification are numerous, for example:

- The use of wetlands to act as water supplies or places for tailwater discharge may increase the time these wetlands are inundated.
- Barriers to flow such as barrages and bund walls can alter the flooding and drying regime, change the salinity of coastal wetlands and present a barrier for migration for many species, for example Vietch and Sawynok (2005).
- Flood harvesting may reduce run-off to wetlands. Changes brought about through agricultural, urban areas and industrial areas can significantly impact the quality and quantity of run-off entering wetlands and consequently these processes change infiltration rates and therefore also bring about changes in base flow rates, which sustain many water bodies in dry times, for example Burrows (2004).
- The over-abstraction of surface and groundwater can lead to a lack of water for wetlands, changing the extent of wetland areas and the species composition of the affected area, for example Fensham and Fairfax (2003).

Groundwater wetlands

Comparisons of a survey which documented springs in western, northern and central Queensland in 1896 and 1898 with 1998 and 2000 reported that 87 of 107 spring groups or 81 percent were no longer active. Reduced pressure due to water extraction is the likely reason for this (Fairfax and Fensham 2002).

Floodplain wetlands

Large-scale water resource development such as that seen in the Murray-Darling Basin and elsewhere has had a dramatic influence on the water regime of floodplain wetlands. Although spatial variations in wetlands mean that different wetlands on different floodplains will be impacted slightly differently, alterations in hydrological regime can have the following impacts:

- destruction of wetland habitat
- decrease in local, regional and in some cases international biodiversity values
- reduction in the number of species and the abundance of waterbirds
- loss of fish, vegetation, invertebrate, crustacean and amphibian diversity
- increased incidence of blue-green algae blooms
- loss of lateral connectivity between river and floodplain resulting in a loss of material flows
- invasion of exotic species
- increased susceptibility to pest outbreaks, for example midges
- reduced water quality
- increased salinity and associated toxic effects (Thoms *et al*. 2002).

Research in parts of Australia that have extensive water resource development, in particular the Murray-Darling Basin, have focused on the use of environmental flows to manage and improve the health of wetland areas (Davis *et al*. 2001; Mawhinney 2003; Kingsford and Auld 2005).

The increased awareness of the impacts of water resource development on wetlands has also led to a campaign for the preservation of systems that have largely intact floodplains and hydrology, particularly in arid areas, for example the Paroo catchment, in the Murray-Darling Basin and the Lake Eyre Basin (Walker, Puckridge and Blanch 1997; Kingsford 1999b; Kingsford, Curtin and Porter 1999).

Estuarine wetlands

Structures such as floodgates, barrages and bund walls in estuarine wetlands can change the ratio of saline and freshwater that is available. This will therefore change the type of wetland that can exist in these areas. Mangroves that are cut off from marine influence will suffer dieback and eventually other freshwater species will take over. Variables such as rainfall and the catchment size of estuaries are important to the species diversity in mangroves, so a reduction in the freshwater flow may also adversely affect the species composition of mangrove areas (Duke 1997). Groundwater extraction may alter the hydrology and water quality of estuarine areas. Zones of mixing of salt and fresh groundwater occur in coastal areas (Lait 2004). The location of this interface is easily changed by anthropogenic impacts. For example if excessive pumping, low rainfall or displacement reduces the head of freshwater, the interface will move inland. When this occurs freshwater ecosystems that have a dependence on the groundwater will become saline. Also, if too much freshwater enters the groundwater the interface will move seaward and other more saline ecosystems may be affected (Lait 2004).

Habitat modification

Wetland habitat modification can take a number of forms, including changes in hydrology and water quality, which are discussed in other sections. Examples of habitat modification are clearing, draining and damming, altered water regimes, contaminants, grazing in wetlands, cropping, extraction and mining, commercial harvesting, barriers to fish, recreation, fire and dumping (Bunn *et al*. (eds) 1997). While clearing, draining and filling a wetland remove habitat for wetland species from the landscape, other modifications may result in a change and/or degradation of the habitat. These changes have implications for the species composition and abundance within the wetland. Wetlands can be physically modified in a number of ways. In many wetlands, physical modification also results in changes to their hydrology.

Excavation

Modification of wetlands by excavation to increase their water holding ability can result in changes in the hydrology of the wetland and can have implications for biodiversity. For example when a number of groups of spring wetlands in Queensland were surveyed, it was found that 16 percent of active wetlands had been destroyed as a result of excavation, 10 percent suffered major damage and 15 percent minor damage (Fensham and Fairfax 2003). The effects of this were documented as a reduction in plant species with the assemblage consisting of generalist wetland species in those wetlands damaged by excavation. This may also have some consequences for fauna (Ponder and Clark 1990). In all wetland types, changing ephemeral wetlands into permanent wetlands either by changing the morphology or hydrology has the potential to change patterns of productivity and composition of the species assemblage (Kingsford 2000).

Grazing in wetlands

Grazing of wetlands can be detrimental, but it can also be a management tool, especially in terms of weed management. The grazing of wetland areas and stock watering at wetlands is an important resource for landholders. Many managers and researchers in Queensland, particularly in tropical areas, have the opinion that grazing could be non-detrimental and even improve the health of ecosystems if appropriate stocking regimes were used; however, sustainable carrying capacities have not been determined for all wetland areas.

Grazing has also been found to have the potential to alter wetland habitat and cause degradation to the wetland and surrounding areas, for example grazing around watering points in arid zones has been shown to cause declines of 15–38 percent in a broad range of native plant and animal species (Landsberg *et al*. 1997). Jansen and Healey (2003) studied the relationship between frogs, wetland condition and livestock grazing intensity at 26 wetlands on the floodplain of the Murrumbidgee River. They found species richness and some individual species of frogs declined with increased grazing intensity.

In Queensland, grazing has been studied in terms of impacts on wetland ecosystems and as a part of a management regime that helps control weeds in wetlands. Burrows and Butler (2001) have published results on the impacts and management of grazing from waterholes in the Upper Burdekin catchment, which is discussed in the section on the Dry Tropics (see page 13). A project tilted 'The lower Burdekin grazing project', undertaken by WetlandCare Australia, has investigated the use of light grazing as a management tool for exotic pasture grasses, and has found some advantages to grazing in wetlands where these grasses have become naturalised (WetlandCare Australia 2006b). In spring wetlands, while the impacts of grazing can be severe, fencing wetlands totally from stock often led to the proliferation of perennial species such as the common reed, which can reduce the diversity of wetland flora and, by increasing evapotranspiration, which removes surface water habitat for aquatic fauna, so some grazing may be preferable (Fensham and Fairfax 2003). The EPA and the CSIRO in Townsville are also conducting a project on the effects of grazing and fire on weeds in ephemeral wetlands of Townsville Town Common. Some results of this project have been published (Williams, Collins and Grice 2005).

The Queensland Department of Primary Industries and Fisheries (DPI&F) and Meat and Livestock Australia are currently developing a wetland module for the Channel Country, which should be available in June 2006.

Modification of wetlands for ponded pastures is regarded as a considerable threat to the biodiversity of wetlands in Queensland, with potential negative implications also for wading birds, animal health, human health and water harvesting for non-pasture-related activities as well as large-scale coastal zone processes (Hyland 2002). In a study of barramundi in ponded pastures in coastal areas, it was found that water quality in the ponded pasture systems was periodically poor, with high pH (>9), low dissolved oxygen and high temperatures. Although fish kills were not observed in ponded pastures, they occurred in a variety of habitats associated with ponded pastures (Hyland 2002). The study also found that barramundi occurred in eight out of 20 ponded pasture systems, and that barramundi are most likely to occur in pondage systems constructed across tidal channels or close to upper intertidal pools. Entrapment of juvenile barramundi occurred in pondage systems constructed across tidal channels. In one study site on pondage systems in tidal channels, the occurrence of trapped barramundi ranged between 39 percent and 78 percent. As most pondage pastures in intertidal areas dried out, this resulted in all the trapped fish dying. Sustained survival of barramundi over several years occurred in one pondage that did not dry completely. This demonstrated the potential of ponded pasture systems to provide fish habitat given appropriate management was in place.

Barriers to migration

Barriers to the migration of aquatic organisms between wetlands, to the river system or to the estuary are an issue that is closely linked to the modification of hydrology, and are often the cause of hydrological changes. Barriers to migration can be physical or chemical. Physical barriers include dams, weirs, barrages, causeways, ponded pastures and in some cases weeds. Chemical barriers are normally water quality attributes such as low temperature, turbidity, low dissolved oxygen and acidity. New South Wales Fisheries studied the response of juvenile fish and prawns to different pH levels in laboratory experiments. The results showed that juveniles of various fish species avoid even slightly acidic water when given a choice (Johnston *et al*. 2003).

Movement between habitats is mostly considered in terms of fish in Queensland. Fish movement is considered important to allow:

- adult fish to breed
- juvenile fish to spread upstream
- adult fish to return from spawning grounds
- fish to repopulate following drought
- fish to return upstream after being washed downstream during floods
- fish access to food supplies and different habitats (Department of Primary Industries and Fisheries 2004).

Structures that assist in fish passage are a potential management strategy, and a new dam, weir or other such structure across a waterway (marine or freshwater) may require a fishway. The best design for these structures in Queensland is still being researched and the Department of Primary Industries and Fisheries is undertaking monitoring to inform this design process (Department of Primary Industries and Fisheries 2004).

4. Threats to wetland ecosystems

The following impacts from coastal drainage systems with floodgates have been cited (Johnston *et al*. 2003) as:

- impacts on juvenile fish and prawn migration
- reduced fish passage and recruitment of juvenile fish behind floodgates
- sublethal effects of poor water quality, such as 'redspot' disease in fish
- loss and fragmentation of fish habitat
- increased fish kills
- increased export of acid and metals from ASS
- increased acid drainage
- nutrient accumulation
- increased monosulphidic black ooze formation in drains and transport to estuary
- wetland loss and reduced birdlife
- more fires leading to loss of organic topsoil (or peats) and scalding.

These impacts are not all direct effects on wetlands from floodgates alone, but include impacts on downstream environments as a result of the drainage or extensive modification of wetlands in combination with other factors. Improvement in water flow between habitats and reinstatement of flushing regimes (for example tidal flushing in coastal areas) are potential management responses to these problems, although given the potential risk from ASS not all these options should always be undertaken. For coastal areas management guidelines exist for managing floodgates and drainage systems (Johnston *et al*. 2003).

Insect control

Wetlands have often been associated with populations of insects such as mosquitoes and midges that are considered a pest and also can have impacts on human health. The control of insects in wetlands has traditionally been to use pesticides; however, these can be toxic to other aquatic animals, and there is the possibility that the target insect will become resistant to the pesticide over time (WetlandCare Australia 2006a).

Another approach used in coastal wetlands is runnelling, which is a technique used on estuarine wetlands. This involves the widening of natural drainage lines to remove standing water and increase tidal flushing (EPA 2006e) and is considered to have less impact than pesticides. In one study on the impacts of runnelling on nekton, the overall effect appeared to be a reduction in abundance of most species studied in the immediate vicinity of runnels at some times of the year (Connolly 2005). However, the authors felt that given the large area of runnels in some areas that even this reduction may be significant. They recommended that due to the apparent influence of runnels on nekton, the potential effects of saltmarsh modification on non-target animals should be considered as this management technique becomes more prevalent. Other studies have found that while there appear to be some ecological effects close to runnels, there is, at present, little basis to discontinue runnelling based on ecological evidence (Breitfuss, Dale and Connolly 2004; Jones *et al*. 2004).

Other research on management of insects in wetlands indicates that large populations of nuisance insects may be related in part to the health of a wetland, with healthy wetlands being more likely to provide habitat for predators of these insects (Pinder, Davis and Lane 1992). Higher nutrient levels may also result in an increase of algae, which may supply an additional food source for midge larvae, and reduce oxygen levels, thereby discouraging predators from entering wetlands (Pinder, Davis and Lane 1992). In a study that investigated mosquito breeding in surface flow constructed wetlands, the wetland with the greatest biodiversity of macrophytes and macro-invertebrates had the least number of mosquito larvae (Greenway, Dale and Chapman 2003). The authors recommended that in constructed wetlands the presence of mosquito larvae can be minimised by increasing macro-invertebrate biodiversity, by planting a variety of macrophyte types and species, excluding aggressive plant species, and maintaining at least 30 percent open water.

Pollutants

The main classes of pollutants that may affect wetlands are:

- plant nutrients, for example nitrogen and phosphorus
- inorganic compounds such as salts
- toxic compounds such as heavy metals and pesticides
- organic matter such as sewage effluent
- suspended solids (Bunn *et al*.(eds)1997).

As wetlands are depositional environments (at least in the short term) accumulation of contaminants associated with sediment often occurs in these areas (Bunn *et al*. (eds) 1997). While the processes that occur in wetlands can reduce or ameliorate contaminants in water, it is often overlooked if a wetland's capacity is overloaded by pollutants. These compounds can be as damaging to wetland ecosystems as they are to other natural systems (Boon and Bailey 2000). Wetland sediments where the majority of pollutants are stored can be the source of internal loadings of pollutants. These pollutants can therefore be made available with shifts in conditions, for example acidification or changes in redox states (see for example URS (2003)). A discussion of the threat posed to natural wetlands by eutrophication (plant nutrients and organic matter) is provided in the section Potential impacts on wetland ecosystems with nutrient enrichment (see page 48).

The impact of water pollution and nutrient enrichment on coastal wetlands has been cited as a research priority in a recent wetlands workshop held by the Coastal CRC (Coastal CRC 2005a).

Research has been conducted on shallow lakes and wetlands in terms of the concept of the alternative stable state hypothesis (Boon and Bailey 1998; Boon and Bailey 2000; Bailey, Boon and Morris 2002). Studies from around the world have shown that a wide range of lentic water bodies can exist as macrophyte-dominated or phytoplankton-dominated systems. The theory states that the system is stable at a range of conditions until cumulative disturbance is large enough to override the ecosystem's self-stabilising ability, when the ecosystem reaches a threshold and reacts suddenly to a gradual change (Boon and Bailey 1998).

A change in state represents a fundamental change in ecosystem function and is difficult to reverse. This theory was tested for a lake in Victoria, which reacted, as the theory predicted, to elevated nutrient loadings (Bailey, Boon and Morris 2002). The authors found a shift from macrophytes to algae and phytoplankton as nutrient loads increased. In particular they found that:

- Aquatic systems dominated by submerged aquatic plants are resilient to low levels of nutrient enrichment, but higher loading can lead to a very rapid loss of these plants.
- As nutrient loads increase, the growth of submerged aquatic vegetation may be stimulated depending on other environmental conditions, in particular light availability and sediment characteristics. It is not always possible to predict the result of large influxes of nutrients, but the risk of a sudden and detrimental change is increased.
- It is important to protect submerged macrophytes because they provide protection against algal blooms by:
    - o providing habitat for zooplankton, which graze on algae
    - o reducing light availability for algal growth
    - o producing compounds which inhibit algal growth
    - o reducing nutrients available for algal growth
    - o supporting the chemical conditions that favour phosphorous retention by the sediment and nitrogen loss to the atmosphere.

Based on the findings above, the following general management advice was given:

- Submerged aquatic macrophytes are desirable in shallow lakes and wetlands and management activities should ensure their continual persistence.
- Harvesting of submerged macrophytes when nutrient levels in the water column are high increases the likelihood of algal blooms, which may prevent re-establishment of submerged aquatic plants.
- Harvesting of submerged macrophytes may result in the establishment of other aquatic plants that are less desirable.

- Dense mats of floating plants or algae that grow in response to nutrient enrichment can cause deoxygenation of the water column.
- When constructing artificial wetlands there needs to be awareness of a limit to the potential use of wetlands to treat nutrient-enriched waters. This is because the buffering capacity of sediments will become saturated.
- Monitoring programs that address only blue-green algae could easily miss significant algal blooms caused by other types of phytoplankton.

Given this study was conducted in temperate Australia, the general applicability of these findings for tropical and subtropical wetlands should be investigated. However, the study does illustrate a need for a better understanding of the effects of nutrient enrichment of wetlands for different types.

Salinity has been researched in many of the wetlands of Western Australia and the south-east states, where salinity is impacting on the biota of wetlands. The concept of alternative stable states has been applied to salinity, as a basis to define different states that may occur with changes in wetland salinity in Western Australia (Davis *et al*. 2003; Strehlow *et al*. 2005). The authors identified contrasting aquatic vegetation states that were closely associated with different salinities. They found that salinisation resulted in the loss of freshwater species of submerged macrophytes and the dominance of a small number of more salt-tolerant species. With increasing salinity, these systems may undergo further change to microbial mat-dominated systems composed mostly of cyanobacteria and halophilic bacteria (Davis *et al*. 2003).

The ability to recognise and predict a change in states with changes in nutrients or salinity is important to the decision-making processes. This information is also important for the development of restoration or rehabilitation strategies.

Other pollutants, such as heavy metals and pesticides, have received relatively less attention for many freshwater wetlands in Queensland, although research may have been undertaken on this issue by industry groups that has not been identified or made available for this review. Research that has been undertaken in estuarine wetlands includes:

- the effects of oil slicks on mangrove communities (Burns, Codi and Duke 2000)
- the impacts of herbicides, in particular diuron, have been implicated in the severe and widespread dieback of mangroves in Mackay region (Duke *et al*. 2005)
- a current project being undertaken as part of the Coastal CRC aims to characterise the impact of industrialisation on environments such as mangroves, mud flats, saline grasslands and saltmarshes (Coastal CRC 2005b).

In addition to direct contamination of wetlands, the potential exists for contamination of groundwater from the application of agricultural chemicals (fertilisers, herbicides, insecticides) as well as urban, mining and industrial sources. Groundwater contaminants are most likely to pose a problem for ecosystems in wetlands, lakes or estuaries fed by groundwater discharge (Sinclair Knight Merz Pty Ltd 2001).

The establishment of buffer zones may enhance the management of pollutants entering into any aquatic environment (McKergow *et al*. 2004b). Large variations exist in the width of buffer zones recommended from a review of a number of studies (Gunn 2001). Although there is a summary of information regarding buffer widths for streams and wetlands in Price, Lovett and Lovett 2004, some of the wetland managers who attended the workshops held as part of this review recommended further research investigating the widths needed to buffer wetlands of different types as this information has implications for management (Appendix 4). Any management advice arising from this research needs to be clear and detailed, including issues such as: At what stream order do you stop requiring buffers? Of the many gullies that feed into streams which ones should have riparian widths? (Appendix 4).

Weeds and feral animals

The presence and nature of weed and feral animal species that exist in wetlands has not been scoped in detail as part of this report, and only general discussion of the impacts is provided here. Wetlands are particularly susceptible to weeds, with 14 of the top 18 environmental weeds in Australia occurring in wetlands (in 1991), and 11 of those in tropical wetlands (Humphries, Groves and Mitchell 1991; Douglas *et al*. 2001).

In Queensland wetlands, weeds such as water hyacinth and naturalised pasture grass such as Hymenachne and para grass have been a focus of study in terms of the effects these species are having on wetland ecosystems (Douglas *et al*. 2001; Houston and Duivenvoorden 2002; Perna and Burrows 2005). Two studies investigated changes in species diversity in wetlands with weed species invasion (Houston and Duivenvoorden 2002; Douglas, Bunn and Davies 2005). Both studies found a drop in plant species diversity but an increase in the productivity of plants. The impact of this increase in productivity was a greater demand for oxygen overnight, leading to anoxic conditions for aquatic organisms and the potential to significantly change fire regimes, with para grass producing approximately twice the fuel load of native grass, which may result in hotter fires (Douglas *et al*. 2001). While the two studies both found a decrease in plant species diversity, some of the faunal effects documented in the studies were not the same. The study of water hyacinth in the backwaters of the Fitzroy River (Houston and Duivenvoorden 2002) found:

- that macro-invertebrate communities in beds of Hymenachne had a different assemblage than in native plants
- an increased incidence of the introduced fish *Xiphophorus maculatus* in Hymenachne beds of 75 percent compared to zero percent in native plant beds.

A study of seasonally flooded areas on the Magela Creek Floodplain in Kakadu

National Park, Northern Territory (Douglas *et al*. 2001), found:

- a significant negative impact on wet season terrestrial invertebrate biodiversity
- few impacts on the aquatic invertebrates, fish communities or the aquatic food web.

The differences in results may be due to the differences in the two studies, with the Northern Territory study (Douglas *et al*. 2001) conducted in an area where para grass invasion was still quite patchy, while Houston and Duivenvoorden (2002) sampled in beds that were dominated by the weed as well as those without weeds.

Management of weeds is a critical issue. Combinations of variables that aid in increased prevalence of weeds include high nutrient levels, increased turbidity and hydrological change (Perna and Burrows 2005). The use of Roundup Bioactive has been found to reduce the cover of para grass by 90 percent, with no evidence of adverse effects on invertebrates and fish (Douglas *et al*. 2001). However, since para grass reinvades treated areas, follow-up controls are needed. In the floodplain lagoons in the Burdekin catchment, a method for removing mats of water hyacinth has been trialled (Perna and Burrows 2005). Mechanical harvesting of water hyacinth and removal of plant matter to avoid deoxygenation of the water when material decomposes from these lagoons resulted in rapid and substantial increases in dissolved oxygen and improved suitability of habitats for fish. As low dissolved oxygen passes sequentially through weed-infested lagoons, upstream areas should be harvested first (Perna and Burrows 2005). However, like pesticides, the conditions occurring in the water bodies, such as modified hydrology, increased nutrients and turbidity, are each likely to give Hymenachne the competitive advantage, so mechanical harvesting would be part of ongoing management of the area.

As discussed in the section Grazing in wetlands (see page 68), a project titled *The lower Burdekin grazing project* undertaken by WetlandCare Australia has investigated the use of light grazing as a management tool for exotic pasture grasses, and has found some advantages to grazing in wetlands where these grasses have become naturalised (WetlandCare Australia website 2005). The key management outcome found in updates so far is that exclusion of grazing is not an environmentally sound option for seasonally dry tropical wetlands where invasive exotic pasture species such as para grass have become naturalised. However, permanent grazing pressure also results in poor outcomes for wetlands, including a loss of plant diversity and reduced recruitment of overstorey tree species. Appropriate timing and duration of seasonal spelling is the primary focus for ongoing grazing trials. A study undertaken on the Townsville Common has found that cattle grazing significantly reduced the para grass cover (Williams, Collins and Grice 2005). However, no significant effects on the three most common native species were found. This indicates that decline in para grass did not increase species richness. The authors suggested that the groundcover of dead straw (from para grass) may inhibit the recruitment of species, and the use of fire to remove this straw should be investigated. While grazing did reduce para grass the authors also felt that it would be important to document the longer-term effects of grazing on native species, given an observed decline and a reduction in seed production in common reed.

Exotic fauna species in wetlands were not reviewed as part of this report. However, a number of exotic species of plants and animals occur in wetlands. Species have also been translocated from other catchments, via stocking of water bodies by government agencies, stocking groups or individuals (Burrows 2004). In general, species of exotic or translocated aquatic animals that are introduced into wetland areas compete for habitat, predate existing aquatic fauna and are the sources of possible spread of diseases (Burrows 2004). Other terrestrial animals such as pigs and buffalo may cause significant damage to the vegetation and soil structure by grazing within wetlands. This disturbance may also lead to water quality problems. Mulrennan and Woodroffe (1998) found that the impacts of buffalo might have been a factor in the expansion of tidal creek and saltwater intrusion on the Mary River floodplain in the Northern Territory.

Most participants of workshops and interviews cited weed research and management strategies as an important area of research. The issue of weeds was seen as one of the key threats to wetlands, in particular in northern areas of the state. Although some information has been found as part of this review, it appears that research and management advice regarding weed control in wetlands is lacking, or that this information needs to be better communicated. Indeed, participants of three out of four workshops (Appendices A1, A2 and A3) felt that it was an area that needed investment not only in terms of research but also in terms of on-ground works. It is recommended that further scoping of this issue be undertaken with relevant professionals in the field. Interestingly, the research gaps relating to exotic fauna species were not raised at workshops; however, this is not necessarily an indication that no knowledge gaps exist.

Climate change

Climate change is recognised as a potential threat to wetland systems across the world. Climate change is likely to affect precipitation, evaporation and transpiration, soil moisture, snowfall and snowmelt, storm frequency and intensity, and run-off, floods and droughts, although the nature of changes to these parameters will be different for different areas (Ragab and Prudhomme 2002). These hydrological changes are likely to bring about changes in water quantity, quality and demand.

Changes in estuarine wetlands have been used as an indicator and in some cases as analogies of the types of changes that can be expected with climate change. The two most prominent examples in the literature are the continued encroachment of mangroves into other wetland types such as saltmarsh, and saltwater intrusion. While saltwater intrusion has occurred in some coastal catchments in Queensland, the most dramatic example of large-scale saltwater intrusion is occurring on the Mary River floodplain in the Northern Territory.

On the east coast of Australia, in particular in southern Queensland through to South Australia, substantial invasion of mangrove plants into saltmarshes has occurred in the last 50 years (Adam 2002). Up to an 80 percent loss has occurred in some estuaries (Saintilan and Williams 1999). This type of invasion is one of the predicted early responses to climate change, although in the case of the Australian east coast it is unlikely that this is the only reason for this invasion, as documented sea level rise is less than the vertical rise in mangroves (Adam 2002). In some micro-tidal locations in Australia, for example Shark Bay in Western Australia, the predicted rise will completely inundate existing mangrove zones (Semeniuk 1994), which may lead to losses of these ecosystems. Loss of mangroves of these ecosystems will result in a loss of benefits such as flood surge protection and stabilisation of shorelines.

Saline intrusion into freshwater wetlands is another process that could cause widespread changes in wetland type and function. The northern parts of Australia are particularly susceptible to this form of change, as in many places freshwater wetlands extend for up to 100 km along rivers with a relatively small rise in relief (Hughes 2003). For example, the expansion of tidal creeks in the Mary River catchment has extended up to 4 km inland, with some 17,000 ha affected and a further 30-40 percent of the plain threatened (Mulrennan and Woodroffe 1998). A number of causes have been suggested for these changes, but this process, if not directly related to sea level rise is a good illustration of the types of changes that could be expected (Mulrennan and Woodroffe 1998).

Changes in drought frequency in inland wetlands and the possibility of reduced river flow for some Australian rivers may reduce the extent of wetland areas (Hughes 2003). Estimations from the Macquarie Marshes in New South Wales based on regional scenarios are that semi-permanent and ephemeral wetland vegetation in the marshes could be reduced by 20-40 percent by 2030. This estimation is based on water allocation practices staying at current levels (Hassall and Associates 1998; Hughes 2003).

The alternative scenario of increasing rainfall in the inland regions of Australia could also transform many ephemeral wetlands into permanent water bodies. A change in permanency will have implications for the types of organisms that utilise wetlands, as the flora and fauna in arid wetlands are highly adapted to a cycle of drying and flooding (Kingsford, Curtin and Porter 1999). Although the predictions relating to climate change are uncertain, it is likely to impact on waterbirds in the arid zone (Roshier *et al*. 2001b).

The impact of climate change and rising sea levels on wetlands is likely to be exacerbated by human activity, for example if less rain falls it is more likely that demand for water will be much greater. Many coastal wetlands are presently confined to a narrow strip by structures put in place to protect agriculture or urban and industrial development. Therefore, if sea level rises, there may not be room to accommodate wetland migration in a terrestrial direction (McFadden, Spencer and Nicholls 2005).

The effects of climate change are difficult to document and separate from other factors without the use of long-term datasets, which are generally lacking in Australia (Hughes 2003). Climate change was indicated as a research priority at a recent wetlands workshop held by the CRC (Coastal CRC 2005a).

Recommendations

From the limited discussion of threats undertaken as part of this review, it appears that while the threats that may impact on wetlands are well known, the exact nature of an ecosystem's response and the best way to manage wetlands in response to these threats is not well known (Appendix 3). Most participants of workshops and interviews cited on-ground management strategies as areas where information was difficult to find (Appendices A2 and A3). The issues of weeds and grazing were seen as key uncertainties, in particular in northern areas of the state (Appendices A1 and A3). Although information has been found on grazing and weed management as part of this review, it appears that research and management advice regarding weed control in wetlands is lacking, or that this information needs to be better communicated. Indeed, participants of three out of four workshops felt that it was not only an area that needed investment in terms of research but also in terms of on-ground works.

It is recommended that further scoping of best management practice for wetlands of different types be undertaken with relevant professionals in the field (Appendices A2 and A3).

5. Implications of research for the assessment, management and rehabilitation of wetlands

Assessment and monitoring of wetlands

The assessment of wetlands has not been conducted in this document. A comprehensive review of techniques and indicators that have been used in Australia and elsewhere for assessing wetland condition has been completed as part of the Victorian State Water Quality Monitoring and Assessment Program (Butcher 2003) and a review of wetland indicators for Queensland is currently being undertaken by DNR&W as a Wetlands Strategy project. Butcher (2003) should be accessed for information on the assessment of palustrine wetlands. In summary, Butcher (2003) concluded that:

- Large-scale wetland condition monitoring programs do not exist yet in Australia, but many agencies are at the stage of developing them.
- The majority of ecological health monitoring in Australia and internationally has focused on rivers, and techniques for rivers may not work for all wetlands. Testing the appropriateness of any technique should be undertaken before implementation.
- Investigation of assessment techniques is needed to inform the development of a monitoring program for wetlands in Victoria. This would also be the case for most wetland types in Queensland.

Indicators of wetland condition were also reviewed and the following recommendations were made (Butcher 2003):

- Algae are a promising indicator of wetland condition. Diatoms in particular have been found to be useful indicators of changes in salinity, pH and nutrient threats.
- Macro-invertebrates may be useful in assessment and monitoring, as a broad indicator of condition, but are not good early warning indictors.
- Fish are not a suitable indicator without further work to understand their ecology and relationships to wetlands.
- Amphibians are potentially a suitable indicator.
- Waterbirds as indicators of wetland condition are not appropriate, unless correlative links with other ecological elements have been established; however, waterbirds have the potential to be the best indicator for large-scale assessments.
- Macrophytes are good indicators of wetland condition, in particular hydrology, salinity and nutrients.
- Standard water quality and physical features should be part of the core dataset.

Based on the findings above and the information gathered as part of this review, several issues need to be addressed to establish a basis for the assessment of wetlands in Queensland:

- A lack of survey data will be a significant issue for some wetlands, in particular palustrine wetlands, as this will hinder the development and implementation of standardised methods in the assessment of wetland condition.
- Little conceptual understanding exists of some wetland types currently within Queensland. An understanding of ecosystem functioning is highly desirable for the implementation of any monitoring and assessment program of natural resources. For example the modification of wetland light regimes must be considered as an important change in the ecology of wetland systems. The implications of a change in light regime are discussed extensively by Scheffer (1998) and others, and represents a gap in current knowledge on many Australian wetlands. Information on light regimes should be collected as part of the information required to construct conceptual ecological models for Queensland wetlands.
- Most assessment of wetlands is to assess biodiversity values, such as health or conservation significance. If wetlands are to be assessed for other functions, such as nutrient retention and water regulation, suitable methods of assessing these functions will need to be determined.
- Similarly, long-term monitoring programs that enable human impacts to be separated from climatic variability appear to be almost non-existent for wetland systems.
- Queensland has the widest range of wetland types in Australia, based on the types listed under the Directory of Important Wetlands classification. Given the variation in biophysical conditions across Queensland, survey data from different regions and types may not be applicable to other regions and types. The creation and funding of long-term ecological research sites would contribute new and very valuable information on Queensland wetlands.

Currently, the Queensland Government is developing a monitoring and assessment system for streams and estuaries based around a conceptual understanding of the drivers, pressures and condition of these ecosystems (Marshall *et al*. 2006). Based on biogeographical regionalisation (classification) of riverine ecosystems, the state has been divided into similar functional groups (Marshall *et al*. 2006). For all other wetland types, with the possible exception of mangroves, it would be hard to find biological data that could be used to find natural groupings. While it may be tempting to use the groupings derived from streams in wetlands of different types, it would be unwise to assume that lentic and lotic water bodies will follow the same pattern, without first undertaking some survey work to establish if this is the case (Butcher 2003). Further confounding the assessment of wetlands is that within geographic areas, wetlands of different types may not have the same species composition. It may then be more pertinent in the short term to base a regionalisation on the landscape drivers of aquatic ecosystems and adjust these regions based on biological information as it becomes available (Hawkins *et al*. 2000).

Management of wetlands

While the outcomes of a number of studies give good examples of generalised wetland management across different types (e.g. options for weed control through grazing), the information is geographically patchy. In terms of management, most people contacted as part of this report regarded information on management issues as a knowledge gap (see workshops, Appendix). This may be a result of:

- little information being available
- a lack of understanding of the applicability of differing management advice that exists for other biogeographical areas
- a lack of translation of scientific information into practical guidance for landholder use
- poor communication of this information to managers of natural resources.

It may be that all factors play a part. These issues, while highlighted at workshops, were not the primary focus of this review, so further scoping of these issues is needed. Similar to the assessment and monitoring of wetlands, a lack of baseline data will hinder informed decision making. As discussed in Chapter 2 for wetlands that are not within river channels, there is limited monitoring of hydrological, water quality or ecological data. In particular, long-term monitoring and historical data are lacking.

Where possible, management implications have been discussed under the various sections of this report; however, there are a number of general implications for wetland management:

- Wetland processes and functions are highly spatially and temporally variable.
- A lack of condition data means that only highly visible change in wetlands may be noticed.
- Wetland types, which are more visible in the landscape or have more tangible values (such as the presence of commercial or recreational fish species), may be better managed than others such as ephemeral wetlands.
- A lack of quantification of the functions of different wetland types means that it is possible that a loss of ecosystems will occur whose importance to the landscape is as yet largely undocumented.
- Without a better understanding of anthropogenic processes affecting wetland functions that are valued by humans, the ability of wetlands to perform these functions may be compromised.

Wetlands rehabilitation

Currently in Queensland, in particular catchments that discharge into the Great Barrier Reef area, substantial money will be invested on ground works to improve the health of wetlands. While a number of groups have considerable expertise in wetland rehabilitation, such as WetlandCare Australia and the Australian Centre for Tropical Freshwater Ecology, there is a general lack of guidelines or written material to guide the rehabilitation of wetlands. Guidelines for both the rehabilitation and construction of wetlands should be further researched and developed using the principles outlined in sections Wetland design (see page 44) and the value of constructing and restoring wetlands for biodiversity (see page 59).

6. Recommendations and knowledge gaps

Recommendations

General understandings of important issues gathered from this project are listed below:

- The definition of wetlands used in this project (and the Queensland Wetlands Programme) was too broad for a detailed discussion of the functions, threats and management of different aquatic ecosystems. The adoption of the concept of 'systems' such as those used by the Wetland Mapping, Classification and Inventory project (of the EPA) for use in policy, management and monitoring documentation could assist in developing a better information base. However, for each of these systems the development of a more detailed classification scheme is needed.
- There were broad literature and knowledge gaps for palustrine wetlands (that is, classified in terms of vegetation, those off-stream areas traditionally thought of as 'wetlands'). These wetlands are widely represented in Queensland, yet basic information on them was lacking. This highlighted a general need to prioritise these wetland types for further investment.
- Tables (i) and (ii) illustrate the level of research (biogeographically based) found by the project. A relative paucity of information about wetlands occurring in inland non-arid areas is highlighted for further investment.
- Spatial and temporal variation is a dominant factor for characterising and understanding wetland ecosystem components, processes and functions. Long-term monitoring programs are needed.
- Evidence exists that management regime impacts on wetland ecosystem components and functions. For example reduction in hydrological connectivity can impact on fish life history stages and also the values placed on wetlands associated with fish production.
- A number of generic values are often attributed to wetlands. These values are largely unquantified and are variable depending on wetland type, position in the landscape, climate and a range of other factors. There is a lack of acknowledgement of the importance of understanding the distinct ecological characters and environs for wetlands along with their common features.
- On-ground works and the protection of wetlands can be undertaken based on current knowledge; however, good management practices are needed to ensure that systems are monitored for the influence of these activities on changes to a wetland's ecological character and ecosystem services. The information gained will increase our understanding of wetland ecosystems, which will in turn provide a better knowledge base for future projects.
- Information detailing the effects of implemented management actions is often unavailable. Constructed wetlands are used and proposed for the control of water quality issues in agricultural areas. However, information relevant to Australia, especially for tropical and subtropical regions, is sparse. Information from international sources also lacks clarity on the beneficial role that agricultural-based constructed wetlands can have on improving downstream water quality. Temporal variation in much of the current research suggests long-term studies are essential.
- Groundwater is potentially an important source of water quantity and quality for wetlands, and the current level of understanding of interactions between groundwater and surface water in wetlands is low. Where groundwater connectivity is identified as a process important to wetland functioning, indicators specific to groundwater ecosystem assessment should become part of standard wetland assessments.

6

- While international evidence exists that a number of anthropogenic processes impact on the ability of wetlands to retain nutrients, causal relationships between high-risk agricultural activities, wetlands and near-shore water quality are not clear. This is a result of:
  - a lack of quantification on the ability of wetlands to significantly improve the water quality in diffuse agricultural settings
  - international literature suggesting that to improve the water quality of near-shore areas, relatively large areas of the drainage catchments must be returned to or left as wetlands. Landscape placement of wetlands is also likely to be important. These factors have not been considered or validated at this time for tropical Queensland
  - activities that are likely to impact on a wetland's ability to improve water quality (although known to some extent) are not well quantified and therefore a wetland's ability to improve water quality is hard to predict.

Knowledge gaps

A number of knowledge gaps are identified as part of this project and priority issues are listed below:

- A need exists for more detailed process studies. In particular:
  - Long-term whole-of-system studies of wetlands are needed, as there is a lack of understanding of their different ecological characters and functions, in particular palustrine wetlands. This understanding is critical in managing and rehabilitating wetlands to maintain the functions and processes that provide the ecosystem services often attributed to wetlands.
  - Changes to the ecological character of wetlands have been linked to reduction in wetland functions such as biodiversity and water quality improvement. Further information about the nature and extent of modification of wetlands through anthropogenic processes is needed if these functions are to be maintained.
  - Most research on wetlands document high spatial and temporal variability. Longer-term studies will therefore enhance understanding of the natural ecological and hydrological processes that contribute to variability that occur in wetlands. This understanding will be important in assessing ecosystem services provided by wetlands. These services are currently masked by natural variability, for example water quality improvement.
  - While hydrological modification is often cited as a threat to wetland ecosystems, explicit impacts are not well understood in Queensland. Hydrological and ecological connections between wetlands and other aquatic ecosystems are altered in many agricultural and urban settings. This currently has large potential ramifications for the wetland ecology and delivery of ecosystem services to all freshwater and near-shore aquatic and associated ecosystems.
- If wetlands are to be constructed or restored to meet water quality objectives, the following issues should be further investigated:
  - The ability of wetlands to improve water quality in diffuse agricultural settings needs investigating. The CSIRO is currently running a project in the Wet Tropics; however, it is possible that more study will be required given variation in design, climate and the documented spatial and temporal variability of wetlands.
  - Guidelines for constructing and restoring artificial wetlands for specific objectives are needed. Guidelines are especially required in agricultural settings. Designs should incorporate, where possible, features that enhance habitat values of these wetlands. Findings of the Sugar Industry Infrastructure Package wetlands project in the Tully-Murray and Herbert catchments and the CSIRO project in the Tully-Murray are envisaged as being an initial reference for this issue.
  - International studies estimate that 2–7 percent of a catchment area needs to be left as or restored to wetlands for a significant reduction in nutrients exported from a catchment to be achieved. This estimate requires validation for Queensland, in particular in tropical areas.

  - The flux of water quality parameters entering and exiting wetlands constructed for the purpose of water quality improvement needs more investigation. Currently, monitoring is limited but would be a valuable information source.
  - Given the number of wetland construction and restoration projects occurring worldwide, a further dedicated review, accessing international literature, is recommended to add to the information already recorded.

- Ecological benefits of artificial wetlands should be assessed in terms of the whole aquatic ecosystem because in many areas artificial wetlands may act as habitat or refugia for aquatic organisms where other wetlands have been removed or are in decline (e.g. dams, constructed wetlands and bore drains). However, artificial wetlands are unlikely to replace all the attributes, processes and values provided by intact original wetlands.
- Baseline data to support informed decision making is lacking. For wetlands that are not within river channels, there is limited monitoring of hydrological, water quality or ecological data. In particular, long-term monitoring and historical data are lacking. Options such as environmental histories and oral histories projects could be considered to help address this lack of data.
- Information is needed on methods to better manage wetlands, as information for on-ground management can be difficult to find.

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Appendices

Appendix 1:

Draft report on interviews held as a component of the project Understanding Queensland Wetlands: Information review and gap analysis, in Townsville and Cairns between 31 June and 6 July 2005

Background

As part of the project Understanding Queensland's Wetlands: Information review and gap analysis, it was initially proposed that three scoping and gap analysis workshops would be conducted in Townsville, Rockhampton and Toowoomba. In planning for the Townsville workshop it became apparent that a large number of workshops had been conducted or were being planned for the Townsville region. In particular, other organisations were planning two workshops for June, which were also dealing to some degree with the effects of wetlands on downstream water quality. In order to lessen the time demands on researchers and managers in the region, it was decided to visit each organisation separately. This report is a summary of the comments made in these interviews.

List of participants

- Anthony Morrison, Acting Manager Environmental Planning, Environmental Protection Agency (EPA)
- Jane Waterhouse, Great Barrier Reef Marine Park Authority (GBRMPA)
- Bart Kellett, PhD candidate, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
- Jim Wallace, Team Leader Integrated Water Management Group, CSIRO
- Marcus Sheaves, Senior Lecturer, James Cook University (JCU)
- Damien Burrows, Aquatic Ecologist, Australian Centre for Tropical Freshwater Research, JCU
- Vern Veitch, State Environmental Officer, Sunfish
- Ian Duncan, Senior Project Officer (NAP), Landscape and Community Services, Department of Natural Resources and Water (DNR&W), Townsville
- Melissa Brown, Coordinator Water Resource Planning (Burdekin) DNR&W, Townsville
- John Russell, Principal Fisheries Biologist, Department of Primary Industries and Fisheries (DPI&F), Cairns
- Alf Hogan, Fisheries Biologist, DPI&F, Walkamin
- Rasiah Velupillai, Acting Principal Scientist, Landscape and Community Services, DNR&W, Mareeba.

Interview format

An EPA project officer travelled to Townsville and Cairns to discuss this project with a number of individuals from organisations that were either undertaking projects on wetlands, or from organisations that may benefit from having more knowledge of our project and the other projects being undertaken as part of the wetland program in Queensland.

While some questions were formulated, due to the diversity of people interviewed it was decided to keep the interviews informal and these questions were used more as prompts. The main points of discussion were: projects that were being undertaken into wetlands; gaps in wetland research; discussion around the proper management of wetlands (both natural and constructed); restoration of wetlands; monitoring and assessment of ecosystem health in wetlands; and other contacts in the region. It should be noted that for the purposes of this report we use the term 'wetlands' throughout, but are only discussing the types of wetlands that this review will be focusing on, which are inland wetlands (not permanent rivers) and estuarine wetlands. Both natural and constructed wetlands have been included.

The project officer also attended a workshop held by the CSIRO titled Ecological Risk Assessment for Wetlands of the Lower Burdekin. It was agreed that the notes/outcomes of this workshop would be sent to us and incorporated into this report (still outstanding). The workshop was attended by regional body members and representatives from the local farming community as well as government departments.

In addition to face-to-face discussion, the project officer has been in telephone and email contact with a number of other individuals to collate literature and other information for inclusion in the final products. These discussions are not included as part of this report.

Projects underway or about to commence in Northern Region relating directly to wetlands (at June 2005)

- the effects of grazing and fire on the ephemeral wetlands of Townsville Town Common. EPA/CSIRO (Julie Holden, EPA; Tony Grice, CSIRO)
- Sugar Industry Infrastructure Package (SIIP), Tully and Herbert wetlands (due for completion/reports July). Contact Alf Hogan, DPI&F)
- PhD project, Bart Kellett (CSIRO) Ecological risk assessment for wetlands in the Lower Burdekin — Underway
- The filter function of wetlands in Tully-Murray catchment. Jim Wallace, Dave McJanett, CSIRO. Commencing July 2005
- Tully-Murray Water Quality Improvement Plan (CSIRO)
- contribution of wetland habitats to fisheries output and food chains in the Fitzroy Estuary. Marcus Sheaves (JCU/CRC for Coastal Zone, Estuary and Waterway Management) — underway
- student projects from Coastal and Estuary Ecosystem Ecology Group, JCU
- rehabilitation of East Trinity wetlands. DNR&W, EPA, DPI&F, JCU. Contact John Russell. Ongoing since 2000
- GBR Coastal Wetland Protection Programme. Commonwealth Government (DEWR) — underway
- Various projects regarding wetland rehabilitation and management, Australian Centre for Tropical Freshwater Ecology. Ongoing.

Discussion:

Issues around management and restoration of wetlands

Most of the discussion of issues around the management and restoration/creation of wetlands focused on the following points:

Restoration/creation

- A number of interview participants commented that when constructing or restoring wetlands it was very important to have an idea of the functions that the wetland is being restored for, especially in highly modified landscapes where naturalness may not be achievable. As well as a potential gap in knowledge, design criteria of constructed/restored wetlands for tropical areas were also a cause of some differences of opinion. One theory is that shallow weedy wetlands are more suitable for water quality improvement whereas deeper waterholes are better fish habitats, so to address both objectives, a mosaic of wetlands needs to be created or restored within the landscape. Others feel that there is a need to quantify this theory; otherwise, shallow wetlands are potentially building up sediment, which will be scoured and transported downstream in the wet season. They also feel that if wetlands are deep enough they can possibly function as a downstream water quality improver, a place for flood detention, a zone for groundwater recharge and a fish habitat area, and the shallow areas can act as refuges.

Hydrology

- Connections to other aquatic ecosystems are very important as many created and restored wetlands have very good natural colonisation rates on first filling. (Alf Hogan of DPI&F is currently looking at the timing of this; rates are possibly flood-related).
- Natural wetlands maintain shape and depth in large flood flows. Therefore, any changes in flooding will impact wetlands. This includes increased flood harvesting.
- In cane growing areas, since the land has been laser levelled, smaller events now equal big events in terms of run-off. This has implications for base flow in the dry season, as water runs into wetlands and rivers, and infiltrates into soil. This increase in run-off has implications for water quality within wetlands as the run-off contains sugars, which can reduce the dissolved oxygen of wetlands. Trash blanketing has led to a decrease in sediment coming off cane paddocks; however, the run-off from trash-blanketed paddocks can have higher amounts of sugar.

Weeds

- Weeds are a critical issue. Cutting dense weed mats and removing the weeds is making big improvements in water quality (dissolved oxygen) and ecosystem health. The approach should be used to fix symptoms even though this may not eliminate the cause, as it may not be possible to eliminate the cause in highly modified environments.
- Because weeds are such a critical issue, some grazing of wetlands is preferable to total exclusion. In arid zone wetlands some work has been done on fencing and better water quality monitoring. CSIRO has a project on the Townsville Field Training Area. Improved management is needed through timing of grazing.

Institutional issues

- On a broader scale, wetlands are not protected well enough under legislation. In particular, not enough recognition is given to the importance of first order streams and ephemeral wetlands. Water extraction needs to be managed with wetlands in mind to avoid acidification and saline intrusion.
- Too much responsibility lies with local government; they now have increased environmental responsibilities but do not have increased funding to do this.
- More emphasis should be placed on an incentive scheme to protect wetlands, for example through the taxation system.
- In order to better manage wetlands, need to get the community on board. Mediums other than science can be effective in doing this. For example in Burdekin, historical photos have had a great deal of success in convincing the community of a problem with many wetlands in the area.

Wetlands and reef water quality

Some researchers expressed some uneasiness about the management of wetlands, especially natural wetlands, to protect reef water quality. Some concerns were raised on this issue:

- They are important ecosystems in their own right, and using them to filter poor quality water will have negative effects on their functioning and biodiversity.
- The number of wetlands that would need to be restored to maintain reef water quality is not possible in an agricultural landscape. In terms of reef water quality it would probably be better to focus effort on sustainable farming practices that may benefit both reef and wetland ecosystems.
- Wetlands can be the ‘kidneys’ of the reef is uncertain, as big events are the things that are a threat to the reef, and wetlands are better at retaining nutrients at time of low flow.

Other points raised

- In altered environments it may be better to go for health of the system, not naturalness. The emphasis should be on ensuring the wetland can maintain all the species it possibly can. May need ongoing maintenance to achieve this.
- Fish stocking of fish such as barramundi probably is not having much impact, as they tend to be predatory on each other as well as other fish.

Monitoring and assessment of ecosystem function

Many of the participants commented that there was very little monitoring of wetlands, and of those projects that included monitoring, it was often discontinued when the project was completed as there was no funding to continue it. In particular, participants felt that long-term data about wetlands was almost non-existent, and given the spatial and temporal diversity of wetlands, this information was crucial to managing them. In terms of being assessed for the health of the ecosystems, the feeling was that most wetlands had been assessed or surveyed at some point, but no ongoing assessment exists for most wetlands.

Some projects mentioned by participants included:

- SIIP, Tully and Herbert wetlands. Some monitoring/assessment. Mostly using fish species to compare natural and constructed wetlands
- ACTFR does some monitoring of wetlands
- WetlandCare Australia may also do some monitoring (contact Jim Tait)
- CRC savannahs project on vertebrate fauna. Housed within EPA (not just wetlands)

- CSIRO water quality improvement plans (Douglas and Tully-Murray). As part of Tully-Murray, the CSIRO is involved in some water quality monitoring around impacts of restoration of riparian areas
- community monitoring of some projects.

Some regional issues mentioned that hinder monitoring:

- Phys-chem. monitoring can be expensive, so alternative measures should be developed. At the moment there is a lack of indicator species for macro-invertebrates in tropical regions. In terms of indicator fish species, in general noxious ones indicate poor health; other than that, not enough information is known about fish in the area.
- From a community monitoring perspective, lack of equipment is an issue, especially in high flow events. One possibility would be to further research the use of remote sensed images to extrapolate water quality data.

Knowledge gaps

Many of the people interviewed felt that much of the accepted understanding of how wetlands function and the ecosystem service they provide is based on premise rather than on scientific knowledge. The following issues were raised as potential gaps, by a number of participants:

- The filtering capacity of wetlands in tropical areas needs a great deal more study. How much nutrient is tied up in wetlands and for how long is not known. A study, which will be commenced by CSIRO in July 2005, may to some degree address this, as they will be looking to quantify this on a wetland in the Tully-Murray catchment.
- The number of wetlands in a catchment that would need to be restored to maintain reef water quality is not known.
- Process studies and wetland classification needs to be undertaken. Food chain and ecosystem data is needed as we do not understand how different types of wetlands function or even what different types of wetlands exist.
- Sustainable grazing regimes for wetlands need investigating. Grazing is good for control of weeds, but at what level this benefit stops and grazing becomes detrimental is unsure. (This may be in part addressed by the CSIRO/EPA Townsville Common study.)
- Groundwater interaction and hydrological impacts on wetlands are not well known. For example in northern region, sand extraction and aquaculture are two land uses which may affect hydrological processes at a regional level. There does not seem to be any good information about the possible effects, so it is difficult to make an assessment about these types of developments.
- In terms of fisheries, it is known that wetlands are important, but what fish are dependent on different types of wetlands is not known. This is important to know for management of wetlands. A number of species of fish are freshwater and marine dependent. The life cycle of many species is largely unknown, including the effects of environment and habitat modification.
- Development of design criteria is needed for constructed wetlands.
- Research is needed into the connectivity of wetlands and the river, coastal and marine system, not only in terms of sediment and nutrients, but also resources. Links between land use, wetlands and the reef are not clear or proven. How does what happens in coastal areas affect the marine system needs to be known?

Other issues raised by individuals:

- Algae is an understated driver of water quality and needs more research in the tropical area.
- Impacts of recreational sport fishers, for example what is being harvested out of wetlands and what impact is it having on wetland function needs to be known.
- Carbon storage guidelines need to be developed for wetlands.
- Impacts on acidic and saline wash-off from soils into wetlands require more study.
- A lack of knowledge between what is happening on the landscape at paddock level and the quality of the aquatic environment is evident.

Conclusions

The comments from researchers and managers in the north of the state indicate that although there are a number of people with considerable expertise in the area, many information gaps still exist in relation to wetlands. In the Townsville area many projects on wetlands are just starting up, and these projects may partially address some of the knowledge gaps that have been highlighted by interview participants.

Appendix 2:

Draft report on workshop held as a component of the project Understanding Queensland's Wetlands: Literature review and gap analysis, held in Brisbane on 22 August 2005

Background

As part of the project Understanding Queensland's Wetlands: Information review and gap analysis, it was initially proposed that three scoping and gap analysis workshops would be conducted in Townsville, Rockhampton and Toowoomba. It was decided to hold another workshop in Brisbane, as the south-east region is a priority area in this study, and also because many people involved in wetland management and research in other areas are based in Brisbane. This report is a summary of the comments made at this workshop.

In addition to workshops, the project officer has been in touch with a number of other individuals to collate literature and other information for inclusion in the final products. These discussions are not included as part of this report.

List of participants

- Brian Stockwell, Principal Catchment Ecologist, South East Region, Department of Primary Industries and Fisheries (DPI&F)
- Thorsten Mosisch, Healthy Waterways
- Lana Hendon, Coordinator Wetlands Package, Coastal CRC
- Mike Ronan, Principal Planning Officer, Environmental Protection Agency (EPA)
- Jon Marshall, Scientist, Aquatic Ecosystem Health, Department of Natural Resources and Water (DNR&W)
- Glenn McGregor, Scientist, Aquatic Ecosystem Health, DNR&W
- David Moffatt, Senior Scientist, Aquatic Ecosystem Health, DNR&W
- Bernie Powell, Principal Scientist, Land Science and Regions, DNR&W
- Shon Schooler, Research Scientist, CSIRO Entomology
- Arthur Knight, Senior Biodiversity Planning Officer (Wetlands), EPA
- Marion Saunders, Senior Conservation Officer, EPA
- Glen Moller, Senior Scientist, Aquatic Ecosystem Health, DNR&W
- Peter Negus, Myriam Raymond and Louisa Davis, Water Quality Processes, DNR&W (Workshop organisers).

Workshop format

The topics for discussion at the workshop are shown in Box 1. Due to the diversity of interests and experience of the participants, the format was used as a guide and the workshop was modified to suit the experience and interests of the group.

In particular, issues were raised by the participants regarding the scope of the project, which the participants felt was too broad; and that they felt unable to discuss wetlands as a whole, and thought that the discussion should be based around different wetland types.

These concerns made it difficult to follow the proposed format. The approach taken after some discussion was to list the different geographical areas in south-east Queensland, the wetland types associated with these areas, and the work that had been undertaken on them.

Discussion also focused on general gaps in wetland research. This approach has the potential to generate more discussion and a modified version of this format will be conducted at Rockhampton and Toowoomba.

Box One: Proposed topics of discussion for the Brisbane Workshop

1. Presentations;

- Overview of the Queensland Wetlands Program
- Aims and scope of literature review and gap analysis project

2. Group Discussion: Topics to include;

- Wetland Function
    - o What do we know about how wetlands function, difference with wetland types;
    - o What are the gaps in our understanding of how wetlands function
- Wetland Landscape processes and ecosystem processes
    - o What role do wetlands play in improving downstream quality? What are the risks associated with this process for wetland ecosystems?
    - o What role do wetlands play in other landscape processes/ecosystem services?
    - o What types of wetlands perform these functions, are there differences between wetland types?
- Restoration/ Construction of wetlands
    - o Restoration: what are the most important factors to consider when restoring a wetland and how can these be incorporated into design features?
    - o Can wetlands be designed to meet multiple objectives? (ie downstream water quality improvement and maintenance of biodiversity)
- Assessments of ecosystem health
    - o What programs exist to assess the health of wetlands, especially in the South East? Frequency of assessment?
- Monitoring of wetlands
    - o Are wetlands in the area monitored?
    - o If so who does it, how are they monitored and what is the timing?
- Current or future Projects
    - o List of projects that are currently being undertaken or likely to start in next 12 months.?
- What are most important knowledge gaps, what sort of research is needed to address these?

Discussion:

General points raised

- That the definition of wetlands is too broad. Some participants were of the opinion that the term ‘wetlands’ is fine for policy documents, but in terms of understanding these ecosystems, they operate in many different ways, so discussing wetland function as a whole is not appropriate.
- Largely due to the problem with wetland definition some participants felt that the scope and objectives of the project were too broad and unmanageable. Questions arose on whether the project was to include floodplains, riparian areas and seasonal (as opposed to ephemeral) rivers.

Projects and contacts on wetlands in different geographical areas in Queensland

Island wetlands

The wetlands found on the sand islands off the coast of Queensland have biological characteristics and water chemistry that are extremely variable and there are many different types of lakes. Also, many island wetlands are oligotrophic, which is important in terms of impacts.

- People to contact and studies done in the area include:
    - o fish studies on Fraser Island, Angela Arthington and Chris Marshall, Griffith University (GU and DNR&W)
    - o Wade Hadwen, GU; completed his thesis plus papers on Fraser Island freshwater lakes
    - o wet heath studies conducted by Clifford and Specht 1979 (see *The Vegetation of North Stradbroke Island*, University of Queensland Press)
    - o sand mining companies may have information; contact the environmental officer for sand mining at Kingfisher Bay
    - o studies on frogs on islands as many are endemic, Greg Miller, EPA

- councils with islands in their area may have information, for example the environmental officer, Dunwich (North Stradbroke Island, Redlands Shire Council)
- Mal Cox, Queensland University of Technology, has done some work on islands
- Land Resource Assessments, DNR&W, have information about location, soils and some vegetation of wetlands.

Coastal wetlands

- People to contact and studies done in the area include:
  - Coastal CRC, in urbanised south-east Queensland, coastal wetlands (Lake Coombabah)
  - Moggill Office, EPA (55 Priors Pocket Rd, Moggill), contact Harry Hines
  - Dr Jean Marc Hero (ecology amphibians and reptiles); Rod Conolly (saltmarshes), GU
  - Peter Mackay, Bull Island Mangrove Productivity Masters, through Norm Duke. Sewerage outflows to mangroves (Cooloola Shire)
  - local councils may have information, for example Gold Coast, Peter Owen. Brisbane City Council Management Plans have information on indicator species for wetland areas; people to contact are Stacey McLean, Lee Slater, Andy Stevens and Peter Owen, Geological Services Brisbane City Council
  - Land Resource Assessments, DNR&W, have some information about location, soils and some vegetation of wetlands
  - DPI&F work on ponded pastures, Stuart Hyland report: The impacts of ponded pastures on barramundi and other finfish populations in tropical coastal wetlands
  - Fiona Manson, PhD on refugia in fisheries. Title: Mangroves and fisheries: are there links between coastal habitats and fisheries production?
  - WQSIP WQ06 biota with increasing levels of salinity and turbidity
  - northern New South Wales is using wetlands for filtering of intensive livestock effluent filtering
  - economics of wetlands, Beth Clouston, Coastal CRC; Tor Hundloe, Geoff MacDonald, cane lowlands; Jackie Robinson, Coastal CRC.

Inland wetlands

These also include semi-arid/arid wetlands as well as those in south-east Queensland, as some of the workshop participants had expertise in these areas.

The types of inland wetlands discussed included perched wetlands, farm dams, weirs/dams, sediment traps, floodplain wetlands, swamps and lakes. In the inland areas, there are salinity gradients in inland wetlands. A range of types exist based on salinity. Also, there are groundwater and surface water wetlands. Some wetlands are known to be one or the other but in other cases the distinction is not as clear.

- People to contact and studies done in the area include:
  - Brian Timms (University of Newcastle) has done a number of studies in the Paroo and other inland catchments
  - Dave Moffatt has undertaken wetland mapping and inventory in Murray-Darling Basin (present at workshop). Also has biological data for many lakes
  - Lake Broadwater, some information around (Darling Downs, natural occurring lake)
  - Logan/Albert water resource planning process (Also Carbrook wetlands in that area)
  - Condamine Balonne Water Allocation and Management Plan (WAMP), plus other WAMP reports
  - Rob McCosker (Landmax Consultants), environmental scans of Border Rivers and Condamine Balonne
  - Martin Thoms and staff (Narran Lakes, among other studies of Macintyre, Condamine-Balonne, Cooper, etc)
  - internal Sunwater reports
  - SE Water has grey reports relating to farm dams, mostly about water quality and algal problems

- South African research: building block approach
- bird studies in lakes, Richard Kingsford (University of New South Wales); Roger Jaensch (Wetlands International)
- DPI Fisheries, Michael Hutchison, Deception Bay
- The State of Rivers reports have data available where wetlands occur in area that was studied (Glen Moller, DNR&W, present at workshop)
- Baffle Marika Johnston, see Burnett Mary Regional Group
- thermal springs have a high degree of endemism (Helen Byers),
- GAB springs, EPA, Rod Fensham
- study of boggo mosses in Dawson catchment in relation to the impact of Nathan Dam
- Echidna Creek reports on riparian functions (CRCCH, in DNR&W library)
- Andrew Moser Water Services, DNR&W, Bundaberg area
- Keith Hughes, Groundwater dependency of wetlands: study undertaken in a drought found that in the drought groundwater driven wetlands were growing (not found as part of this study)
- Land Resource Assessments, DNR&W, have some information about location, soils and some vegetation of wetlands.

Monitoring/management/restoration

- community estuarine monitoring for wetlands like Boondall, DNR&W, south-east Queensland coast care
- Ecosystem Health Monitoring Program (EHMP) (in-stream)
- an information/management gap for wetlands is systematic monitoring; because of this, the extent of modification of wetlands is unknown
- monitoring is a management tool; sometimes monitoring or condition assessment is the only management being done
- Water Resource Plan monitoring may include some wetlands, in Murray-Darling Basin and Lake Eyre, and waterholes may be monitored
- Ambient Baseline Monitoring group says some sites may have been sampled, mostly in-stream
- Streams and Estuaries Assessment Program (SEAP) has so far not included wetlands, but they need to be included within this framework to ensure consistency. This is a recommended project
- environmental flows program, assets identified by the regions and AEH (see Jon Marshall); some problems with identifying wetlands as assets as there is not enough information on individual wetlands, and many that have value are artificial
- management is defined on values or as assets; management for multiple objectives is needed and achievable
- the term ‘wetlands’ is too generic to discuss biological indicators, as they are too diverse to have a broad scale implementation; better to look at these within groups of wetlands.

Knowledge gaps

- systematic monitoring of wetlands (mentioned in earlier section); some discussion that this should tie in with other water monitoring programs, in particular Stream and Estuary Assessment Program (SEAP)
- carbon sequestration capability. This is not quantified for wetlands. Some research has been done by Australian Institute of Marine Sciences (AIMS) (mangroves); however, there is no knowledge for other types of wetlands. The variability of the system in terms of carbon storage is also unknown
- groundwater-surface water interaction/ connectivity in wetlands. How important is it? Over the entire system there is a need for a better understanding of groundwater
- the role of wetlands as water quality buffers needs more research in terms of:
  - possible impacts that this use may have on the wetland ecosystem. Some research has been undertaken on thresholds to maintain health of wetlands, but more is needed. Also, thresholds will depend on wetland type, for example some wetlands are oligotrophic
  - wetlands as water quality filters in diffuse agricultural settings. Also, there are age issues with wetlands as nutrient filters

- What is best management practice for wetlands? (also see River Management Conference proceedings for phosphorus study)
- the effect of wetland size has not been quantified for many of the ecosystem services
- research on the cost of rehabilitation versus protection needs to be completed, as rehabilitation can be very expensive
- hydrology of wetlands:
    - o for environmental flows for wetlands, quantification of how much water a wetland needs. New South Wales Wetland Recovery Project is buying $15 m water for wetlands, in particular the Macquarie Marshes and Gwydir Wetlands; some research into environmental flows for wetlands. In terms of environmental flows for wetlands in Queensland, there may be some in WAMP reports.
    - o for hydrological models, there is a problem with the quality of data; the science is not there to back modelling up, and the theory is not backed up by real data; issue of quality of science and data
- the impacts of grazing on wetlands, in particular what grazing regimes are appropriate. In some areas, (north) there is evidence that grazing is crucial to controlling weeds; also in other places there is a reliance on wetlands for drought fodder. Research should be concentrated on appropriate gazing regimes and the sensitivity of different wetlands to grazing. Previous work to build on from WetlandCare Australia, ACTFR, CSIRO and DPI&F
- in general, not enough information about appropriate fire regimes in wetlands or their effect on biodiversity. Some work will be available through QPWS, Townsville Common study (CSIRO/EPA) and Northern Territory (ERISS)
- aquatic weeds are a research gap as only anecdotal evidence exists of the impacts occurring in wetlands; some work done in rivers. Current projects looking at riparian vegetation, for example effects on macrophytes and invertebrates. CSIRO project on the evapotranspiration of large infestations in rivers
- research is needed into aquatic plants that are good for nutrient removal. Also, aquatic plants can be used to identify values of specific wetlands quickly. May be a field guide for interpretation
- methodology is needed to rapidly identify all ecosystem services that a wetland will provide if these aquatic plant-based values are to be used to apply values to wetlands
- science communication problems. Values of wetlands need to be communicated to farmers
- more research is needed into the economics of wetland management
- acid sulphate soils:
    - o intensive development pressure is where more information is needed
    - o also, inland forms associated with salinity are unknown in Queensland
    - o management strategies/guidelines need more work
    - what types of fish rely on wetlands is a gap, especially floodplain wetlands in south-east Queensland
    - in arid zones refugia values have been identified, but how many are needed to fulfil this role is unknown
    - more studies are needed on the environmental history of wetlands. These studies give details of how much a wetland has changed over time. Also, information on successional history. Ralph Dowling, EPA, Sunshine Coast Succession study. Some work done on Boobera Lagoon, northern New South Wales
    - oral history projects would help in the accumulation of anecdotal evidence about wetlands, for example history within indigenous communities. One such study was done by Ian McNiven, PhD thesis, Prehistoric Aboriginal Settlement and Subsistence in the Cooloola Region, Coastal South-east Queensland
    - mangrove management for fisheries needs more research.

Conclusions

This workshop highlighted some of the difficulties in discussing and reviewing wetlands due to the number of ecosystems a term such as ‘wetlands’ encompasses. It also highlighted a number of areas with significant gaps in knowledge relating to wetlands.

Appendix 3:

Draft report on a workshop held as a component of the project Understanding Queensland's Wetlands: Literature review and gap analysis, in Rockhampton on 22 September 2005

Background

As part of the project Understanding Queensland's Wetlands: Information Review and Gap Analysis, it was initially proposed that three scoping and gap analysis workshops would be conducted in Townsville, Rockhampton and Toowoomba. This report is a summary of the comments made at the workshop held in Rockhampton.

In addition to workshops the project officer has been in telephone and email contact with a number of other individuals to collate literature and other information for inclusion in the final products. These discussions are not included as part of this report.

List of participants

- Don Cook, Senior Principal Biodiversity Planning Officer, Environmental Protection Authority (EPA)
- Kylie Joyce, Senior Conservation Officer, EPA
- Peter Stafford, Leader Marine Ecology Program, Central Queensland University
- Jeanie Heaslop, Fitzroy Basin Association
- John McCabe, Extension Officer, EPA
- Richard Stewart, Fisheries Biologist, DPI&F
- David Hickey, Extension Officer, DPI&F
- Darren Moor, Senior Advisor, DNR&W
- Andrew Baldwin, Fitzroy Basin Association
- Peter Stephen, Fisheries Technician, DPI&F.

Workshop format

The general format of the workshop is shown in Box One. Due to the diversity of interests and experience of the participants, this format was used as a guide and the workshop was modified slightly to suit the experience and interests of the group. The main points of discussion were: projects that were being undertaken into wetlands; gaps in wetland research; restoration of wetlands; monitoring of wetlands and; other contacts in the region. It should be noted that for the purposes of this report, we use the term 'wetlands' throughout, but are only discussing the types of wetlands that this review will be focusing on, which are inland wetlands (not permanent rivers) and estuarine wetlands. Both natural and constructed wetlands have been included.

Box One: Proposed topics of discussion for the Rockhampton Workshop

1. Presentations;

- Overview of the Queensland Wetlands Program
- Aims and scope of literature review and gap analysis project

2. Group Discussion: Topics to include;

- Wetland types within the region
    - o What types of wetlands are there?
    - o Main types of study/ people to contact on each type?
    - o Which wetlands do we have a good understanding of?
    - o Which wetlands don't we have much information on?
- What role do wetlands play in other landscape processes/ecosystem services?
- Restoration/ Construction of wetlands
- What programs exist to assess the health of wetlands in the area?
- Monitoring of wetlands in the area
- A list of the projects that are currently being undertaken, or are likely to start, in next 12 months in the region.
- What are most important knowledge gaps, what sort of research is needed to address these?

Discussion:

Projects and contacts relating to wetland type

Coastal wetlands

Properties of coastal wetlands and management issues listed in this discussion were:

- north of Gladstone there is a narrow strip of mangroves, and extensive mud flats (the Mackay area is a bit different)
- naturally occurring grass-sedge wetlands
- man-made bunds turn once tidal wetlands into freshwater wetlands
- it is possible to get large effects from small hydrological modification, so there is scope for informed manipulation
- grazing coastal wetlands has impacts on water quality
- in drought, the usual regime of reliance on wetlands for grazing for a few months a year has moved to more intensive grazing of salt flats/marshes.

Contacts and projects listed in this discussion were:

- industry funded reports in Calliope River (Gladstone: Peter Saunders)
- DPI&F has not got much on salt flats; DPI&F Gulf nutrient dynamics study
- some bird studies exist
- Norm Duke, CRC Coastal, historical coastlines project
- DPI&F have mapped changes of extent of coastal wetlands
- some monitoring of mangroves in Gladstone
- rehabilitation work on mangroves, Judith Wake, CQU
- ponded pastures contacts, John Grimes and Peter Long, DPI&F
- GLM Package DPI&F: Chris Chilcott and Warrick McGrath
- Peter Stafford submitted bibliography to CRC as part of project.

Inland/riverine wetlands

Properties of riverine wetlands and management issues listed in this discussion were:

- that waterholes and oxbow lakes have varying degrees of permanence; some are permanent, or permanent within 100-year timescale
- a number of stranded oxbow lakes on floodplains exist
- riverine wetlands tend to be on private land; may have remnant vegetation
- there has been rapid change brought about by hymanaece. In the river, this may happen over a few years, and there have not been many studies in this area on the effect of weeds
- some uncertainty about turbidity levels of wetlands (brought about by weeds?) as in last flood flow after the initial flush the river went clear, but in periods of low flow turbidity is more of a problem.

Contacts and projects listed in this discussion were:

- in the Fitzroy, surveys since 1994 on birdlife
- studies in Murray-Darling Basin on repopulation of oxbows
- Marcus Sheaves is running a project, which is looking at processes occurring within coastal pools
- ARIDFLO in west (Lake Eyre Basin)
- Bob Packett/Bob Noble cores on wetlands
- Bill Sawnoch, Sunfish fisheries research
- Shoalwater Inquiry report; many volumes published
- fish in riverine wetlands, Peter Long, DPI&F
- impacts of tourism; Desert Channels NRM
- in Emerald area, integrated area wide management monitoring of irrigation (may have some information)
- EIS' of major developments in area; may have some information
- Horseshoe Lagoon project with coastal wetlands program
- Dr Larelle Fabbro, Central Queensland University in Rockhampton; studies on algae management

- Browyn Masters, DNR&W, community sediment monitoring
- Mackay, long-term monitoring, DNR&W
- stormwater: Mackay coastal wetland city council plan.

Inland lacustrine

Properties of inland wetlands and management issues listed in this discussion were:

- most heavily impacted broad-based floodplain wetlands
- weeds are a problem in these landscapes
- lakes, saline and fresh, with differing degrees of permanence in area
- where wetlands dry out, that's important as it removes algae; also when drying there is a huge surge in productivity
- roads and other structures can lead to hydrological isolation
- artificial wetlands can be a good habitat; however, main problem is that they do not remain stable long; over 10 years or so some really good fringing vegetation or riparian vegetation can develop, but then it tends all to be lost when dam level raised etc.

Contacts and projects listed in this discussion were:

- Richard Kingsford study on the Macquarie Marshes; used to have waterbirds breeding two years out of three; no longer the case because of water abstraction
- WaterWise CD for Cooper Creek is a good resource
- Fitzroy Basin Association (FBA): exploratory idea of similar project to WaterWise CD for Fitzroy
- Directory of Important Wetlands has some information
- Sunwater @ Fairburn
- Sunwater concerned with fish passage at Clare Weir etc.

Palustrine wetlands

Properties of riverine wetlands and management issues listed in this discussion were:

- wet heaths: low nutrient systems; changes in nutrient regime has led to changes in ecosystem, that is, rushes around edges from eutrophication
- *Melaleuca* wetlands: weed invasion is a problem; weeds were not able to invade in wet conditions; however, now wetlands are dry they have invaded; this is a problem as *Melaleuca* germinate in dry, so weeds are outcompeting seedlings.

Contacts and projects listed in this discussion were:

- see studies on Tweed and Clarence in New South Wales
- GLM package, focusing on ephemeral wetlands
- National Parks and Wildlife staff in different bioregions have information on fire regimes and management
- proposal for cotton on Cooper Creek resulted in some studies
- data sets: rabbit virus work in Moncoonie Lake and Diamentia Lake; also Bulloo Dams, Robert Wicks Research Centre
- Australian locus studies.

How wetlands function

- Kel Roberts: DNR&W, Fitzroy River WAMP. Commence to flow data for wetlands in system. In general this information is not well known or documented
- grazing regimes need more work; understand broad principles, but more work is needed. Townsville Common Study is currently in progress (CSIRO/EPA)
- broad threats understood, but how these affect any individual wetland type is not known
- what is there might be good, but do not know what is meant to be there (i.e. is broad scale wetland change occurring?)
- natural processes may in some areas no longer be useful. In modified areas we may have to decide what type of wetlands we want.

Ecosystem services

Some issues raised by participants at the workshop were:

- For most ecosystem services we know that wetlands do provide them in general terms, but quantification of these services is poor, as is our understanding of what processes affect a wetland's ability to perform these functions.
- Often opinions are contradictory. For example with riparian planting in rivers, some say that it is essential, others that it is unnecessary.
- An important management point often overlooked is that you have to remove plants out of the system for total nutrient removal; see Margaret Greenway and Keith Boulton (Byron Shire / Southern Cross University).

Contacts and projects listed in this discussion were:

- Dee River CQU: wetlands used for mine tailings
- Lake Alistair: cyanobacteria, Narrelle Fabbro (CQU) 50–60 years
- CSIRO Burdekin is fencing riparian areas
- Bob Noble and Bob Packett, DNR&W
- groundwater recharge: Calliope groundwater map
- Leo Divenoon, Calliope Valley, irrigation recharge
- DNR&W, quality of groundwater under irrigation, Ed Donohue
- Richard Kingsford, University of New South Wales, wildlife biodiversity
- agricultural: study on diffuse sources by CSIRO in Burdekin
- Lagoon systems, Alf Hogan, DPI&F (report in progress)
- pilot wetlands in cane areas (no monitoring)
- recreation study: how state lands are managed, DNR&W, Brisbane.

Monitoring

Some issues raised by participants at the workshop were:

- assessments need redoing to check data variability in wetlands and the cycle of change
- the question your asking and what information you want largely determines the type of monitoring that you do
- apart from water monitoring / gauging network, regular monitoring of issues doesn't take place unless a big issue or problem occurs
- Pygmy Goose (vulnerable) species that is sensitive to water quality, so it is a good indicator species.

Contacts and projects listed in this discussion were:

- Vicky Shearer, freshwater ecologist with CQU, Gladstone. Has been involved in monitoring
- Wayne Houston, does some monitoring
- long-term monitoring of birds at the airport and Murray Lagoon.

Creation/restoration/rehabilitation

- A question that arises is that even when wetlands are created, why won't species use them?
- There is the potential for conflict between water quality objectives and biodiversity.
- Guidelines do exist for components of the system, for example construction guidelines exist for fish passage and ponded pastures.
- There is an issue with interdepartmental policy needing legislative change.
- Education is an issue even within government departments, for example Main Roads is starting to liaise with Fisheries regarding fish passage through culverts.
- Some good information gets lost, for example Brisbane City Council natural channel design manual is no longer readily available.
- Fisheries Act requires waterway works not to have fish barriers to connectivity; however, this is only for a defined watercourse, not overland flow.

Projects in area next 12 months or so

- FBA
  - stormwater infrastructure with coastal shire councils
  - Bill Sawnock: key barriers to fish movement
  - coral to coast
  - Reef coastal wetland program
  - rapid assessments
  - draft project Broadsound joint program
  - Incentives program
- DPI&F
  - coastal wetland fish movement issues
  - Alf Hogan created wetlands; if outcomes are good may do some around Mackay
  - Coastal grazing systems, in particular ponded pastures (just starting)
  - Grazing Land Management wetland component will start soon; will also be looking at ephemeral wetlands
- Mackay WhItsunday's Regional Group
  - coastal planning, which will include wetlands; may also include Fitzroy; focus will be on water quality and incentives/ paddock monitoring
  - recovery plan for Yellow Chat
  - EPA marine couch monitoring on Curtis Island
  - Emerald Theodore Irrigation Area (Integrated Area Wide Management)
  - Incentive work in Mackay/Desert Channels
- Rockhampton City Council
  - Murray Lagoon: research funds for university study to look at filling with recycled water
  - Gladstone wetland: looking at setting up a field-based research area.

Knowledge gaps

- large problem is that knowledge is not broadly enough distributed (i.e. a communication gap)
- quantification of the benefits of having good biodiversity
- fish role as nutrient sink; can they be used for nutrient reduction
- fish ladders for different species
- weeds:
  - research on Parthenium. Pasture management. Best practice is known but not adhered too (communication issue)
  - control of *Hymenachne*. Currently controls are mostly chemical, which is not so good for wet areas. Also look at finding replacement species for ponded pastures
- in some cases wetlands are grazed and are still in good health; a worthwile study would be using this case study to find out why this is the situation (i.e. what is going right in these cases that is not happening elsewhere?)
- best management practices for wetlands of different types need to be developed
- oral history to document changes in wetlands (ties in with photo project at ACTFR)
- impacts of bore capping on GAB
- anecdotal information on wetlands may be important for maintenance of groundwater. Groundwater information gap in general terms
- values of tidal salt flats; impacts on them and what are the carbon outputs into marine system is not known
- gap in knowledge about the type of information needed to manage wetlands in different settings, that is, agricultural urban industrial
- refugia in arid zones; more survey work needed
- impacts on wetlands if used as water quality filters; also thresholds of different wetlands to increased nutrients and pollutants
- tidal incurrence: impacts of freshwater on coastal systems
- broad threats understood, but how these affect any individual wetland types is not known
- what is there might be good, but do not know what is meant to be there (i.e. is broad scale wetland change occurring? e.g. wet heaths are low nutrient systems, and change in nutrient regime has lead to changes, that is, rushes around edges from eutrophication).

Appendix 4:

Draft report on workshop held as a component of the project Understanding Queensland's Wetlands: Literature Review and Gap Analysis, in Toowoomba on 4 October 2005

Background

As part of the project Understanding Queensland's Wetlands: Information Review and Gap Analysis, it was initially proposed that three scoping and gap analysis workshops would be conducted in Townsville, Rockhampton and Toowoomba. This report is a summary of the comments made at the workshop held in Toowoomba.

In addition to workshops, the project officer has been in telephone and email contact with a number of other individuals to collate literature and other information for inclusion into the final products. These discussions are not included as part of this report

List of participants

- Janey Adams, Community Scientist, Northern Basin Laboratories, Goondiwindi (now with Griffith University)
- Geoff Titmarsh, Principal Natural Resource Officer, Land and Community Sciences, DNR&W, Toowoomba
- Charles Ellway, Senior Planning Officer, Water Services, DNR&W, Toowoomba
- Tariq Khan, Aquatic Scientist, Land and Community Sciences, DNR&W, Goondiwindi
- Kate Reardon-Smith (PhD candidate), University of Southern Queensland
- Gavin Prentice, Queensland Murray Darling Catchment Committee, Toowoomba
- Plaxy Barratt, Queensland Murray Darling Catchment Committee, Toowoomba
- Paul Clayton, EPA, Toowoomba.

Workshop format

The general format of the workshop is shown in Box One. Due to the diversity of interests and experience of the participants, this format was used as a guide and the workshop was modified slightly to suit the experience and interests of the group. The main points of discussion were: projects that were being undertaken into wetlands; gaps in wetland research; restoration of wetlands; monitoring of wetlands and; other contacts in the region. It should be noted that for the purposes of this report, we use the term 'wetlands' throughout, but are only discussing the types of wetlands that this review will be focusing on, which are inland wetlands (not permanent rivers) and estuarine wetlands. Both natural and constructed wetlands have been included.

Box One: Proposed topics of discussion for the Toowoomba Workshop

1. Presentations;

- Overview of the Queensland Wetlands Program
- Aims and scope of literature review and gap analysis project

2. Group Discussion: Topics to include;

- Wetland types within the region
  - What types of wetlands are there?
  - Main types of study/ people to contact on each type?
  - Which wetlands do we have a good understanding of?
  - Which wetlands don't we have much information on?
- What role do wetlands play in other landscape processes/ecosystem services?
- Restoration/ Construction of wetlands
- What programs exist to assess the health of wetlands in the area?
- Monitoring of wetlands in the area
- A list of the projects that are currently being undertaken, or are kely to start, in next 12 months in the region.
- What are most important knowledge gaps, what sort of research is needed to address these?

Discussion:

Current and past projects of the different organisations represented at the workshop relating to wetlands

Toowoomba NRM staff

- Resource Operations Plan (ROP) monitoring program. Within ROP, planning waterholes are listed as an area for knowledge improvement
- Sustainable Rivers Audit (SRA), see MDBC
- Surface Water Monitoring Program, Queensland Murray-Darling Basin and little bit of Lake Eyre
- waterholes: some work already undertaken as part of the Dryland Refugia project (CRCFE); also as part of ROP there will be more work on these as part of environmental assets program (no water storages as part of this process, but weir pools may be selected)
- previous work by David Moffatt and Cath Thrupp on wetlands in Queensland Murray-Darling Basin (Report: The Ecological Condition of Floodplain Wetlands in the Queensland Murray Darling Basin)

Northern Basin Laboratory (now part of Griffith university)

- was funded through a joint venture with the CRC for Freshwater Ecology and the Murray Darling Basin Committee to foster research in this area. This laboratory is in the process of wrapping up operations
- laboratory staff have been working on the CRC Freshwater Ecology project and on Narran Lakes projects (hydrological connections among other things). Contact Martin Thoms
- Martin Thoms's team (University of Canberra) is also undertaking a land and water funded project to map wetlands in Border Rivers; also collecting food web data. The aim is to look at spatial arrangement and processes, to see if there are groups of wetlands that stand out from others, as they may need special protection. As part of this study the team will also be calculating commence-to-flow values for wetlands. Mike Reid is the contact who is a postdoc at the University of Canberra, working with Martin Thoms
- Freshwater Ecology Gaps workshop conducted when the northern laboratories started up. Janey Adams to send a copy.

The University of Southern Queensland

The main work being undertaken on wetlands in the university is a PhD undertaken by Kate Reardon-Smith:

- Kate's PhD is tilted: Vegetation community responses to altered flow regimes and weed invasion in riparian woodlands of the Upper Condamine Floodplain, eastern Australia

Toowoomba staff, EPA

- largest program is the wetlands mapping and classification project
- valuing exercise non-social and economic; will develop an environmental decision support tool which, once set up, others can add social and economic values too
- developing AQUABAMM pilot in Burnett, currently for in-stream processes, but are also thinking of modification for wetlands in the future
- management guidelines to link in with wetland profiles, but at a smaller scale; currently project is focusing on the Condamine catchment.

Queensland Murray Darling Basin Committee (regional body)

- have a wetland management manual (Gavin Prentice to send a copy), which was developed for them by World Wildlife Fund, sent to EPA and Murray-Darling Bason laboratories for comment. Builds on the work that David Moffatt *et al*. did on wetlands
- assisting shires in the Border Rivers with camping reserves on the river network
- also assisting landholders with rivers restoration/ rehabilitation projects
- in the next 12–18 months, looking to move into more work on wetlands
- workshop some years ago looking at proposal to base a freshwater ecology centre in northern Murray-Darling Basin. Geoff Titmarsh (DNR&W) has sent a copy.

Wetland types, and projects undertaken on them

Riverine wetlands

- probably most information about these wetlands, but they are still largely ignored in non-technical areas as they do not fit the traditional view of what a wetland is
- studies: Dryland Refugia, CRCFE (largely in-stream waterholes)
- fencing projects with landholders
- an issue for landholders is the dense regrowth in gullies; since nothing lives under this dense canopy, they are a source of sediment to river
- trees for fish project.

Lacustrine wetlands

- naturally few lakes exist in the area; Lake Broadwater and the lakes at Currawinya are the main ones
- a number of artificial and modified natural lacustrine wetlands exist, for example Lake Coby, ring tanks, etc.
- a PhD project is currently underway (1st year) on whether ring tanks provide biodiversity, Griffith University, Susie Lott
- Information on Lake Broadwater from local wildlife group; alternatively, local QNPWS (Wampo Shire), James Haig
- Currawinya information, Roma QWPS office.

Palustrine wetlands

- Margaret Brock has done studies on terminal wetlands in New South Wales
- studies on Narran Lakes (number of different types of wetlands); not much published yet, but a couple of articles were published in the 4th Australian Stream Management Conference
- Lower Balonne scoping study: joint venture; speak to Marietta Woods, Dubbo DNR&W
- Neil Foster, DNR&W is a good contact in New South Wales (Tamworth)
- Richard Kingsford's WISE website.

Monitoring of wetlands

Riverine wetlands

- surface water program in-stream only, which has mostly flow, but also a little bit of water quality data
- salinity monitoring, which is in-stream only
- Smart Rivers (private group of irrigators) have a monitoring program in place for rivers and other wetlands. Monitoring is undertaken by Lee Benson and looks at ecological functioning. Probably the only ecologically based project in the region. Reports are on website (see smartrivers.com)
- water quality monitoring in the Balonne
- Sustainable Rivers Audit in-stream monitoring
- some work done on fish by David Moffatt (DNR&W)
- DPI&F long-term fisheries monitoring project.

Lacustrine wetlands

- In artificial lakes there has been monitoring of fish and blue-green algae. Sunwater will have that information.

Palustrine wetlands

- no monitoring of these systems, although photo point monitoring has been set up by QMDBC at a couple of places; also some work on biodiversity in the Gondal Basin, and they are interested in starting more of this type of work.

Restoration of wetlands

QMDBC: how-to information is usually collated and held in people's heads, and then expert opinion from EPA and DNR&W is sought; no documented procedure yet, but this may happen.

Knowledge gaps

- lack of information on wetlands, for example with the assessment and decision support project (EPA) an appropriate spatial unit has to be selected, but whatever unit is decided upon, much of the data (or answers to questions) is not available for many units, for example if looking at flow modification from natural, this information only exists for in-trunk streams. There are things in this process that we think are important, but they have been left out, as the information does not exist
- fish passage areas: where are the connections in the landscape?
- underlying drainage network is a large gap for the management of all wetlands. There is no definitive 1:100,000 drainage layer. Best layer is one provided by DNR&W, but this is not accurate enough
- basic gap in knowledge is what types of wetlands exist in this area; for some like Lake Broadwater there will be information, but for most others not really. This will be filled in to a large degree by the mapping and classification project
- buffer widths for all wetland types are basically an unknown; this has been often discussed in the past, but the widths used are basically a best guess, and have not been looked at in terms of what is actually needed. This has implications for clearing and fencing projects. Also at what stream order do you stop this requirement, and as many gullies feed into streams, which ones should have riparian widths?
- management problem: when catchment is shared with neighbouring states, management and knowledge of the whole catchment is not possible as all data stops at the border
- how the groundwater/surface water interaction impacts on ecology of wetlands. Should talk to groundwater people as they have a good understanding of groundwater movement. Dave Free, DNR&W; Des McGarry, Leon Leach, NRS. Also, a workshop has been held in this area for target setting on groundwater dependent ecosystems
- in regard to providing incentives for the management of wetlands, information on costs and benefits of better management are hard to find. Costs such as fencing are easy, but valuing the benefits of doing these things are not; the benefits of protection and rehabilitation need to be better quantified.

Conclusions

Discussions undertaken at Toowoomba highlight that while a number of projects have been undertaken relating to wetlands, spatial and other information on wetlands is lacking. The EPA's Mapping and Classification project will document where and what types of wetlands are in the area, but the character of some types of wetlands is still largely unknown.

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