ENVIRONMENTAL WATER REQUIREMENTS TO MAINTAIN WETLANDS OF NATIONAL AND INTERNATIONAL IMPORTANCE

FINAL REPORT

Prepared for Environment Australia

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FINAL REPORT

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Front Cover: Manning Lake photographed by Jenny Davis in spring 1999.

EXECUTIVE SUMMARY

- A wide range of human impacts have resulted in changes to wetland water regimes throughout Australia. Regional issues affecting wetland water regimes include river regulation, diversion and abstraction in the Murray-Darling Basin, excessive inundation in the Western Australian wheatbelt and parts of the coastal plain, and aquifer draw-down in the Great Artesian Basin. Specific local impacts which affect wetland water regimes include hydrological alterations associated with urban and agricultural development. Increasingly, decisions must be made regarding the amount, duration and timing of water required to restore aspects of wetland structure and function or prevent further degradation.

- In both Australia and overseas, environmental water allocation has focussed on rivers. Initially the prime motivating concern was improving fish habitat and meeting fish passage requirements. Later, broader issues were considered, such as the maintenance of ecosystem processes. Where wetlands are associated with river systems some attempt has been made to incorporate them into the environmental flow allocation process for the river.

- Wetland environmental water allocation differs from that of rivers in several aspects. Variability of water quantity in wetlands is associated with the presence of habitats of different depths. These habitats are characterised by particular plant and waterbird communities. There is generally a close connection between water quantity and the spatial extent of wetland habitat. While the determination of environmental flows for rivers generally occurs at large scales, with the examination of entire river systems, environmental water allocations for wetlands may sometimes occur at much smaller spatial scales.

- Management of environmental water allocation for wetlands in Australia has mainly focused on wetland systems where the hydrology is altered by water extraction, however the issue of drainage into wetlands and inundation as a result of rising water tables also needs to be addessed. That is, wetlands can have 'too much water' as well as 'too little water'.
- Water regimes of the following wetlands are managed to meet environmental and other objectives. The history of this management is summarised.
  - Macquarie Marshes (north-west NSW).
  - Lower Gwydir Basin Wetlands (northern tablelands of NSW).
  - Kerang Lakes (Victoria).
  - Wetlands of the Lachlan River Valley (southern inland NSW).
  - Lake Merreti and Lake Woolpolool (Chowilla Floodplain, SA)
  - Barmah-Millewa Forest (Victoria-NSW border)
  - Lakes of the Gnangara Mound on the Swan Coastal Plain (WA)
  - Twin Swamps, the Swan Coastal Plain (WA)

  Measures aimed at protecting the water resources of the Great Artesian Basin are also briefly presented. These measures have the effect of protecting mound springs, although generally they are designed to protect the water resource for consumptive use.

- Approaches to determining the environmental water requirements of wetlands can be divided into hydrology-driven and ecology-driven methods. Hydrology-driven approaches involve first the description then the restoration or partial restoration of the historic (pre-disturbance) water regime of the wetland. It is assumed that the biota is adapted to the pre-disturbance water regime and that the restoration of this regime will result in a healthy ecosystem. Ecology-driven approaches involve the determination of the water regime requirements of the existing or preferred biota, and the provision of that regime. Ecology-driven approaches may lead to more defensible allocations than those determined by hydrology-driven approaches. Strengths and weaknesses of both hydrology- and ecology-driven approaches were examined through the use of case studies.

- Invasive species are frequently favoured by alterations to water regimes, although in many instances other factors will also be implicated, for example, disturbance or grazing. Ecology-driven approaches to environmental water allocations may include water management strategies to control invasive species. They may also incorporate measures to protect endangered species or communities.

- A comprehensive ecology-driven method was used for the determination of Environmental Water Requirements and Environmental Water Allocations for the groundwater-fed wetlands of the Gnangara Mound on the Swan Coastal Plain, WA. The water regimes of these wetlands are threatened by groundwater extraction. The hydrology of the wetlands and the water requirements of the wetland vegetation, aquatic invertebrates and waterbirds were examined in targeted research programs. The water regime requirements of vegetation were first examined, with an objective of maintaining the existing distributions. These requirements were then compared with the requirements of aquatic invertebrates and waterbirds, for the determination of Environmental Water Requirements. Individual objectives and Environmental Water Requirements were set for each wetland, reflecting their particular environmental values. This approach has similarities with a methodology developed for the determination of water requirements of the vegetation of floodplain wetlands by Roberts *et al*. (2000). It differs in that the requirements of wetland fauna were examined as well as those of vegetation.

- In practice, determinations of environmental water allocations for wetlands generally depend on an assessment of pre-development and current water regimes, and the effects of altered hydrology on wetland vegetation, due to limitations of knowledge regarding the water requirements of biota. The use of objectives based on identified values and the requirements of wetland biota is likely to provide a high level of defensibility for decisions regarding environmental water allocations.

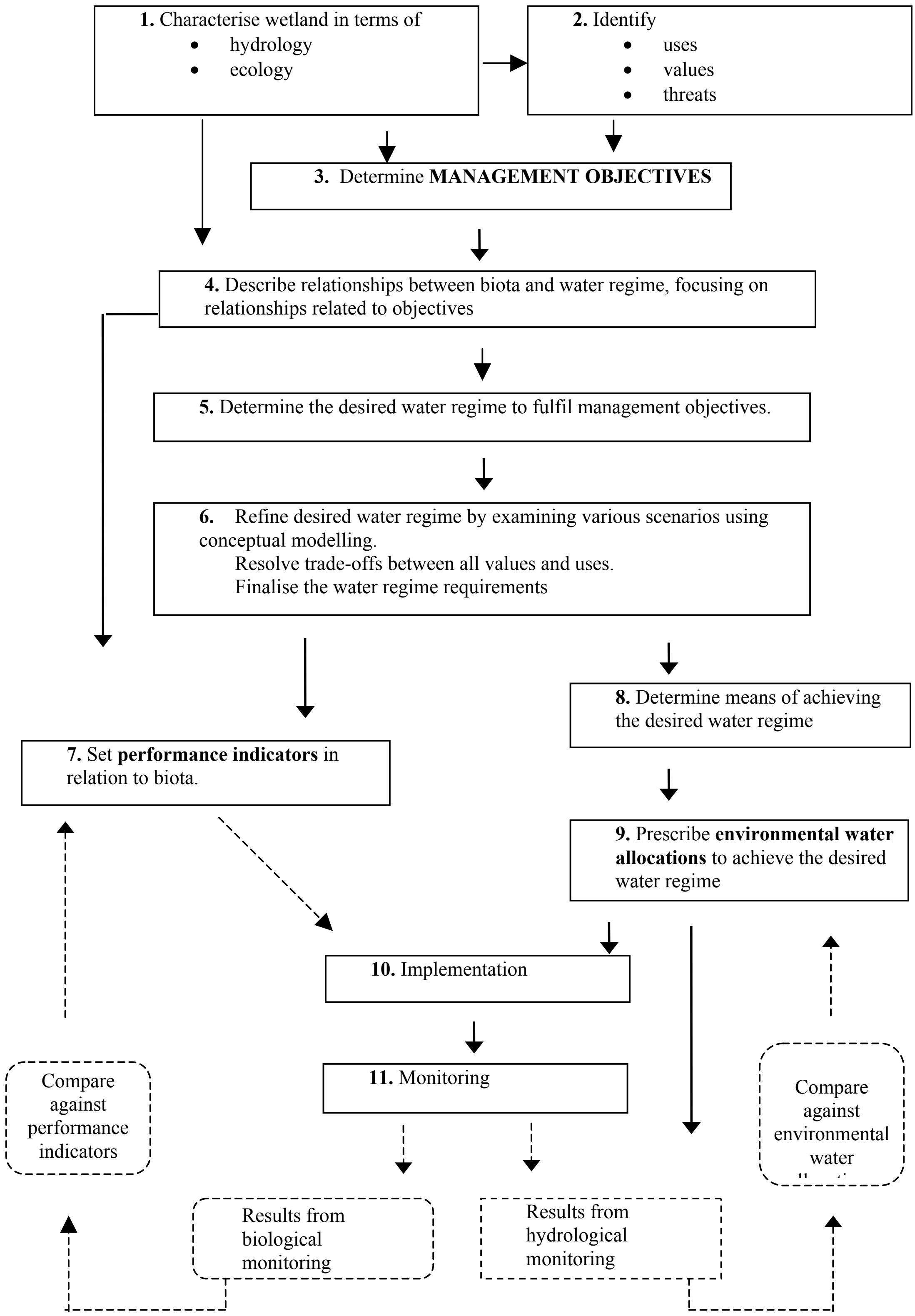
- Australian wetlands are generally characterised by extremely variable water regimes. Natural variations in climate result in variable water regimes both within and between years. Incorporating this variability into the managed water regime is likely to be of greater importance than the maintenance of minimum water levels. Mound spring wetlands are an exception as they are characterised by stable, permanent water regimes.

- This report describes a framework for determining environmental water allocations for wetlands of international and national significance. It incorporates the determination of management objectives based on both hydrological and ecological characteristics of the wetland and the uses, values and threats associated with it. Relationships between the biota and water regime are used to determine the water allocation required to achieve the management objectives. These are refined by using conceptual modelling to examine various scenarios and by considering trade-offs between different values and uses.

The framework was trialed on four wetlands representing different wetland types. These were:

- Thomsons Lake, WA (groundwater dominated). The framework was trialed in most detail at this wetland because of the extensive data available.
- Bool and Hacks Lagoons, SA (floodplain wetland affected by an irrigation scheme).
- Lower Gwydir Wetlands, NSW (a terminal riverine wetland).
- Boggomoss Springs, Qld (artesian springs).

➢ The outcomes of the trials are summarised by the following information. At Thomsons Lake, a Ramsar-listed wetland in south-western Australia, water regime very much influences the extent of shallow water and fringing vegetation, which is important for waterbirds. The water regime is threatened by both groundwater extraction and rising water tables resulting from clearing; these impacts mitigate each other. The water regime of Bool and Hacks Lagoons has been affected by an irrigation scheme, and is now deeper and more permanent. This has adversely affected the health of a stand of *Melaleuca*. The Gwydir wetlands are terminal riverine wetlands affected by upstream abstraction of water for irrigation and other consumptive uses. This has resulted in an overall reduction in water quantity in the wetlands, leading to a change in plant community composition. Boggomoss Springs are artesian springs threatened by aquifer draw-down. Some of the springs are also threatened by flooding from the proposed Nathan Dam.


1. Characterise wetland in terms of
• hydrology
• ecology
2. Identify
• uses
• values
• threats
3. Determine MANAGEMENT OBJECTIVES
4. Describe relationships between biota and water regime, focusing on relationships related to objectives
5. Determine the desired water regime to fulfil management objectives.
6. Refine desired water regime by examining various scenarios using conceptual modelling.
Resolve trade-offs between all values and uses.
Finalise the water regime requirements
7. Set performance indicators in relation to biota.
8. Determine means of achieving the desired water regime
9. Prescribe environmental water allocations to achieve the desired water regime
10. Implementation
11. Monitoring
Compare against performance indicators
Results from biological monitoring
Results from hydrological monitoring
Compare against environmental water

- The presence of physical structures such as dams, weirs, irrigation channels and levee banks may limit the ability to deliver environmental water allocations. Other limitations are related to the relatively large scale of problems, such as rising water tables, and the consumptive demand for water. The ability to determine appropriate water allocations is frequently limited by knowledge regarding both the pre-development water regime and the requirements of biota. Significant opportunities for environmental water allocations exist where abstraction is characterised by a large amount of wastage (eg, unregulated artesian bores) and in isolated wetlands where water regimes may sometimes be manipulated relatively easily.

Acknowledgements

Dr Chris Gippel critically reviewed the manuscript at several stages during its preparation and provided a number of unpublished reports and other publications. The constructive comments of Dr Jane Roberts and Dr Paul Bailey are also gratefully acknowledged. Rod Smith of Birds Australia provided information regarding the waterbirds of Thomsons Lake. Alan Rossow of Murdoch University prepared Figures 1 and 2.

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INTRODUCTION

This project is a component of the National River Health Program, which aims to protect Australia's water resources. It is an adjunct to the research program undertaken by States and Territories and funded by Environment Australia under the Environmental Flows Initiative. This program lies within the policy context of the Council of Australian Governments Water Reform Framework. Important principles directing the Environmental Flows Initiative include:

- environmental flow decisions should be based on sound scientific knowledge
- water resource developments should be ecologically sustainable
- allocations should be reviewed five years after they are allocated
- allocations should be made to allow adjustment of allocations as necessary
- methods for determining environmental flows (for given broad geographic areas or types of environment) should be as consistent as possible throughout the country.

This project, Environmental Water Requirements to Maintain Wetlands of National and International Importance, was concerned with the determination of water requirements for important wetlands with water regimes that are threatened by human impacts. The objectives of this project were:

- to identify those wetlands in Australia of international and national importance that are threatened by current or future changes to flow regime
- to develop a method for determination of appropriate environmental flows that will protect these wetlands against decline in their ecological character

- to identify the practical limitations and opportunities available for implementation of environmental flows to these systems.

For the purposes of this project, wetlands are defined as lentic waters lacking direct surface connection with the sea. Lakes (including seasonal, ephemeral and permanent), marshes, ponds, forested and shrub swamps, inland deltas, peatlands, bogs, springs, rock pools, and subterranean karst wetlands are covered. Wetland aggregations which include wetlands belonging to these categories have been covered by this project. Wetlands listed as Ramsar sites have been identified as being of international importance and have met one or more criteria including representativeness, uniqueness, or significant flora or fauna. In addition, there are specific criteria associated with waterfowl (ANCA, 1996). The *Directory of Important Wetlands* (ANCA, 1996) lists wetlands of national and international significance. A wetland may be deemed nationally significant on the basis of

- being a good regional example of a wetland type,
- its ecological or hydrological role, its role as habitat for fauna at vulnerable life stages,
- its provision of drought refuge for fauna,
- supporting 1% or more of the national population of an animal or plant taxon,
- supporting nationally vulnerable or endangered taxa or communities, or
- its cultural or historic significance (ANCA, 1996).

This report is presented in five chapters. The first identifies Australian wetlands of international and national significance threatened by changes to water regime and presents a summary of threats on a regional basis (Chapter 1). This is followed by a review of the literature on environmental water allocations for wetlands (Chapter 2). The history of water allocations to the

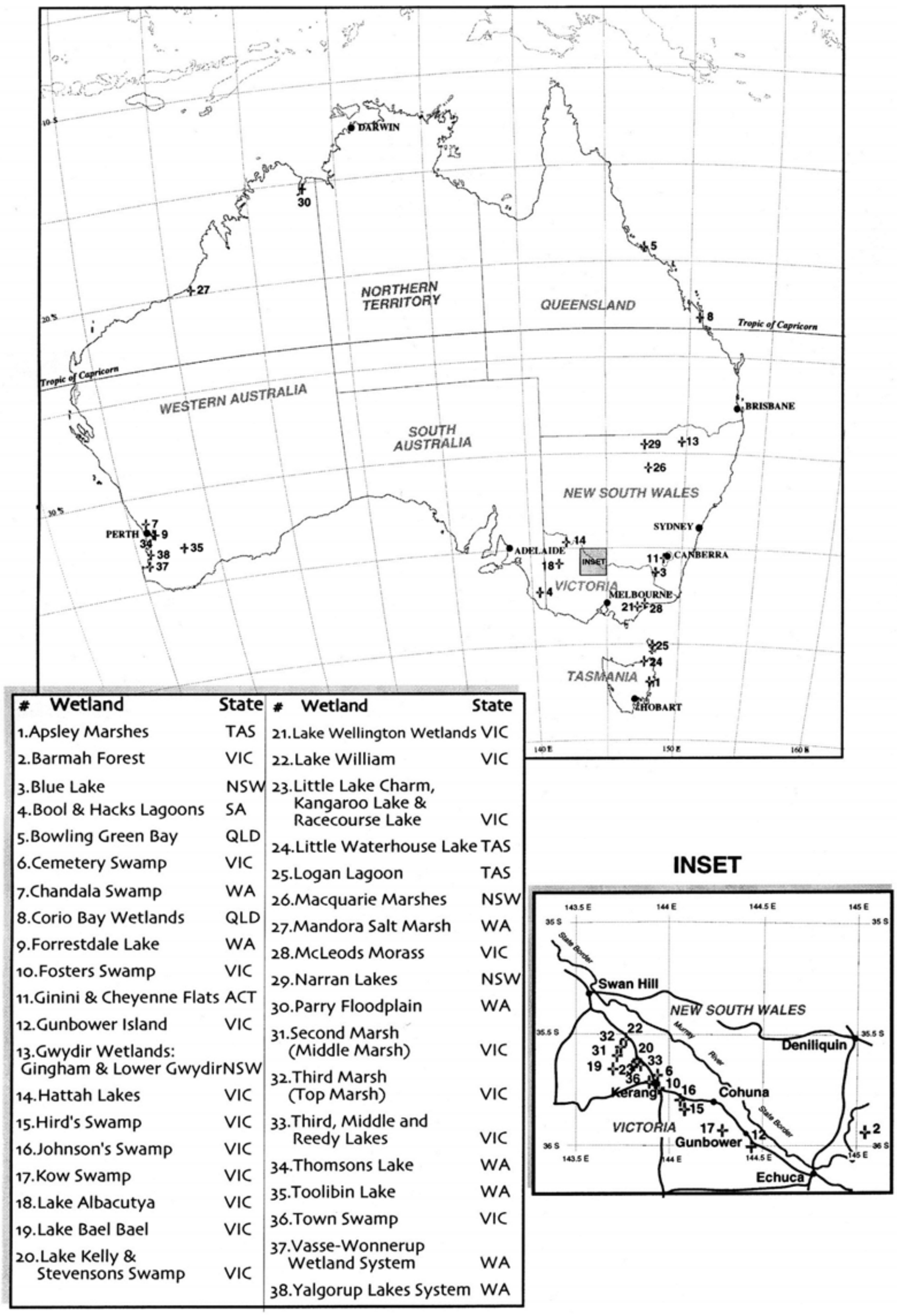
Macquarie Marshes (NSW), the Gwydir wetlands (NSW), Kerang Lakes (Victoria), wetlands of the Lachlan River Valley, Lakes Merreti and Woolpolool of the Chowilla floodplains (SA), the Barmah-Millewa Forests (Victoria/NSW), wetlands of the Gnangara Mound (WA) and Twin Swamps (WA) were examined. In addition, the effects of measures to conserve the water resource of the Great Artesian Basin on mound spring wetlands of this region were examined. This review is followed by a comparison and analysis of various methodologies used for the determination of environmental water allocations for wetlands (Chapter 3). From this a framework was developed (Chapter 4). Finally, opportunities and limitations for environmental water allocations for wetlands were identified (Chapter 5).

1. IDENTIFICATION OF THREATS TO WETLAND WATER REGIMES

Using the Directory of Important Wetlands and internet and library searches, a total of 231 Australian wetlands of national and international importance were identified as having threatened or potentially threatened water regimes. These are listed in Table 1 together with a description of the nature of the threat, and the State and region in which they are located. Of these wetlands, 38 are Ramsar listed; the locations of these are given in Figure 1. The locations of the other wetlands can be found at the Directory of Important Wetlands website (www.ea.gov.au/wetlands).

In the process of identifying important wetlands threatened by potential or existing water regime threats, it was noted that there are regional issues affecting water regimes of Australian wetlands, in addition to local issues. These regional issues include river regulation, diversion and abstraction in the Murray-Darling Basin, excessive inundation in the Western Australian wheatbelt and parts of the coastal plain, and aquifer draw-down in the Great Artesian Basin (Figure 2). Specific local impacts also affect wetland water regimes. These include hydrological alterations associated with urban and agricultural development.

Australia-wide. the draining of wetlands and damplands to convert wet areas to dry land for urban and agricultural use remains an issue. This is occurring in Queensland’s Wet Tropics and eastern Tasmania due to agricultural pressure. Urban pressures are perhaps most pronounced on the perimeters of cities and towns undergoing rapid expansion.



# Wetland	State	# Wetland	State
1.Apsley Marshes	TAS	21.Lake Wellington Wetlands	VIC
2.Barmah Forest	VIC	22.Lake William	VIC
3.Blue Lake	NSW	23.Little Lake Charm, Kangaroo Lake & Racecourse Lake	VIC
4.Bool & Hacks Lagoons	SA	24.Little Waterhouse Lake	TAS
5.Bowling Green Bay	QLD	25.Logan Lagoon	TAS
6.Cemetery Swamp	VIC	26.Macquarie Marshes	NSW
7.Chandala Swamp	WA	27.Mandora Salt Marsh	WA
8.Corio Bay Wetlands	QLD	28.McLeods Morass	VIC
9.Forrestdale Lake	WA	29.Narran Lakes	NSW
10.Fosters Swamp	VIC	30.Parry Floodplain	WA
11.Ginini & Cheyenne Flats	ACT	31.Second Marsh (Middle Marsh)	VIC
12.Gunbower Island	VIC	32.Third Marsh (Top Marsh)	VIC
13.Gwydir Wetlands: Gingham & Lower Gwydir	NSW	33.Third, Middle and Reedy Lakes	VIC
14.Hattah Lakes	VIC	34.Thomsons Lake	WA
15.Hird's Swamp	VIC	35.Toolibin Lake	WA
16.Johnson's Swamp	VIC	36.Town Swamp	VIC
17.Kow Swamp	VIC	37.Vasse-Wonnerup Wetland System	WA
18.Lake Albacutya	VIC	38.Yalgorup Lakes System	WA
19.Lake Bael Bael	VIC		
20.Lake Kelly & Stevensons Swamp	VIC		

Figure 1. Distribution of Ramsar-listed wetlands with threatened or potentially threatened water regimes.

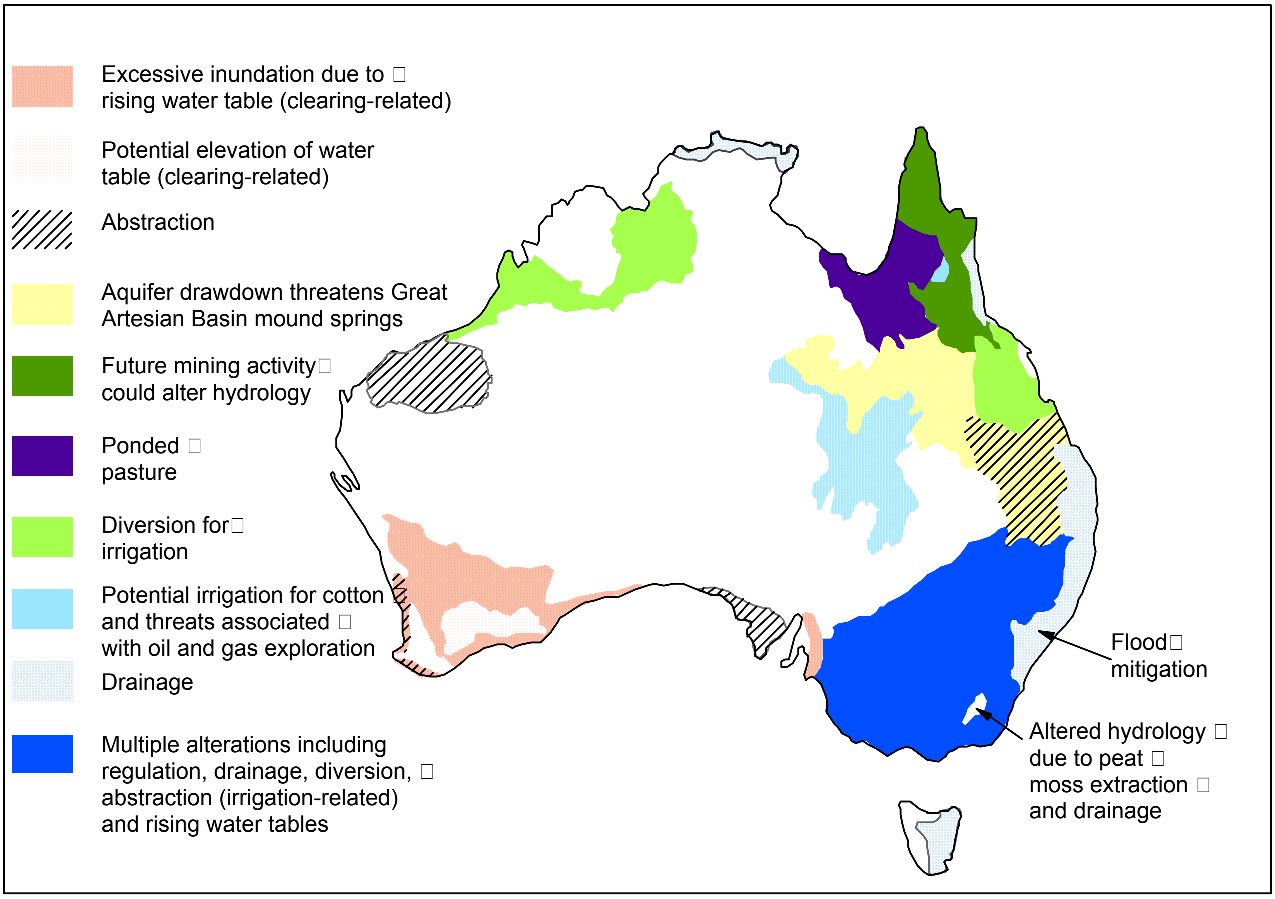


Figure 2 Current and potential threats to wetland water regimes mapped according to IBRA regions.

Table 1. List of Australian wetlands of national and international importance with threatened water regimes.
Except where indicated, the information is from the Directory of Important Wetlands.

Wetland	Nature of flow regime threat	State	Region
Adelaide River Floodplain System	Saltwater intrusion and groundwater extraction	NT	Top End Coastal
Alexandra Bay	Hydrology may be altered by tourist and recreational development	QLD	Wet Tropics
Alexandra Palm Forest	Lowering of watertable caused by drains installed for agricultural purposes	QLD	Wet Tropics
Apsley Marshes	Drains have been dug	TAS	Freycinet
Aramac Springs	Aquifer drawdown caused by water harvesting from Great Artesian Basin. Excavation of springs to increase water storage (Jackson, 1992)	QLD	Desert Uplands
Balonne River Floodplain	Damming, water harvesting from channels & billabongs. Threat of excessive water use associated with cotton production	QLD	Darling Riverine Plains
Bambaroo Coastal Aggregation	Hydrology altered by drainage for agriculture	QLD	Wet Tropics
Banongill Network	Regulation of flow	VIC	Victorian Volcanic Plain
Banrock Swamp Wetland Complex	Water abstraction	SA	Murray-Darling Depression
Barmah-Millewa Forest	Regulation of the Murray and Edward Rivers alters hydrology	VIC/NSW	Riverina
Becher Point Wetlands	Potential threat from groundwater extraction	WA	Swan Coastal Plain
Big Badja Swamp	Drainage of wetland	NSW	South East Highlands
Billabong Reserve	Potential threat from abstraction of water for domestic purposes by a nearby roadhouse	VIC	South East Coastal Plain
Black Swamp	Irrigation	NSW	Riverina
Black Swamp	Altered hydrology due to drainage and road construction	VIC	Riverina
Blackmans Lagoon	Potential threat from drainage	TAS	Ben Lomond
Blencoe Falls- Blencoe Creek	Proposed dam above falls for a hydroelectric scheme	QLD	Einasleigh Uplands
Blue Lake	Sedimentation has occurred, producing deltas	NSW	Australian Alps
Blue Mountains Sedge Swamps	Water diversion	NSW	Sydney Basin
Boggomoss Springs	Aquifer drawdown caused by water harvesting from Great Artesian Basin. Potentially some springs could be flooded by proposed Nathan River Dam.	QLD	Brigalow Belt South
Bool & Hacks Lagoons	Changed water levels in Bool Lagoon threatens recruitment of Melaleucas (LWRRDC, 1997b). Rising water tables are a potential threat	SA	Naracoorte Coastal Plain
Booligal Wetlands	Lachlan River regulation	NSW	Riverina

Booragoon Lake	Potential: excessive inundation	WA	Swan Coastal Plain
Wetland	**Nature of flow regime threat**	**State**	**Region**
Bowling Green Bay	Hydrology of Barratta Creek & the Haughton River which drain into these wetlands have been modified- diversion to this system for irrigation	QLD	Brigalow Belt North
Brixton Street Swamps	Groundwater extraction	WA	Swan Coastal Plain
Broke Inlet System	Possible future water supply demands	WA	Warren
Bromfield Swamp	Attempts to alter drainage patterns and to mine peat	QLD	Wet Tropics
Bulloo Overflow /Carypundy Swamp	Potential alteration to hydrology: upstream removal of water would reduce flood frequency	NSW	Channel Country
Bunguluke Wetlands, Tyrrell Creek & Lalbert Creek	Diversion (both to the wetlands and away from them) and levee banks for flood mitigation	VIC	Murray-Darling Depression
Burdekin Delta Aggregation	Diversion for irrigation:an artificial aquifer recharge pumping program- divertes water from the Burdekin River-irrigated agriculture	QLD	Brigalow Belt North
Burdekin-Townsville Coastal Aggregation	Diversion for irrigation from Burdekin River into these wetlands	QLD	Brigalow Belt North
Byenup Lagoon System	Potential: peat mining & catchment drainage	WA	Jarrah Forest
Caledonia Fen	Drainage lines may be formed by cattle trampling	VIC	Australian Alps
Camballin Floodplain	Diversion (dam)	WA	Dampierland
Cape Leeuwin System	Current: abstraction from spring feeding swamp. Potential: further reduction of spring flow	WA	Warren
Cape Melville- Bathurst Bay	Hydrology could be disturbed by future coal mining	QLD	Cape York Peninsula
Cape Range Subterranean Waterways	Abstraction for town water supply, 1998 petroleum exploration	WA	Carnarvon
Carbrook Wetland Aggregation	Alteration of the hydrological regime, clearing. Potential drainage of swamp for housing estates	QLD	South Eastern Queensland
Cemetery Swamp	Lake of water supply	VIC	Riverina
Central Highlands Peatlands	Altered hydrology: may have been caused by harvesting of Sphagnum, road construction, logging	VIC	South East Highlands
Chandala Swamp	Diversion	WA	Swan Coastal Plain
Clarence River Estuary	Filling &draining of wetlands	NSW	NSW North Coast
Cobden-Terang Volcanic Craters	Drainage & water extraction	VIC	Victorian Volcanic Plain
Coomoderry Swamp	Altered hydrology	NSW	Sydney Basin

Cooper Creek Overflow Swamps-Windorah	Proposed irrigated cotton production	QLD	Channel Country

Wetland	Nature of flow regime threat	State	Region
Cooper Creek Swamps- Nappa Merrie	Upstream- cotton development	QLD	Channel Country
Cooper Creek- Wilson River Junction	Drilling/pumping sites associated with oil/gas exploration and exploitation	QLD	Channel Country
Corella Lake	Prolonged inundation (tree deaths)	NT	Mitchell Grass Downs
Corio Bay Wetlands	Altered hydrology in one area caused by a barrage	QLD	Central Mackay Coast
Cowley Area	Wetlands in the area have been cleared & drained for agriculture: potential for intensification and continuation of the clearing & draining	QLD	Wet Tropics
Coyrecup Lake	Excessive inundation	WA	Avon Wheatbelt
Creswick Swamp	Hydrology probably severely altered	VIC	Victorian Midlands
Cuba Dam	Impoundment	NSW	Riverina
Cundare Pool/ Lake Martin	Regulation via a diversion channel & regulator at inlet & outlet	VIC	Victorian Volcanic Plain
Dalhousie Springs	Water extraction, drawdown	SA	Stony Plains
Daly-Reynolds Floodplain-Estuary System	Saltwater intrusion. Potentially changed flooding regimes due to clearing for horticulture/mixed farming	NT	Top End Coastal
D'Arcy's Lagoon	Drainage	TAS	D'Entrecasteaux
Darling Anabranch Lakes	Water regulation	NSW	Murray Darling Depression
Davies Plain	Drainage lines may be formed by cattle trampling, 4 wheel driving, hiking.	VIC	Australian Alps
Dismal Swamp- Water Park Creek	Sandmining could alter hydrology. Increased groundwater flow.	QLD	Central Mackay Coast
Doggerup Creek System	Vegetation clearance causing alterations to inflow	WA	Warren
Doongmabulla Springs	Aquifer drawdown caused by water harvesting from Great Artesian Basin	QLD	Desert Uplands
Dragon Tree Soak	Camel damage could result in exposure & drying out	WA	Great Sandy Desert
Dublin Bog	Peat harvesting	TAS	Central Highlands
Edithvale- Seaford Wetlands	Alteration of hydrology including flood mitigation	VIC	South East Coastal Plain
Edmund Kennedy Wetlands	Potential effects on hydrology by the agriculture of the area	QLD	Wet Tropics
Elizabeth Springs	Aquifer draw down caused by water harvesting from the Great Artesian Basin	QLD	Mitchell Grass Downs
Ellen Brook Swamps System	Clay extraction and changed landuse may lower water levels	WA	Swan Coastal Plain
Eubanangee- Alice River	Floodplain surrounding Eubanagee has been cleared & drained for sugarcane production; potential for exaceration of the above	QLD	Wet Tropics
Finniss Floodplain and Fog Bay System	Saltwater intrusion	NT	Top End Coastal

First Marsh (The Marsh)	Excessively high water levels	VIC	Riverina

Wetland	Nature of flow regime threat	State	Region
Fitzroy River Delta	Present: altered hydrology to prevent tidal intrusion. Potential: altered hydrology from proposed dams	QLD	Brigalow Belt South
Fitzroy River Floodplain	Damming and water harvesting	QLD	Brigalow Belt South
Folly Lagoon	Drainage for agriculture	TAS	Tasmanian Midlands
Forrestdale Lake	Groundwater extraction (public & private)	WA	Swan Coastal Plain
Fortescue Marshes	Dam	WA	Pilbara
Fosters Swamp	Lack of water supply, used for sewage effluent disposal	VIC	Riverina
Fraser Island	Mining	QLD	South Eastern Queensland
Gibbs Road Swamp System	Groundwater extraction (public & private)	WA	Swan Coastal Plain
Gibson Desert Gnamma Holes	Camels occasionally drink gnamma holes dry	WA	Gibson Desert
Gingilup- Jasper Wetland System	Groundwater extraction	WA	Warren
Ginini and Cheyenne Flats	Localised change in drainage caused by past peat moss extraction	ACT	Australian Alps
Great Cumbung Swamp	Regulation- Lachlan River. A reduction of mid-level floods (with return period 3-20 years), and an increase in low flows (< 3 years) return periods with little impacts on major floods. Levees within the swamp (DLWC, 1998)	NSW	Riverina
Gunbower Island	River regulation causing altered flooding regime, illegal deposition of irrigation drainage	VIC	Riverina
Guraga Lake	Water diversion	WA	Swan Coastal Plain
Gurra Lakes Wetland Complex	Altered water regime indicated by death of Red River Gums	SA	Murray-Darling Depression
Gwydir Wetlands: Gingham and Lower Gwydir wetlands	Irrigation pressures on Gwydir River, irrigation operations	NSW	Darling Riverine Plains
Harmer River- Shelburne Bay Aggregation	Hydrology could be disturbed by future mining of silica sands	QLD	Cape York Peninsula
Hattah Lakes	Altered flows in the Murray River	VIC	Murray-Darling Depression
Herbert River Floodplain	Draining & filling of wetlands for agriculture	QLD	Wet Tropics
Heywoods Lake	Diversion	VIC	Murray-Darling Depression
Hird's Swamp	Irrigation tailwater disposals	VIC	Riverina
Horse Park Wetland	Possible changes to hydrology from proposed urbanisation	ACT	South Eastern Highlands
Innisfail Area	Hydrology in northern section has been altered by drains	QLD	Wet Tropics
Irwin Flat	Increased flow (potential)	SA	Murray-Darling Depression

Wetland	Nature of flow regime threat	State	Region
Johnson's Swamp	Irrigation tailwater disposals	VIC	Riverina
Joondalup Lake	Groundwater extraction	WA	Swan Coastal Plain
Kanyapella Basin	Artificial hydrological regime	VIC	Riverina
Karakin Lakes	Possible future groundwater extraction	WA	Swan Coastal Plain
Kemps Marsh	Drainage (potential)	TAS	Central Highlands
Koondrook and Perricoota Forests	Regulation- Murray River	NSW	Riverina
Kooraweera Lakes	Hydrology altered by channel construction & alteration of natural channels	VIC	Victorian Volcanic Plain
Kosciusko Alpine Fens, Bogs and Lakes	Drainage could be altered by trampling in some fens/bogs	NSW	Australian Alps
Kow Swamp	Abstraction for irrigation	VIC	Riverina
Lachlan Swamp (part of mid Lachlan Wetlands)	Regulation- Lachlan River	NSW	Riverina
Lake Albacutya	Surface flow regime modification, rising water-table	VIC	Murray-Darling Depression
Lake Bael Bael	Altered hydrological regime: floods too frequently & holds water for too long	VIC	Riverina
Lake Barlee	Potential for mining of lake bed	WA	Murchison
Lake Bookaar	Dams, potential for further dams	VIC	Victorian Volcanic Plain
Lake Brewster	Used for water storage- reduced variability of water levels. Is dried out before summer to reduce losses due to evaporation.	NSW	Riverina
Lake Broadwater	Irrigation	QLD	Brigalow Belt South
Lake Colongulac	The lake receives discharge from the Sewerage Treatment Plant	VIC	Victorian Volcanic Plain
Lake Corangamite	Input dammed/ diverted	VIC	Victorian Volcanic Plain
Lake Cowal/Wilbertroy Wetlands	Proposed gold mine (tailings dam, drainage proposals, levee bank construction)	NSW	NSW South Western Slopes
Lake Cronin	Disturbances to the catchment area may alter hydrology: elevation of hypersaline groundwater table would be catastrophic	WA	Mallee
Lake Dulverton	Development may have led to reduced water inflow to the lake.	TAS	Tasmanian Midlands
Lake Elphinstone	Water pumped from the lake: is now dry	QLD	Brigalow Belt North
Lake Eyre Mound Springs	Water drawdown: increased extraction of groundwater from artesian bores	SA	Stony Plains
Lake George	Lake is dammed on one side	NSW	South East Highlands
Lake Gnarput	Altered hydrology as outlet to Lake Corangamite has been lowered	VIC	Victorian Volcanic Plain
Lake Gore System	Excessive inundation	WA	Esperance Plains

Wetland	Nature of flow regime threat	State	Region
Lake Hindmarsh	River regulation: diminished flow	VIC	Murray-Darling Depression
Lake Kelly & Stevensons Swamp	Stevensons Swamp used to dispose of local drainage	VIC	Riverina
Lake Lalbert	Diversion. Proposed redistribution of Avoca River flood flow would ensure flooding every 2 years.	VIC	Murray-Darling Depression
Lake McLarty System	Groundwater extraction on small rural holdings	WA	Swan Coastal Plain
Lake Mipia Area	Road crossing- interrupts flow of water but has not caused any major changes to vegetation	QLD	Channel Country
Lake Newland	Water withdrawals	SA	Eyre and Yorke Blocks
Lake Nichebulka	Diversion would be a threat	NSW	Mulga Lands
Lake Ranfurly	Disposal of saline groundwater	VIC	Murray-Darling Depression
Lake Thetis	Change to hydrology	WA	Swan Coastal Plain
Lake Tyrrell	Salt extraction from one side of the lake may affect the groundwater	VIC	Murray-Darling Depression
Lake Walbyring	Excessive inundation	WA	Avon Wheatbelt
Lake Wellington Wetlands	Altered hydrological regime due to dams, drains and levee banks have altered river flow & flow between wetlands	VIC	South East Coastal Plain
Lake William	Used as an evaporation basin	VIC	Riverina
Lake Woods	Prolonged inundation (tree deaths)	NT	Mitchell Grass Downs
Lashmar Lagoon	Flooding: surrounding land is cleared	SA	Lofty Block
Lindsay-Werrikoo Wetlands	Drainage & water regulation	VIC	Narracoorte Coastal Plain
Little Lake Charm, Kangaroo Lake & Racecourse Lake	Abstraction for irrigation. The hydrology of Kangaroo Lake is highly modified: level does not fluctuate naturally (also Racecourse Lake)	VIC	Riverina
Little Waterhouse Lake	Remobilised dunes could alter drainage. Threat of drainage for agriculture	TAS	Ben Lomond
Loch Luna Wetland Complex	Water abstraction	SA	Murray-Darling Depression
Loch McNess System	Groundwater extraction	WA	Swan Coastal Plain
Logan Lagoon	Drainage	TAS	Furneax
Long Swamp	Past & proposed future peat extraction- lower water table	NSW	Sydney Basin
Longneck Lagoon	Weir impedes drainage	NSW	Sydney Basin
Loveday Swamps	Excessive inundation: drowned Red River Gums	SA	Murray-Darling Depression
Lowbidgee Floodplain	Water regulation, channelling & diversion	NSW	Murray Darling Depression

Wetland	Nature of flow regime threat	State	Region
Lower Aire River Wetlands	Artificial breaching of Aire River mouth bar has resulted in lowering of lake water levels	VIC	South East Highlands
Lower Goulburn River Floodplain	Elevated water table due to irrigation	VIC	Riverina
Lower Lough Calvert & Lake Thurrumbong	Drainage diversion- reduced frequency & extent of inundation	VIC	Victorian Volcanic Plain
Lower Mirrool Creek Floodplain	Irrigation	NSW	Riverina
Lower Murray Swamps	Levee banks- floodplain; stressed Red River Gums	SA	Murray-Darling Depression
Lower Snowy River Wetlands System	Various engineering works now alter the hydrology preventing sheetflow over the floodplain, as previously occurred (DCE, 1992)	Vic	South East Corner
Macquarie Marshes	River regulation, abstraction for irrigation	NSW	Darling Riverine Plains
Mandora Salt Marsh	Potential: groundwater extraction for cotton	WA	Great Sandy Desert
Maringup Lake	Groundwater extraction (further)	WA	Warren
Mary Floodplain System	Saltwater intrusion	NT	Top End Coastal
McCarley's Swamp (Ludlow Swamp)	Excessive inundation:seepage of water from adjacent perched artificial lakes that receive mine effluent)	WA	Swan Coastal Plain
McLeods Morass	Stormwater, sewage effluent	VIC	South East Coastal Plain
Menindee Lakes	Regulation: dam & weir on the Darling River	NSW	Darling Riverine Plains
Merrowie Creek	River regulation & abstraction for irrigation	NSW	Riverina
Mid Murrumbidgee Wetlands	River regulation	NSW	Riverina
Middle Lough Calvert	Artificial hydrological system	VIC	Victorian Volcanic Plain
Millstream Pools	Groundwater extraction	WA	Pilbara
Mitchell River Fan Aggregation	Some development of ponded pasture	QLD	Gulf Plains
Moates Lake System	Potential: hydrology could be altered by further catchment clearing	WA	Jarrah Forest
Mortijinup Lake System	Excessive inundation	WA	Esperance Plains
Mount Buffalo Peatlands	Drainage lines could be formed by walkers	VIC	Australian Alps
Moyle Floodplain and Hyland Bay System	Potential saltwater intrusion	NT	Top End Coastal
Mt Soho Swamps	Inappropriate fire management could result in exposure, & consequent loss of water, also change in discharge to swamp.	WA	Warren
Murrays Lagoon	Flooding	SA	Lofty Block

Wetland	Nature of flow regime threat	State	Region
Naen Naen Swamp & Gum Lagoon	Lack of surface flows: diversion of Marcollat Watercourse	SA	Naracoorte Coastal Plain
Narran Lakes	Upstream extraction for irrigation; QLD portion of the Narran River	NSW	Darling Riverine Plains
Natimuk Lake, Natimuk Creek & Lake Wyn Wyn	Water level manipulation. Raising the outlet at Natimuk Lake has restricted flows along Natimuk Creek to Lake Wyn Wyn	VIC	Murray-Darling Depression
New England Wetlands	Drainage, damming	NSW	New England Tableland
Newington Wetlands	Seawalls reduce areas of mangrove & saltmarsh	NSW	Sydney Basin
Noosa River Wetlands	Urban expansion; clearing & filling of saltmarshes	QLD	South Eastern Queensland
O'Hares Creek Catchment	Sand & clay extraction	NSW	Sydney Basin
Orford Bay- Sharp Point Dunefield	Future- mining	QLD	Cape York Peninsula
Paroo Overflow	Threatened by abstraction (Timms, 1997). Lower flow to wetlands & lower variability	NSW	Mulga Lands
Parry Floodplain	Current: Regulation; Lakes Kununurra and Argyle. Receives declining frequency of floods; may result in decreased waterbird habitat (Schofield, 1998). Potential: rising water table (Schofield, 1998).	WA	Victoria Bonaparte
Perth Airport Woodland Swamps	Drainage of swamp areas has occurred	WA	Swan Coastal Plain
Pike-Mundic Wetland Complex	Possible. Groundwater seepage associated with irrigation- caused salinity changes	SA	Murray-Darling Depression
Pink Lake	Groundwater extraction	WA	Esperance Plains
Port Musgrave Aggregation	Future- (possible) bauxite mining	QLD	Cape York Peninsula
Port of Cairns and Trinity Inlet	Wetlands drained, filled	QLD	Wet Tropics
Princetown Wetlands	Regulation of upstream water flows, drainage of wetlands north-east of Princetown	VIC	South East Highlands
Raak Plain	Groundwater hydrology affected by mining for gypsum	VIC	Murray-Darling Depression
Riverland Wetland Complex	Changes in flows and regimes due to water regulation	SA	Murray-Darling Depression
Rock Flats	Drainage can be altered by walkers	ACT	Australian Alps
Rottnest Island Lakes	Groundwater extraction	WA	Swan Coastal Plain
Round Mountain	Diversion	NSW	New England Tableland
Rowles Lagoon System	Excessive inundation	WA	Coolgardie
Russell River	Drainage associated with canefields	QLD	Wet Tropics
Second Marsh (Middle Marsh)	Altered hydrology: increased flooding frequency; water is held for longer, affected by groundwater intrusion	VIC	Riverina
Southeast Karumba Fan Aggregation	Future development of ponded pasture	QLD	Gulf Plains
Spectacle Lakes	Water abstraction	SA	Murray-Darling Depression

Wetland	Nature of flow regime threat	State	Region
Spectacles Swamp	Groundwater extraction	WA	Swan Coastal Plain
Spring Tower Complex	Dewatering of limestone aquifer	QLD	Einasleigh Uplands
Swanpool/Belmore Swamp	Drainage	NSW	NSW North Coast
Tang Tang Swamp	Rising water table	VIC	Riverina
The Coorong, Lake Alexandina & Lake Albert	Regulation, drainage	SA	Naracoorte Coastal Plain
Third Marsh (Top Marsh)	Altered hydrology: increased flooding frequency; water is held for longer	VIC	Riverina
Third, Middle and Reedy Lakes	Altered hydrology: lakes were previously marshes	VIC	Riverina
Thomsons Lake	Groundwater extraction	WA	Swan Coastal Plain
Tookayerta & Finniss Catchments	Draining	SA	Lofty Block
Toolibin Lake	Excessive inundation	WA	Avon Wheatbelt
Tower Hill	Lowering water levels due to groundwater changes with irrigation	VIC	Victorian Volcanic Plain
Town Swamp	Irrigation tailwater disposal	VIC	Riverina
Tully River- Murray River Floodplains	Hydrology of deep water lagoons affected by extensive agricultural drainage networks. Potential: establishment of new drainage networks	QLD	Wet Tropics
Unnamed Wetland BEN015TA	Possibly future drainage & infilling	TAS	Ben Lomond
Unnamed Wetland FUR011TA	Altered drainage	TAS	Furneax
Unnamed Wetland FUR013TA	Altered drainage	TAS	Furneax
Unnamed Wetland WSW009TA	Drainage	TAS	West and South West
Upper Lough Calvert	Diversion of floodwater & run-off due to road embankments & the Lough Calvert Drainage Scheme	VIC	Victorian Volcanic Plain
Upper Naas Creek	Changes to drainage caused by cattle & sheep trampling, also by channels dug for sheep watering holes	ACT	Australian Alps
Vasse-Wonnerup Wetland System	Landfill of floodplain wetlands	WA	Swan Coastal Plain
Wallenjoe Wetlands	Elevated water levels due to drainage discharge	VIC	Riverina
Wannamal Lake System	Current: excessive inundation. Potential: water diversion, vegetation clearance	WA	Swan Coastal Plain
Watervalley Wetlands	Rising groundwater, changed water flows	SA	Naracoorte Coastal Plain
Werai Forest	River regulation	NSW	Riverina
Willie Creek Wetlands	1989-1990 creation of a barrage to raise lake water levels, creation of a dam 1.5 km east of swamp- reduced surface run-off. Potential: groundwater extraction for Broome expansion	WA	Dampierland

Wetland	Nature of flow regime threat	State	Region
Wingecarribee Swamp	Peat mining has led to the collapse and drainage of the wetland (Tranter, 1999)	NSW	Sydney Basin
Wooleen Lake	Potential for siltation of the lake if overgrazing occurred	WA	Murchison
Wyvuri Swamp	Hydrology affected by road & drain construction	QLD	Wet Tropics
Yalgorup Lakes System	Extraction of groundwater (& interference with seepage near new rural smallholdings)	WA	Swan Coastal Plain
Yambuk Wetlands	Water level manipulation; drainage & channeling has altered the hydrology	VIC	South East Coastal Plain
Yantabulla Swamp (Cuttaburra Basin)	Possible future upstream abstraction	NSW	Mulga Lands
Yaouk Swamp	Peat mining. Also much of the swamp has been drained	NSW	South East Highlands
Yealering Lakes System	Excessive inundation	WA	Avon Wheatbelt
Yellilup Yate Swamp System	Excessive inundation	WA	Esperance Plains
Yorkrakine Rock Pools	Water diversion	WA	Avon Wheatbelt

2. REVIEW OF THE LITERATURE DESCRIBING ENVIRONMENTAL WATER ALLOCATIONS FOR WETLANDS

Introduction

This review examined the determination of environmental water allocations for wetlands in Australia. The wetlands considered were standing enclosed water bodies, and include permanent, seasonal and ephemeral waters. The provision and maintenance of appropriate water regimes is considered the most important management issue for many Australian wetlands (Adam, 1997). Water regimes of many wetlands have been altered by regulation, extraction of water for agricultural, domestic and industrial uses, the use of wetlands as areas for water storage, and changes in land use. Human impacts on wetland water regimes can result in both increased and decreased inundation, as well as altered variability in inundation and seasonality (ANCA, 1996). Davis and Froend (1999) noted that water levels in urban wetlands on the Swan Coastal Plain in Western Australia have risen due to land clearing resulting in local rises in the water table and increased surface run-off. Groundwater extraction also poses a threat to some wetlands in the same region in the form of lower water levels and prolonged dry phases. Management of environmental water allocation for wetlands in Australia has mainly focused on wetland systems where the hydrology is altered by water extraction, however the issue of drainage into wetlands and inundation as a result of rising water tables also needs to be addressed. That is, wetlands can have ‘too much water’ as well as ‘too little water’.

Environmental Flow Allocations for Rivers

In both Australia and overseas, environmental water allocation has focussed on rivers. Initially the prime motivating concern was improving fish habitat and meeting fish passage requirements. Later, broader issues were considered, such as the maintenance of ecosystem processes (Arthington and Pusey, 1992). Approaches include methods based on historical discharge, habitat analysis and species requirements (Swales and Harris, 1995).

Approaches to the determination of environmental flow allocations in rivers have included two historical discharge or 'rule-of-thumb' methods, the Montana Method and Flow Duration Curve Analysis. These are based on the use of historical flow records, using a fixed proportion of the 'natural' flow which occurred prior to development. There is generally a strong emphasis on maintaining minimum flows (Pusey, 1998). For this reason, their reliance on criteria developed overseas, they are not considered suitable for Australian streams (Arthington and Pusey, 1992; Richardson, 1986). Australian river systems are characterised by high flow variability. Preservation of periods of low or no flows are important for the maintenance of their ecological character.

Habitat Analysis Methodology (Burgess and Vanderbyl, 1996) was developed in Queensland to determine environmental flows for rivers and streams (Arthington, 1998). It is based on a panel of experts workshop, with four distinct elements:

- identification of generic habitat types existing within the catchment
- determination of the flow-related ecological requirements of each habitat
- development of bypass flow strategies to meet those requirements
- development of a monitoring strategy to check the effectiveness of flow strategies

(Arthington, 1998, p.26).

Instream habitat modelling methods, such as Instream Flow Incremental Methodology (IFIM), are based on the determination of habitat preference curves for species. Habitat availability is modelled for change in discharge (Swales and Harris, 1995).

The Holistic Approach to environmental water allocation assumes that if the essential components of the natural flow regime are incorporated into the modified flow regime, the biota should persist and the ecological integrity of the ecosystem should be maintained (Arthington, 1998). The essential components of the natural flow regime are determined from an analysis of historical flow records (Pusey, 1998). Where the Holistic Approach is used for the determination of environmental flows in rivers the entire ecosystem and geomorphic processes associated with flows are examined. Water quantity is described in terms of the effect of velocity on the maintenance of such habitats as riffles. Habitat Analysis Methodology is considered to fit within the Holistic Approach (Arthington, 1998).

Environmental Water Allocations for Wetlands

Environmental water allocation for wetlands associated with river systems has frequently been incorporated into the flow allocation process for the river system [eg, the Murrumbidgee wetlands (Shields, 1998)]. Although developed primarily for rivers, the Holistic Approach to environmental flow determination is also considered applicable to wetlands (Arthington and Pusey, 1992). Essential components of a wetland's water regime include the quantity of water, and the timing, duration and frequency of inundation (McCosker, 1998). The use of Habitat Analysis Methodology in wetland environmental water allocations could involve the identification of habitat types according to depth or frequency/duration of inundation. Both Habitat Analysis Methodology (Burgess and Vanderbyl, 1996) and Young *et al.*'s (1999) Environmental Flows Decision Support System (EFDSS) allow for the consideration of wetlands as one habitat or zone, alongside riverine habitats and zones.

Wetland environmental water allocation however differs from that of rivers in that there is not such a direct relationship between water quantity and geomorphic processes in wetlands. Variability of water quantity over time in wetlands results in habitats of different depths. These habitats are characterised by particular plant and waterbird communities. There is generally a close connection between water quantity and the spatial extent of wetland habitat. For example, on the Chowilla floodplain, a relatively small decrease in flood volume can result in a large reduction in the inundated area (Taylor *et al.*, 1996).

There are two main approaches to wetland environmental water allocation, based on hydrology and ecology respectively (Gippel, 1996). Hydrology-driven approaches are similar to the historical discharge methods described above for rivers. They involve the attempted description and reinstatement of the water regimes that existed prior to development. Information regarding the pre-development water regime is gathered from historic data where these exist. Modelling may be required where historic data are not available. The Holistic Approach of environmental water allocation for rivers is hydrology-driven in that it is based on incorporating the essential elements of the pre-development flow regime into the modified flow regime. The ecology-driven approach involves estimating the water regime requirements of wetland species, communities and ecosystem processes. The determination of environmental water allocations is based on meeting these requirements.

While the determination of environmental flows for rivers generally occurs at large scales, with the examination of entire river systems, environmental water allocations for wetlands may sometimes occur at much smaller spatial scales. Roberts *et al.* (2000) consider that it may be possible to return small isolated wetlands to their pre-development water regimes through the use of regulators (water gates) or other devices. In contrast, they consider that for large wetland systems downstream of consumptive demand for water, this will not be possible. In these systems they argue that a realistic goal is rehabilitation rather than restoration. They describe a process, with steps, for the determination of the water regime requirements of vegetation. The water regime requirements of vegetation have frequently been examined in the development of water management plans for wetlands (eg McCosker and Duggin, 1993; Keyte, 1994; WAWA, 1995).

Invasive species are frequently favoured by alterations to water regimes. Examples include the invasion of the weed *Phyla canescens* (lippia) associated with reduced water quantity (Keyte, 1994), and the increased spawning of carp in the Barmah Forest floodplains associated with river regulation (Blanch, 2000). Environmental water allocations may include water management strategies to control invasive species. Similarly, environmental water allocations for wetlands may incorporate measures to protect endangered species or communities.

Riverine wetlands

Water regimes of the following riverine wetlands are managed to meet environmental objectives:

- Macquarie Marshes (north-west NSW).
- Lower Gwydir Basin Wetlands (northern NSW).
- Kerang Lakes (Victoria).
- Wetlands of the Lachlan River Valley (southern inland NSW).
- Lake Merreti and Lake Woolpolool (Chowilla Floodplain, River Murray SA)
- Barmah-Millewa Forest (Victoria-NSW border)

Groundwater-fed wetlands

Groundwater-fed wetlands which are the subject of environmental water allocations include:

- Lakes of the Gnangara Mound on the Swan Coastal Plain in Western Australia
- Twin Swamps, also on the Swan Coastal Plain, Western Australia

The determination of environmental water allocations for these wetlands was reviewed by treating each as a case study. Measures aimed at protecting the water resources of the Great Artesian Basin are also briefly reviewed. These measures have the effect of protecting mound springs, although generally they are designed to protect the water resource for consumptive use.

CASE STUDIES

Riverine wetlands

River regulation occurs in many regions of Australia, however it is particularly widespread in the Murray Darling Basin. It results in the alteration of wetland water regimes. Riverine wetlands may be divided into two broad categories: floodplain wetlands and terminal wetlands. Dams can affect floodplain wetlands by capturing flood pulses which would otherwise have led to overbank flows to floodplains (Kingsford, 2000). This water is later released to the channel for diversion for consumptive uses. The resultant increased low flows have resulted in increased permanency of the water regimes of some floodplain wetlands. The water regimes of floodplain wetlands can also be altered by conversion into off-river storages, or flooded by dams (Kingsford, 2000). Dams and diversions lead to an overall reduction in the quantity of water flowing to terminal wetlands (Brereton, 1994). Other water regime issues for wetlands resulting from river regulation include over-allocation of water for consumptive use, loss of connectivities, altered hydrology caused by levee banks, and loss of variability in water regimes, including reduced flooding and the loss of seasonality. Infrastructure such as regulators and water supply channels may be necessary to manage riverine wetland water regimes to meet environmental objectives (Allan and Lovett, 1997).

In the following case studies, there is an emphasis on the effect of altered water regimes on waterbird breeding. This is because colonial waterbirds rely on flooding to breed, and breed only in a few large floodplain wetlands in Australia (Marchant and Higgins, 1990; Kingsford, 2000). Alterations to water regimes which adversely affect their breeding could therefore impact continental populations (Kingsford and Johnson, 1999, cited in Kingsford, 2000).

Macquarie Marshes (NSW)

The Macquarie Marshes is a large (200 000 hectare) semi-permanent wetland which is inundated by the Macquarie River (Directory of Important Wetlands website). The Macquarie River generally terminates at the Marshes, except during large floods, when it flows through to the Darling River (Kingsford, 2000). The Marshes are a Ramsar site and are of considerable importance for waterbirds (Directory of Important Wetlands website). Upstream extraction has occurred since European settlement but increased with the construction of the Burrendong Dam in the late 1960s and the Windamere Dam in the early 1980s (Allan and Lovett, 1997). During the design of the Burrendong Dam, it was calculated that a release of 50 000 ML would result in the filling of levee banks at waterbird breeding sites. This release was promised but was not delivered for economic and political reasons; in 1967 only 18 500 ML was granted to the Marshes. In the 1986 Macquarie Marshes Water Management Plan, the allocation was increased to 50 000 ML (known as a Wildlife Allocation), based on the earlier calculation (Brereton, 1994). The main objective was the protection of waterbird habitat (DLWC and NPWS, 1996). This quantity was found however to be inadequate, due to increased irrigation in the area (DLWC and NPWS, 1996). It has been estimated that the Macquarie Marshes has been reduced in area by approximately 40 - 50 % over 50 years, resulting in a major loss of waterbird habitat (Kingsford and Thomas, 1995).

In 1994 the 1986 MMWM Plan was reviewed, a process which resulted in the 1996 Water Management Plan (Allan and Lovett, 1997) (Figure 1). Objectives of this Plan were:

- To secure the amount of water needed for the maintenance and restoration of the Marshes, and

- To meet the obligations of the Ramsar Convention and other international nature conservation agreements to which Australia is a signatory.

(DLWC and NPWS, 1996, p.3).

The determination of the revised Wildlife Allocation was based on a detailed study involving the examination of

- detailed vegetation maps from 1949, 1963 and 1991,
- Landsat TM Imagery flood maps from 1987 onwards,
- river gauging data since 1895, and
- plant water requirements.

The above list of data examined indicates that both hydrology- and ecology-driven approaches were used. The historical water regime was examined, as were plant water requirements and changes in vegetation.

As a result, the Wildlife Allocation was increased to 125 000 ML per year in the 1996 Plan, with its release timed to match rainfall events. Provision was made for discretionary use to enable the completion of major bird breeding events. Irrigators' access to off-allocation water was reduced[1] as were overall diversions for irrigation (from 395 000 ML per year to 340 000 ML per year). Water bird breeding requirements were considered in the 1996 Plan in terms of flooding extent and duration, and the need to maintain living Red River Gums for nest sites. Successful breeding of colonial nesting water birds is a performance indicator of the 1996 Plan (DLWC and NPWS, 1996). Inclusion of performance indicators in the Plan allow for the assessment of the water management regime. An outline of the history of environmental water allocations to the Macquarie Marshes is given in Figure 3.

[1] Off-allocation in regulated river systems refers to the period "when natural system inflows downstream of the storage, or storage overflows, significantly exceed immediate consumptive demands" (DLWC and NPWS, 1996, p.32). Generally water extracted by irrigators during off-allocation is not debited against their volumetric water allocation.

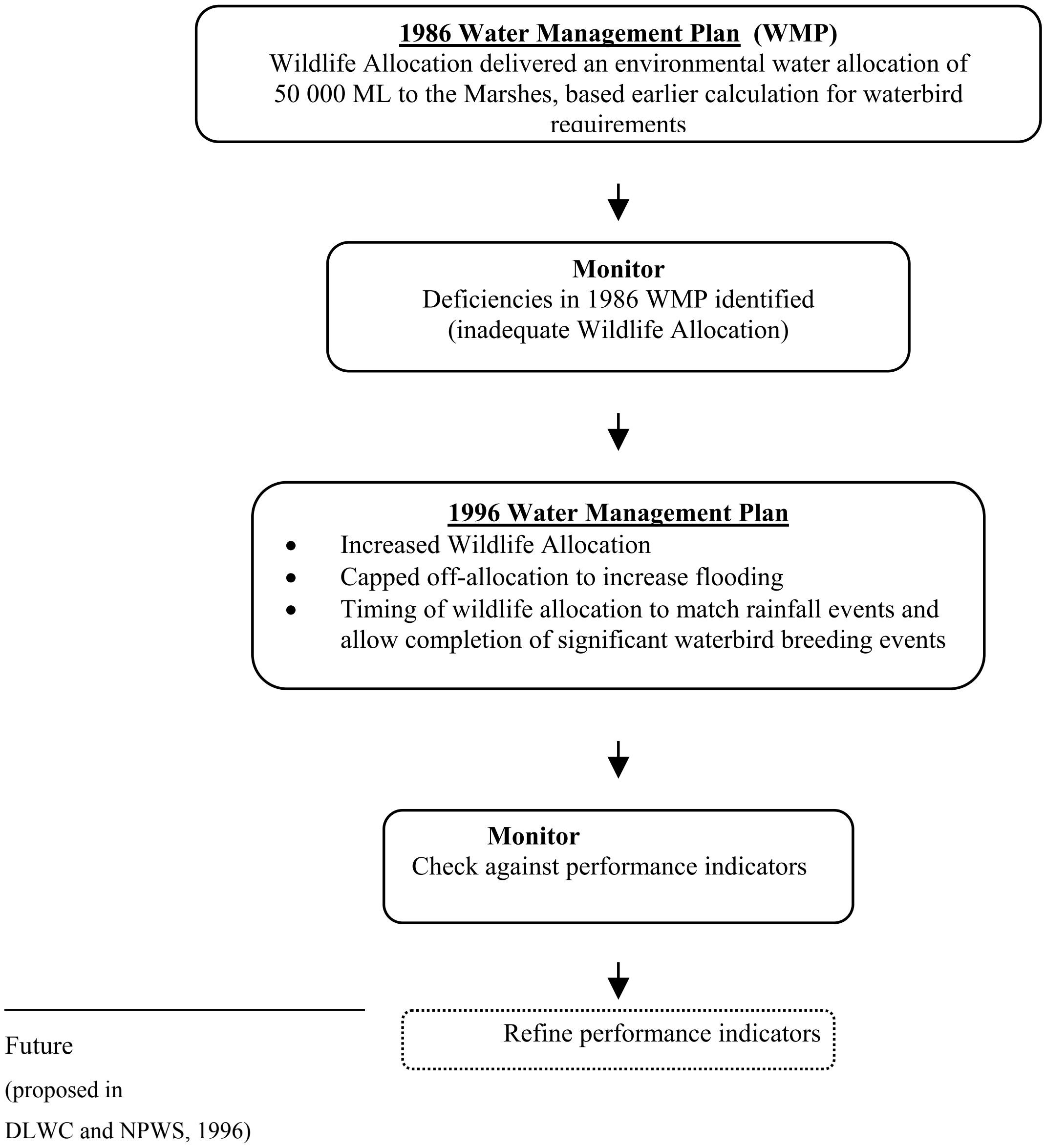


Figure 3. History of the determination of environmental water allocation for the Macquarie Marshes

Gwydir Wetlands (NSW)

This wetland aggregation occurs as a result of the Gwydir River in northern NSW giving way to overland flow due to an extremely low gradient (Allan and Lovett, 1997). The River terminates in the Gwydir floodplain wetlands, the Lower Gwydir and Gingham watercourses (Keyte, 1994). Part of the Lower Gwydir watercourse has recently been listed as a Ramsar site (Nickson, 1999). The wetlands have declined in size as a result of the commissioning of the Copeton Dam in 1976, together with the expansion of irrigation. After the construction of the dam, demand for irrigation water exceeded expectations, resulting in a serious on-going problem of over-extraction of water. It has been estimated that the quantity of water reaching the wetlands was reduced to only 70% of that which was historically available (Allan and Lovett, 1997). As a result, terrestrial vegetation and the weed lippia (*Phyla canescens*) have invaded areas previously dominated by aquatic and semi-aquatic vegetation (Keyte, 1994). Issues to be addressed by environmental water allocations in the Gwydir wetlands are similar to those of the Macquarie Marshes; an overall reduction in water reaching the wetlands as a result of diversion and extraction.

In 1996 an agreement was reached where the wetlands receive the first 500 ML of tributary flows, after which off-allocation is shared evenly between the environment and irrigators. An allocation of 25 000 ML is held in Copeton Dam for the environment. The percentage of this environmental allocation actually delivered to the wetlands is matched to the proportion of the water allocations the irrigators are able to access. For example, if the irrigators can only access 75% of their water allocation, then only 75% of the environmental allocation of 25 000 ML is released to the wetlands (Allan and Lovett, 1997). In the summer of 1998-1999 a large waterbird breeding event occurred, which was seen as indicating the success of the new water sharing rules (Nickson, 1999).

Kerang Lakes (Victoria)

The Kerang Lakes are situated 300 km north-west of Melbourne, and cover an area of 110 500 hectares. Water supply for the Lakes is from the River Murray via the Torrumbarry Irrigation System, the Loddon River System, the Avoca River System and Bendigo Creek. Many of the lakes are Ramsar listed. Those of high conservation significance include Hird and Johnson Swamps, Lake Elizabeth, Lake Wandella, Lake Murphy, Golf Course Lake, Round Lake, Woorinen North Lake, Woorinen South Lake and Lake Cullen. Irrigation and drainage channels divide the lakes, as a result they no longer represent an interconnected system where overflows from one lake affect another. Water regimes in many cases are completely altered due to the use of lakes and streams for the supply of irrigation water (DCNR, 1990; Allan and Lovett, 1997). The lakes are affected by salinity, partly a result of intrusion of saline groundwater. The Victorian government has committed an interim allocation of 27 6000 ML per year to high value wetlands in the north of the state. The Kerang Lakes receive this water, with the primary objective being the reduction of salinity through flushing (Mudgway *et al*., 1996).

Conservation values of the Kerang Lakes were evaluated in 1989, and recommendations made for the management of their water regimes for the purpose of enhancing conservation values (Lugg *et al*., 1989). A management plan was drafted in 1990 for Hird and Johnson Swamps (DCNR, 1990). Although these are both Ramsar wetlands, their character has been significantly altered by irrigation development. Prior to the 1920s they were intermittent swamps dominated by black box. Irrigation development resulted in permanent water regimes in the swamps, which led to tree deaths. The management plan identified values and threats. Values included ibis habitat, waterbird breeding, duck hunting and camping. Excessive coverage of *Typha spp*., *Phragmites australis*, and *Myriophyllum elatinoides* were identified as threats to these values, while the preservation of *Schoenoplectus validus* was seen as beneficial for ibis nesting. Two scenarios were discussed in terms of their likely effects on the coverage of the above wetland plants (especially *Typha spp.*), as well as the preservation of the ibis rookery, control of carp, and effects on salinity. It was determined that complete drying of each swamp for one year in four, with the swamps not to be dry in the same years, would be the best management option (DCNR, 1990).

The REALM model was used to develop a strategy for the use of the interim allocation in ten of the Kerang Lakes (Hydro Technology, 1995). This model is based on water and salt balances. Wetlands of the Kerang Lakes were categorised as permanent and semi-permanent for the purposes of determining the way in which the allocation would be used. Permanent lakes are to be flushed annually, and semi-permanent water regimes are to be restored to wetlands such as Hird and Johnson Swamps which had become permanently inundated. The managed regime involves a five year flow strategy for ten wetlands, where in any one year some are drained, some filled and some flushed (Hydro Technology, 1995; Mudgway *et al*., 1996).

Wetlands of the Lachlan River Valley (NSW)

Wetlands of the Lachlan Valley cover 400 000 hectares and include the Great Cumbung Swamp, Booligal Swamp, Lake Cowal, Merrowie Creek/ Lake Tarwong and Willandra Creek/ Morrison's Lake, Lake Brewster and Lake Cargelligo. Lakes Brewster and Cargelligo have been modified for use as water storages (Kingsford, 2000): Lake Cargelligo is maintained at almost full inundation, while Lake Brewster is allowed to dry in summer (Allan and Lovett, 1997). The Great Cumbung Swamp is a terminal wetland of the Lachlan River. Its hydrology is also influenced by the Murrumbidgee River, as it lies on the confluence of these two rivers (Shaikh *et al.*, 1996). This wetland was historically wet in winter and dry in summer, but since the construction of Wyangala Dam in 1936, some water reaches it in all seasons of the year (Allan and Lovett, 1997). Booligal Swamp has a large ibis rookery, with as many as 40 000 pairs of breeding ibis. Lake Tarwong is considered significant because of its high diversity of birds (Denham and McCauliffe, 1994).

In 1989 and 1990 water was released from Lake Brewster to allow the successful completion of water bird breeding events. In 1992 Environmental Contingency Allocations (ECA) were introduced by the Department of Water Resources in a trial program. An Environmental Flow Package for the Lachlan Valley was developed with the aims of giving the wetlands a more natural flow regime and reducing the impacts of river regulation and water extraction. The initial ECAs were determined using existing knowledge and general ecological principles and were later refined as a result of monitoring (Denham and McAuliffe, 1994). Allocations address water quality problems (such as blue-green algal blooms and salinity) in addition to water quantity issues and are now known as Contingency Allocations (CAs) (Allan and Lovett, 1997).

Contingency Allocations are targeted at waterbird breeding events, in particular ibis breeding. These breeding events are stimulated by periodic inundation, and their successful completion is dependent on duration, i.e., the slow recession of floodwaters or the occurrence of follow-up flooding. River regulation and the extraction of off-allocation water is considered to be responsible for the loss of some inundation events, the more rapid recession of floodwaters and a reduction in follow-up flood events. To ensure completion of bird breeding events, off-allocation diversions are restricted and a Contingency Allocation is used to extend the period of inundation. Contingency Allocations for waterbird breeding events have been defined for Booligal Rookery (11 GL) and Lake Tarwong (9 GL) (Denham and McCauliffe, 1994). Use of these allocations is dependent upon the initiation of bird breeding and natural flows (Allan and Lovett, 1997; DLWC, 1998).

There is also an unregulated flow policy, similar to the “off-allocation” rules of the Macquarie Marshes Water Management Plan. The priorities of this policy include the provision of water to sustain fish populations and wetland ecosystems. Assessments of wetland requirements are made when unregulated water becomes available (Allan and Lovett, 1997). The health of plant communities has been considered in terms of the management of allocations to Booligal Wetlands and the Great Cumbung Swamp (DLWC, 1998).

Lake Merreti and Lake Woolpolool (Chowilla Floodplain, South Australia)

The Chowilla floodplain is located on the lower Murray River and is recognised under the Ramsar Convention. The lower Murray is intensively regulated, with flows controlled by the operation of weirs, barrages near the river mouth and releases from the storages of Lake Victoria on the River Murray and Menindee Lakes on the Darling River. The flow regime is now more stable, with higher summer flows and a reduced frequency of overbank flows (Jensen, 1994, Allan and Lovett, 1997). Floodplain inundation has been reduced, and the proportion of permanent wetlands has increased (Jensen *et al*., 1994). Strategic manipulation of weir levels and releases from the storage lakes have been suggested as mechanisms for returning the floodplain wetlands of the Lower Murray to their pre-development water regime (Jensen, 1994). The water regimes of lakes on the Chowilla floodplain, including Lake Merreti and Lake Woolpolool, have been managed for environmental purposes (Jensen, 1994; Jensen *et al*., 1994). Flushing flows have been re-instated, with the aim of enhancing wetland habitat value and maximising biodiversity (Jensen *et al*., 1994).

Lake Merreti is a freshwater lake fed by backwater creeks of the River Murray. As a result of river regulation, the water regime of Lake Merreti had become more permanent, with less frequent flood events. A regulator had been installed for the purpose of using the lake for water storage. Since 1982 a regulator has been used to protect ibis breeding and create temporary fringe flooding around the edges of the lake (Jenson *et al*., 1994).

Lake Woolpolool lies to the west of Lake Merreti. The water regime of this lake is also managed for the purposes of reducing surface salinisation, to encourage tree regeneration and for the provision of waterbird breeding and feeding habitat (Jensen, 1994). A control valve is operated to allow water inflow when surplus flows are available (Jensen *et al.*, 1994). Localised regeneration of river red gums and successful waterbird breeding events have occurred since the implementation of this water management strategy (Jensen, 1994).

Lakes Merreti and Woolpolool are examples of small wetlands in a highly disturbed system where a return to pre-development water regimes by manipulating levels with regulators is possible (Roberts *et al.*, 2000). On a larger scale, such as the Chowilla floodplain wetlands as a whole, consumptive demand for water is likely to be too high to allow a return to a pre-development water regime.

Barmah-Millewa Forest (Victoria/NSW)

The Barmah-Millewa Forests are located in Victoria (Barmah Forest) and in NSW (Millewa Forest), along the floodplains of the Murray and Edward Rivers (Directory of Important Wetlands website). They are the largest river red gum forests in the world, occupying a total area of approximately 60 000 ha (MDBC, 1990). Habitats include swamps, moira grasslands, marshes, rushlands, open water, streams, black box forest and red gum forest (Allan and Lovett, 1997). The plant associations are related to flooding frequency and duration; reeds, rushes and grass plains occur in areas most frequently flooded, while box forests occur in areas rarely or never flooded (Bren, 1992). The Forest is considered to be of special significance due to its size, the variety of communities, its high productivity, waterbird breeding and the presence of threatened and endangered species (Directory of Important Wetlands website).

The hydrology of the Forests has been altered as a result of river regulation. Prior to construction of the Hume Dam in 1934, the water regime was characterised by high flows in winter and spring, and low flows in summer and autumn (Bren, 1992, Allan and Lovett, 1997, Directory of Important Wetlands website). Since regulation, the rivers have been used to transmit water to downstream users. To achieve this, summer flows are maintained at about maximum channel capacity. Immediately after the Hume Dam was commissioned in 1934, these high summer flows were associated with large losses of water into the forest via effluent streams, which resulted in the deaths of some red gums. Regulators were built at the junction of many effluent streams to prevent these flows (Bren, 1992). However there is still some summer flooding in the Forests as a result of increased river levels during the irrigation season (Atkins, 1993). Rain rejection flows occur when allocations delivered are not used by irrigators due to localised summer rain (Barmah-Millewa Forum and MDBC, 2000). These flows are diverted into the Forests at the Gulf Regulator to avert flooding of the Barmah township. This diversion affects wetlands in the Gulf region (Atkins, 1993). However, much of the Forests is affected by reduced flooding because of diversion of water for irrigation (Directory of Important Wetlands website). It has been estimated that prior to regulation, 70% of the Forest was flooded for an average of 2.9 months in 78% of years. Since dam construction, this degree of flooding only occurs for an average of 1.3 months in 37% of years.

Ecological effects of these alterations to the water regime include changes in species compostion of rushlands, grasslands and forests, reduced tree health and growth rates and reduced waterbird breeding (MDBC, 1990; Bren 1992; Atkins, 1993). Invasions of giant rush, and of river red gums into moira grasslands is considered to be an effect of summer flooding. The area of moira grasslands has been reduced (Bren, 1992).

The Murray-Darling Basin Commission used to provide water for environmentally sensitive areas on an ad hoc basis (Barmah-Millewa Forum and MDBC, 2000). Small volumes of water were periodically released to meet waterbird breeding requirements in summer and fish requirements in winter, based on the knowledge of local interest groups (Kinhill Engineers, 1988). Now water management is based on a more formal approach (Barmah-Millewa Forum and MDBC, 2000). The forest has been divided into management units defined according to water regime patterns or requirements. These units are managed independently. The characteristics of the pre-regulation flow regime deemed most beneficial ecologically are included in the managed regime as far as possible. This is achieved through measures including an environmental water allocation of 100 GL per year from the Hume Dam, and the refinement of procedures for ordering irrigation water from Hume Dam and Yarrawonga Weir. Stakeholders are represented through the Barmah-Millewa Forum. The Barmah-Millewa Forest is an example of a large wetland system with a water regime profoundly altered by river regulation with a formal environmental water allocation.

Groundwater-fed wetlands

As consumptive pressure on surface water resources has increased, irrigators in some regions have turned to groundwater resources (Allan and Lovett, 1997). In regions such as the Murray-Darling Basin, very little is known about the contribution of groundwater to wetland hydrology, and it is virtually ignored in much of the literature concerning environmental water allocations (Hatton and Evans, 1998). In a review of groundwater-dependent ecosystems, Hatton and Evans (1998) concluded that the Great Artesian Basin and the Swan Coastal Plain lakes were examples of groundwater-dependent ecosystems which are well-understood. Examples of groundwater-dependent ecosystems which are little-understood include the Cape Range karstic ecosystem at Exmouth, relict streams in the Central Australian Ranges, saline discharge lakes of the Western Murray Basin, paperbark swamps in the tropical far north, spring ecosystems of the Pilbara and coastal lakes of dunes and beachridge plains in eastern Australia.

In some cases the effect of human impacts on groundwater-dependent ecosystems is reduced water quantity (eg extraction), while in others the effect is super-abundance (eg clearing). Reducing the availability of groundwater may lead to a gradual decline in the spatial extent of the ecosystem, or the health of vegetation. In other cases, thresholds may exist where after a certain point the entire ecosystem is destroyed (Hatton and Evans, 1998).

Lakes of the Gnangara Mound (Swan Coastal Plain, Western Australia)

The Gnangara Mound is a large unconfined surface aquifer. It extends for approximately 2 200 km^2 under the Swan Coastal Plain north of Perth, Western Australia. Due to the Mediterranean climate, with hot dry summers and mild wet winters, recharge of the aquifer primarily occurs in winter. Land use above the aquifer includes state forest, national park and crown land. Of this, pine plantations cover 20 000 ha, while the remainder consists largely of natural bushland. Groundwater is abstracted from the aquifer for water supply for Perth, resulting in reduced recharge. Recharge is also reduced by the pine plantations; the extent depending upon the density of the pines. Clearing for urbanisation, in contrast, results in increased recharge. Variations in rainfall also affect recharge (WAWA, 1995; Allan and Lovett, 1997).

The mound supports over 200 wetlands, most of which are surface expressions of the aquifer (WAWA, 1995). The water regimes of these wetlands are therefore affected by extraction, changes in land use and rainfall variability. Other groundwater-dependent ecosystems which may be threatened by water extraction include *Banksia* woodland and the cave pool fauna of Yanchep National Park. Concern regarding the environmental impact of groundwater extraction from the Gnangara Mound led to the determination of environmental water requirements for the wetlands (Figure 4).

Early 1970s groundwater abstraction began on the Gnangara Water Mound

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1988 ERMP (Environmental Review and Management Program) Prepared by WAWA

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1988 ERMP Assessed by EPA and approved by government.
Increased abstraction allowed subject to meeting the following environmental conditions

- Absolute and preferred minimum water levels for wetlands
- Limits on private abstraction
- The introduction of a management and monitoring program
- Administration mechanisms for agency interaction on groundwater management
- Pine plantations would be managed by CALM with the objectives of achieving and maintaining their water use at a level that is no more than that of the pre-existing vegetation

↓

WAWA 1991 Catchment Protection Policy

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Research program focussed on

- Wetland ecology
- Evaluating, mapping and classifying wetlands

EPA Environment Protection (Gnangara Mound Crown Land) Policy

- identified beneficial uses
- identified activities that can degrade groundwater, native vegetation or wetlands

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WAWA expanded and revised monitoring program, to include

- groundwater levels
- terrestrial vegetation
- wetland vegetation
- wetland invertebrates

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New information regarding groundwater requirements of ecosystems

A small number of breaches of water level criteria had occurred, in both the duration below the preferred minimum level and the absolute minimum level

1993 allocation of groundwater to private users had exceeded the total quota

Public schemes had exceeded the quota

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1993 Government review of the original Environmental Conditions

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Section 46 EPA
Concepts of EWRs and EWPs: EWR: Environmental Water Requirements
EWPs: Environmental Water Provisions
Selected 13 wetlands on the Gnangara Mound and determined EWRs and EWPs for these.
Water Corporation switches off bores as directed by the Water Resources Commission.
New management and monitoring program

1996 EPA approves EWR and EWP process

Figure 4. History of the determination of environmental water allocations for wetlands of the Gnangara Mound

Groundwater extraction from the Gnangara Mound began in the early 1970s. In 1987 the WA Water Authority prepared an Environmental Review and Management Program (ERMP) for the mound. This was assessed by the Environment Protection Authority and approved subject to Environmental Conditions being met. These included the maintenance of wetland water levels (absolute and preferred minimum water levels were set), limits on private groundwater allocation and the establishment of a management and monitoring program (EPA, 1996; Allan and Lovett, 1997).

In response, a major research program was established to examine the impacts of altered water regime on wetland plants (Froend *et al.*, 1993) and aquatic invertebrates (Balla and Davis, 1993) and the use of wetlands by waterbirds (Storey *et al.*, 1993). Research was also carried out on the classification of wetlands according to water quality and invertebrate community data (Davis *et al.*, 1993) and wetland hydrology (Townley *et al.*, 1993). The information from these research projects was used to determine wetland water requirements. The method of integrating the information from the research projects was to first identify the water regimes necessary to maintain fringing vegetation. These regimes were then compared with the requirements of other ecosystem components, such as aquatic invertebrates and waterbirds (WAWA, 1995). The wetland vegetation research indicated that the effect of permanently lowered water levels would be a shift of the fringing vegetation down-gradient (Froend *et al.*, 1993). In applying this knowledge, the water regimes identified were those necessary to maintain the current vegetation distributions, avoiding the down-gradient shift (WAWA, 1995).

Vegetation requirements included a minimum 3 months dry period per year, for tree health, and a minimum inundation depth of 0.8 m to support the sedge *Baumea articulata*. The requirements of vegetation were considered in conjunction with the average seasonal range of the wetland to determine maximum and minimum water levels. Invertebrate requirements of a minimum period of four months per year of water in seasonal wetlands were incorporated into the determination of required water levels. This represents the time required for invertebrates to complete their life cycles. Maximum drying rates of 0.02 m/day were set to enable invertebrates that lay their eggs in the flooded fringing vegetation to complete their life cycles before the wetland dried (WAWA, 1995). The invertebrate research recommended that the maintenance of a mosaic of seasonal & permanent wetlands would meet the requirements of different species. Where water was pumped into wetlands to compensate for extraction, it was recommended that it be done in spring if peak water levels had not flooded the fringing vegetation. This follows the naturally occurring water regime where maximum water levels occur in spring (Balla and Davis, 1993). For waterbirds, management on a wetland-by-wetland basis was deemed necessary as no general relationships were found (WAWA, 1995).

Environmental Water Requirements (EWR) were set for 13 wetlands, including both permanently inundated and seasonal waterbodies. Environmental Water Provisions (EWP) were the actual water allocations for the environment; these were determined by considering social and economic factors as well as environmental needs. The requirements are sometimes met artificially, by pumping groundwater into the wetland. There is concern that artificial recharge of specific wetlands conflicts with the concept of setting

EWRs for representative wetlands as a basis for maintaining all wetlands of the mound. However it is considered appropriate, due to the high demand for water, provided that the artificial water levels are not significantly higher than regional water levels (Allan and Lovett, 1997). The mechanism of setting EWRs and EWPs for 13 representative wetlands was approved by the EPA (EPA, 1996).

Management objectives and performance indicators are set for each of the 13 representative wetlands. These vary between the individual wetlands, reflecting their particular ecological and social values. Examples include:

Coogee Springs

- maintenance of the diversity of aquatic invertebrate fauna,
- maintenance and if possible enhancement of the vegetation, and
- maintenance of water for bird breeding.

Lake Joondalup

- maintenance of the landscape amenity value (WAWA, 1995).

Performance indicators relate closely to the management objectives and allow the management regime to be assessed (WAWA, 1995).

Twin Swamps (WA)

The water regime of Twin Swamps, on the northern Swan Coastal Plain is managed to meet the requirements of the western swamp turtle (*Pseudemydura umbrina*), an endangered species with a very restricted distribution. Duration of flooding may have been reduced from pre-development levels at Twin Swamps by groundwater extraction, clay extraction, changes in landuse and rainfall variations (DCE, 1983). The turtle requires a minimum period of inundation to allow sufficient feeding of aquatic invertebrates to enable it to survive summer aestivation and to breed successfully. The precise water regime requirements of this species have been calculated as a minimum of 0.2-0.3 m from late June to early/mid November (Burbidge and Kuchling, 1994). These requirements are met by groundwater pumping (ANCA, 1996).

Great Artesian Basin Mound Springs (SA, NSW, Qld)

In the Great Artesian Basin protection of the water resource is being achieved through a reduction of wastage. Measures to reduce wastage of water include the capping of bores and the replacement of open earth drains with piped irrigation systems. While these activities are largely motivated by the need to maintain pressure for bore extraction, they also protect the mound springs. Currently 95% of the resource is being wasted due to the use of uncontrolled bores and open earth drains, therefore a change of practices could drastically reduce use. This has occurred to some extent already (Reyenga *et al.*, 1998). The new Water Management Plan for Cooper Creek in Queensland specifically includes the protection of wetlands, and the maintenance of variable and seasonal flow patterns as environmental principles. It provides protection for underground water supplies. A recharge area for the Great Artesian Basin lies within the Cooper Creek catchment, as does the Aramac spring complex (WAMP, 1999). The Olympic Dam minesite near Roxby Downs in South Australia extracts artesian water. Monitoring of water levels and biota is carried out to assess potential impacts of this extraction (Jensen *et al.*, 1998).

Conclusion

The case studies documented here reveal that emphasis has been placed on different ecosystem components in the determination of environmental water allocations to wetlands. Focus has been on reducing salinity (Kerang Lakes), protecting a single species (Twin Swamps), re-instating seasonality (Lake Merreti) and protecting water bird habitat (the Macquarie Marshes and wetlands of the Lachlan Valley). The determination of environmental water allocations for wetlands of the Gnangara Mound was made by examining the water regime requirements of several ecosystem components.

In practice the determination of environmental water allocations has not been a one-off exercise but has involved fine-tuning of allocations over time (illustrated in Figures 3 and 4), demonstrating the role of adaptive management. Increased extraction over time results from an increase in the consumptive demand for water, resulting in an increase in the environmental impacts. The use of environmental water requirements and performance indicators, as used in the management of the Gnangara mound, enables evaluation of the environmental water allocation. Future development and use of models such as the Environmental Flows Decision Support System (Young *et al*., 1999) may assist in the determination of modified flow regimes, but models are likely to be specific to particular types of wetlands and geographical locations. Models could be used to predict drying of wetlands which negatively affects waterbird breeding events, resulting in more strategically managed environmental water allocations.

3. COMPARISON OF METHODS FOR THE DETERMINATION ENVIRONMENTAL WATER ALLOCATIONS FOR WETLANDS

Introduction

Approaches to determining the environmental water requirements of wetlands can be divided into two main methodologies; hydrology-driven and ecology-driven (Gippel, 1996). The hydrology-driven approach involves first the description and then the restoration of the historic (pre-disturbance) water regime of the wetland. It is assumed that the biota is adapted to the pre-disturbance water regime and that the restoration of this regime will result in a healthy ecosystem. Where consumptive demand is high, a return to pre-development conditions will not be possible. In these cases the hydrology-driven approach aims to restore to the wetland a water regime which resembles the historic regime as much as possible (McCosker, 1998).

The ecology-driven approach involves the determination of the water regime requirements of the existing or preferred biota, and the provision of that regime (Gippel, 1996). Ecology-driven approaches include a methodology developed by Roberts *et al.* (2000) for floodplain wetlands based on plant water requirements, and the determination of water requirements of wetlands of the Gnangara Mound on the Swan Coastal Plain in Western Australia, based on the requirements of wetland flora and fauna (WAWA, 1995). The strengths and weaknesses of both hydrology- and ecology-driven approaches were assessed by examining their application in recent case studies.

Methodologies for determining environmental flows for rivers were also considered. These include historic discharge, or "rule of thumb" methods, habitat analysis methods which determine useable habitat by transect analysis and flow simulation, and instream habitat modelling, which determines habitat preference curves for species and models how changes in discharge affect habitat availability (Swales and Harris, 1995). Of these methodologies, historic discharge and habitat analysis methods may be considered hydrology-driven, while instream habitat modelling may be considered ecology-driven.

Habitat Analysis Methodology (Burgess and Vanderbyl, 1996) is a holistic method (Arthington, 1998) developed for riverine systems, It is based on the estimation of flows required to maintain all types of habitat. Wetlands are one of several habitats considered within this methodology (Burgess and Vanderbyl, 1996). Holistic approaches involve the incorporation of the essential features of the natural flow regime into the modified regime (Arthington and Pusey, 1992). Essential features of a flow regime include the perenniality or intermittency of flow, the seasonal distribution of flows, periods of no flow, and variability of flows at various time-scales (Arthington, 1998). Historical flow records from the period prior to regulation are analysed to identify the essential features of the river in question. Arthington and Pusey (1992) suggested that holistic methods are appropriate for wetlands.

In addition to these methodologies, modelling of the ecological effects of various environmental water allocations may also provide useful information for management. The Environmental Flows Decision Support System (EFDSS) developed by Young *et al.* (1999) is a software tool based on expert knowledge of the relationship between river flow and environmental condition. Drawing upon holistic methodologies (Arthington *et al.*, 1998), it enables the ecological effects of proposed flow scenarios to be examined (Young *et al.*, 1999). This approach extends the hydrologic approach to incorporate ecological considerations. It may be particularly useful in the trade-off process between various water users (Young, 1999).

Hydrology-driven approaches

General

The pre-development water regime of wetlands may be determined through the use of historical data where this is available, or through modelling. Significant elements of the pre-development water regime include the quantity, timing, duration and frequency of inundation (McCosker, 1998). This information may be gained from historical hydrological data or from modelling. While hydrology-driven methodologies for the determination of environmental flows overseas have tended to focus on the maintenance of minimum flows, in Australia the importance of maintaining natural variability is considered critical (Arthington, 1998). Management of wetland environmental water requirements may involve the reinstatement of seasonal or ephemeral water regimes (eg Mudgway *et al.*, 1996).

A limitation of the hydrology-driven approach is the lack of a direct focus on current ecological values. Where hydrological disturbance has occurred in the more distant past the vegetation may have inalterably changed as a result of the disturbance, and the historical water regime may not be relevant to the existing biota (Bennett and McCosker, 1994). The biota may also have changed due to factors not directly related to the hydrological disturbance, for example, alteration to the fire regime, cattle or climate change. In these cases return to the pre-development state may not be possible without a high level of intervention, as seed banks have a finite life span (Brock, M., 1998).

Advantages of hydrology-driven approaches in riverine ecosystems include low cost (Growns, 1998), and the lack of reliance on detailed knowledge of the water requirements of wetland biota. However they are considered to have a low level of defensibility in trade-off situations (Growns, 1998). They are not amenable to predictive modelling of the consequences of a lack of compliance with the determined environmental water allocations.

Pusey (1998) argues that the question being addressed by environmental flow allocations in rivers is “how much water can be harvested from a river without ecological damage?” The question for wetland environmental water allocations may be defined as “how much can the water regime deviate from pre-development conditions without ecological damage?” Where it is not possible to return to the pre-disturbance water regime because of consumptive water allocations, there is little basis for the determination of the degree of allowable deviance without reference to the water requirements of the biota. Hydrology-driven approaches in river environmental flow determination have been based on percentages of the “natural” flow (Arthington, 1998). This may not be valid unless the determination is based on biological data as the response of biota to variations in water regime is rarely linear (Roberts *et al*., 2000). Thresholds at which ecological damage occurs can only be determined through detailed analysis of the needs of biota.

Examples of hydrology-driven approaches

Hydrology-driven resource management approach

Knights and Fitzgerald (1994) propose an approach to riverine environmental flow determinations which is hydrology-driven and incorporates socio-economic impact data (Figure 5). Although it uses ecological data, it is hydrology-driven in that possible management measures are modelled in terms of their divergence from the pre-development water regime, implying that the objective of management is to re-instate the pre-development water regime to the extent that socio-economic constraints allow. They argue that their approach is more pragmatic than ecol

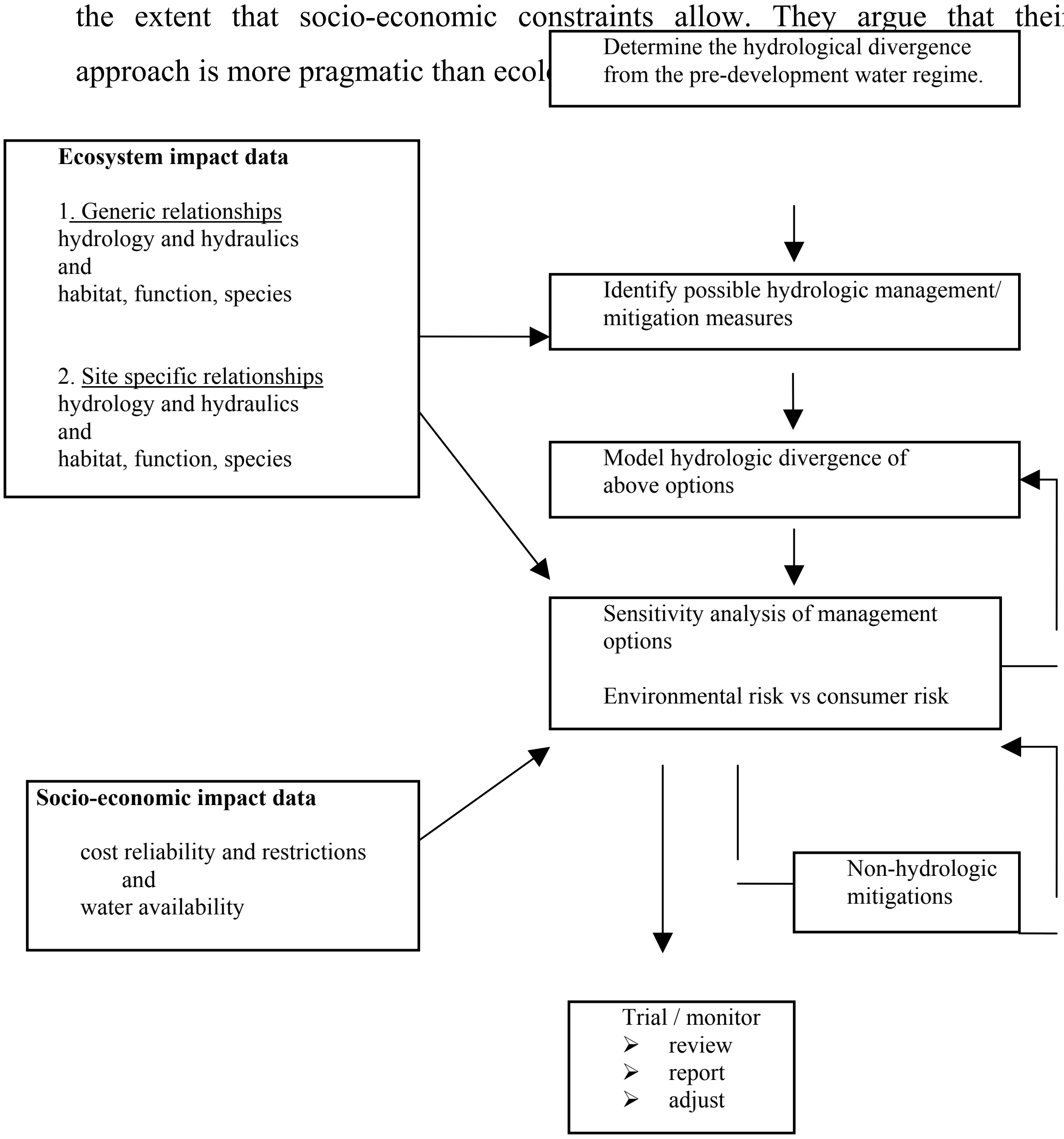

Figure 5 Hydrology-driven resource-management approach (Knights and Fitzgerald, 1994, p.136)

Hydrology-driven approach to the determination of environmental water requirements of the Gwydir wetlands

Bennett and McCosker (1994) used computer simulation to determine the pre-development water regime of the Gwydir Watercourse. The results indicated that inundation of 20 000 ha occurred in 85% of years. A common duration of more than 30 days was suggested. The approach of this hydrology-driven analysis supported estimates of plant water requirements (McCosker and Duggin, 1993: Bennett and McCosker, 1994). The quantity of water required to achieve inundation of areas of water couch and rushes was determineded using the following two methods.

1. calculation of a water budget (McCosker and Duggin, 1993), and
2. the establishment of the relationship between streamflow and area inundated using remote sensing and streamflow records (Bennett and McCosker, 1994).

The two methods produced similar results.

Ecology-driven approaches

General

A significant advantage of ecology-driven approaches is that they directly address the current ecological values and issues facing the wetland, for example, use by waterbirds, presence of endangered species or communities, tree deaths associated with altered hydrology and the presence of invasive species. This means that allocations developed using these approaches should be easily defensible in trade-off situations. Ecology-driven approaches enable conceptual models to be developed which indicate the consequences of various water regime scenarios for wetland biota. Obligations associated with Ramsar-listing may be directly addressed, as water regimes can be managed to meet the breeding requirements of waterbirds (see Briggs and Thornton, 1999). Hydrological elements of key significance may be identified through an examination of the requirements of biota, for example, duration and frequency of inundation and depth.

A disadvantage of ecology-driven approaches is the lack of information regarding species requirements. Additional research may be required where existing information is inadequate (Roberts *et al*., 2000). A limitation is that existing knowledge of plant water requirements is usually based on observation rather than experimentation (Bennett and McCosker, 1994). Longer term studies are required to determine the effects of extreme floods and droughts. Methodologies based on an ecology-driven approach generally involve the examination of historical water regime data (eg Roberts *et al*., 2000, Figure 6), but differ from hydrology-driven approaches in that they are characterised by ecology-based management objectives. In an adaptive management framework, management objectives can be framed as testable hypotheses, which monitoring programs can be designed to test (Chapman and Underwood, 1997). For example, if the management objective is to maintain healthy *Melaleuca*, and a strategy is devised to provide a water regime to achieve this objective, monitoring of water levels and *Melaleuca* health should provide an indication of both whether or not the managed water regime is achieved, and whether the objective is achieved. The results of hydrological and biological monitoring programs can therefore provide further information regarding species response to changes in water depth.

In environments where it is not be possible to return to a pre-disturbance state, ecology-driven approaches may be particularly useful. Roberts *et al*. (2000) consider that restoration to a pre-disturbance state may be achievable in small, discrete wetlands, with the aid of regulators, but may not be possible for floodplain wetlands. Chapman and Underwood (1997) argue that restoration may not be a suitable objective for wetlands affected by urban development.

Examples of ecology-driven approaches

Objectives based on vegetation: methodology for estimating floodplain wetland plant water requirements (Roberts *et al.*, 2000)

Roberts *et al*. (2000) developed a methodology for the determination of environmental water allocations for floodplain wetlands based upon vegetation requirements (Figure 6). This methodology differs from the hydrology-driven approach of Knights and Fitzgerald (1994) and Mudgway *et al.* (1996) in that the management objectives are vegetation-related, and detailed analyses of plant water regimes are required. Plant water regimes are defined as the pattern of water level changes required for the maintenance and regeneration of plant species. Longer-lived woody vegetation is more likely to reflect historic water regimes than herbaceous vegetation, which responds rapidly to changes in water regime (McCosker, 1998). Effects of altered hydrology on floodplain vegetation include tree deaths (Roberts *et al*., 2000), invasion of the weed lippia (*Phyla canescens*) (McCosker, 1998) and river red gum (*Eucalyptus camaldulensis*) invasion of natural moira grasslands (Bren, 1992). This methodology has the advantage of a high level of defensibility during trade-off negotiations, as the determined environmental water allocations or requirements are ecologically based.

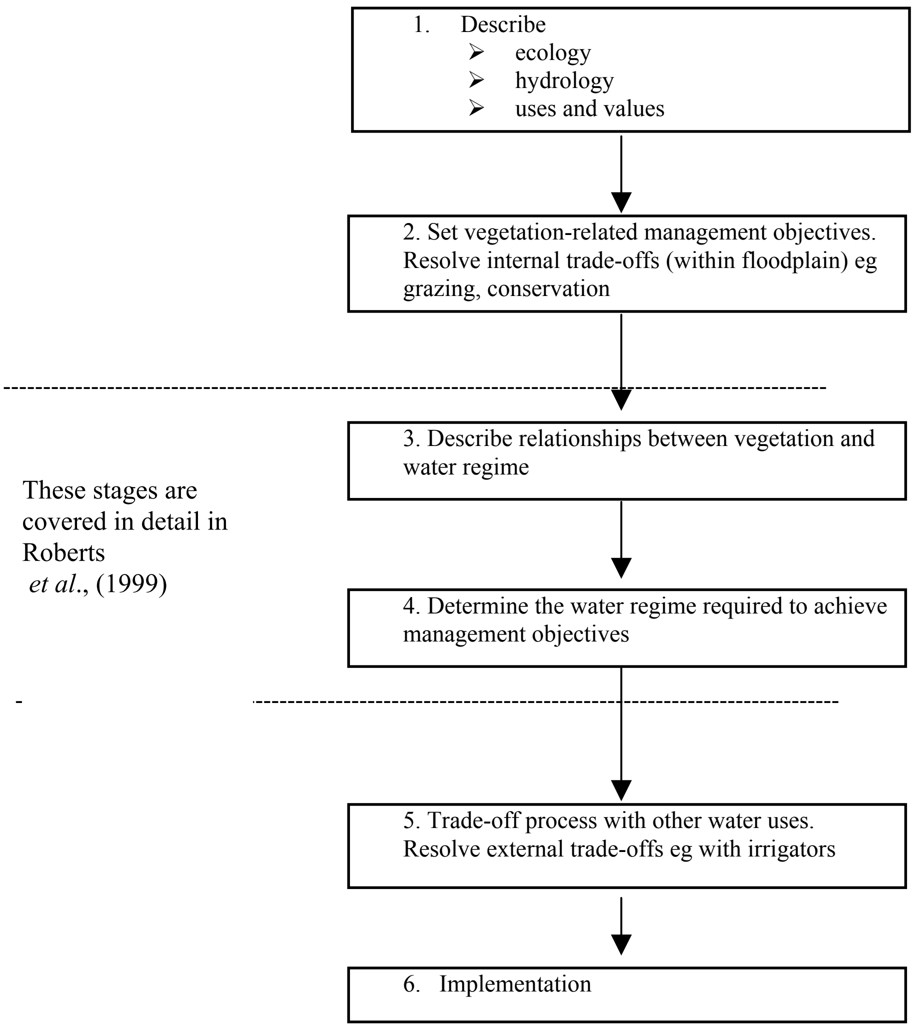

Figure 6. Methodology for estimating floodplain wetland water allocations based on the plant water requirements (adapted from Roberts *et al*., 2000). Other ecology-driven methodologies are examined in terms of the steps of this methodology (Figures 7 to 9).

Framework of methodology used for Gwydir wetlands (McCosker and Duggin, 1993: Bennett and McCosker, 1994: Keyte, 1994)

In the Gwydir wetlands, McCosker and Duggin (1993) examined plant water regime requirements. Four vegetation communities were identified, with their distributions dependent on different flood frequencies. Using a water budget, the quantity of water required to inundate two of these communities was calculated. There was an emphasis on control of the weed lippia (*Phyla canescens*), which had increased in abundance as a result of reduced flow to these wetlands (Figure 7).

1. Describe
- hydrology
- ecology

↓

2. Set flora and fauna-related management objectives.

Implicit: maintain vegetation in good condition (restrict the invasion of the exotic lippia (*Phyla nodiflora*)).
Provide suitable conditions for waterbird breeding

↓

3. Describe relationships between vegetation and water regime.
Four vegetation communities were considered; their distributions were defined in terms of frequency of inundation.

↓

4a. Determine the water regime required to achieve management objectives in terms of frequency and duration of inundation.
The water couch community was considered to require almost annual inundation for periods in excess of 30 days in order for it to compete with lippia.

↓

4b Determined how the desired water regime could be delivered, ie the quantity of water required to achieve the desired inundation.
This was done by using

- water balance calculations (McCosker and Duggin, 1993) and
- remote sensing and upstream flow records to describe the relationship between upstream flow and the area inundated (Bennett and McCosker, 1994)

Figure 7. Determination of environmental water requirements of Gwydir wetlands (McCosker and Duggin, 1993; Bennett and McCosker, 1994)

Objectives based on vegetation, aquatic invertebrates and waterbird use: the determination of Environmental Water Requirements for Gnangara mound wetlands

A comprehensive ecology-driven methodology was used for the determination of Environmental Water Requirements and Environmental Water Allocations for the groundwater-fed wetlands of the Gnangara Mound on the Swan Coastal Plain, WA (Figure 8, WAWA, 1995). The water regimes of these wetlands are threatened by groundwater extraction. The hydrology of the wetlands and the water requirements of the wetland vegetation, aquatic invertebrates and waterbirds were examined in targeted research programs (see Balla, 1994; Balla and Davis, 1993; Davis *et al.*, 1993; Froend *et al.*, 1993; Storey *et al.*, 1993; Townley *et al.*, 1993, Figure 8). The water regime requirements of vegetation were first examined, with an objective of maintaining the existing distributions. These requirements were then compared with the requirements of aquatic invertebrates and waterbirds, for the determination of Environmental Water Requirements. Individual objectives and Environmental Water Requirements were set for each wetland, reflecting their particular environmental values (WAWA, 1995).

This approach has similarities with the Roberts *et al*. (2000) methodology for floodplain wetlands. It differs in that the requirements of wetland fauna were examined as well as those of vegetation. In wetlands where fauna are likely to have direct water regime requirements this approach may be more appropriate.

Where different water regimes favour particular animal or plant groups at the expense of others, the preferred regime may be selected according to the ecology-defined management objectives of Step 2 (Figure 8). For example, in floodplain wetlands of some regulated rivers, the delivery of short duration floods could result in water reaching a comparatively large area of the floodplain, benefiting trees. The delivery of the same quantity of water in a longer duration flood will tend to benefit waterbird breeding (LWRRDC, 1997a). This is an example of a situation where a within-wetland trade-off is required (Step 2, Figure 8).

1. Describe
- ecology
- hydrology
- uses and values

Wetlands mapped and classified according to aquatic invertebrate communities, etc

↓

2. Set ecology-related management objectives (related to waterbirds, aquatic invertebrates and macrophytes, fringing vegetation, control of invasive species). Some management-related objectives are social rather than environmental in nature, eg maintenance of landscape amenity value through the imposition of an artificially permanent water regime.
This step involves the resolution of internal trade-offs (within-wetland) eg conservation, landscape amenity

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3. Describe relationships between vegetation, aquatic invertebrates, waterbirds and water regime.

↓

4. Determine the water regime required to achieve management objectives
Environmental Water Requirements were set for 13 wetlands.
These were based on maintaining the existing distributions of vegetation, in terms of position and extent.
This regime was then compared against the water regime requirements of wetland fauna, and adjusted where necessary.
Water regime requirements were defined according to minimum and maximum water levels.
Variability was incorporated by specifying the maximum numbers of years that certain criteria could be exceeded.

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5. Trade-off process with social and economic factors.
Represented by Environmental Water Provisions: the actual water allocations for the environment.

↓

6. Implementation.

The use of performance indicators (related to the extent of sedge vegetation in the case of Lake Jandabup, for example) allows the testing of the determined water regimes.
ie tests the hypothesis that the provision of the Environmental Water Requirements results in the maintenance of the existing extent of sedge vegetation.

Figure 8. Framework of the methodology used in the determination of the environmental water requirements of the wetlands of the Gnangara Mound, on the Swan Coastal Plain, WA.

Objective based on the protection of an endangered species: the western swamp turtle

Environmental Water Requirements of Twin Swamps were determined to meet the requirements of the endangered western swamp turtle (*Pseudemydura umbrina*) (Figure 9). This species has an extremely restricted distribution. The key water requirement identified was a minimum hydroperiod of 4 months per year. This is an example of a situation where the primary objective for the determination of a wetland environmental water allocation was the protection of a single endangered species.

1. The wetland together with the Ellen Brook Nature Reserve, is identified as comprising the sole remaining habitat of the endangered western swamp turtle.

   The hydrology of Twin Swamps and the water regime requirements of the western swamp turtle are described.

2. Management objective: the maintenance of a water regime which will allow the western swamp turtle to survive and breed.

3. Describe the relationship between the survival and breeding of the western swamp turtle and the water regime.

4. Determine the water regime required to achieve management objectives. (Minimum of four months of inundation required per year, to be achieved by pumping groundwater into the lake in dry years.)

5. Implementation

Figure 9. Determination of environmental water requirements for Twin Swamps, WA (Burbidge and Kuchling, 1994).

Management for waterbirds

Briggs and Thornton (1999) developed guidelines for the management of *Eucalyptus camaldulensis* wetlands for waterbird breeding. A minimum inundation period of 5 to 10 months is required for waterbirds to complete breeding. Two waterbird breeding patterns in relation to water regime have been identified. Birds such as darters, cormorants, herons, white ibis and spoonbills generally nest at wetlands with permanent water in deeper, open areas; in contrast, ducks breed at wetlands which dry out completely between floods (Briggs and Thornton, 1999). The waterbird model of Young *et al.*'s (1999) EFDSS (discussed below) was based on the work of Briggs and others. Briggs and Thornton (1999) concluded that management of the water regimes of *Eucalyptus camaldulensis* wetlands for the optimisation of waterbird breeding should include flooding under nest trees for a minimum of 5 to 10 months, followed by drying before the next flood. Water should be allowed to remain permanently in deeper, open areas. In this way the requirements of both groups of waterbirds can be met.

Objectives based on waterbirds: Kerang Lakes (Hird and Johnson Swamp)

An ecology-driven approach has been used for the determination of the water regime management of Hird and Johnson Swamps, part of the Kerang Lakes in Victoria (DCNR, 1990). The hydrology of these wetlands has been altered. Ecological and social values of waterbird habitat and duck hunting were identified. In the determination of a suitable water regime, the likely response of wetland plants and waterbirds was considered. The effects of water regime on invasive species such as *Typha sp*., water milfoil and carp were also considered. For example, an increase in the percentage cover of *Typha sp*. had occurred as a result of the altered hydrology. This was considered detrimental to both duck hunting and the preservation of waterbird habitat.

The approach used in this study (DCNR, 1990) was to investigate two scenarios in terms of short- and long-term impacts on wetland flora and fauna, with an overall emphasis on maintaining habitat values that would enhance the value of the wetlands for waterbirds and duck-hunters. One scenario was the imposition of a permanent water regime, and the other was to allow the wetlands to dry out between summer and autumn every 3-4 years. The latter option was considered to provide the best long-term waterbird habitat.

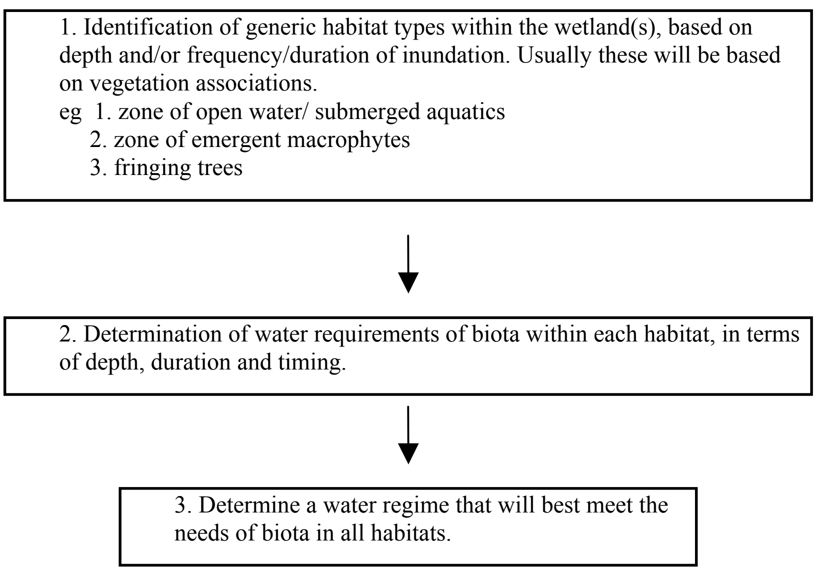
Environmental water allocations for the Kerang Lakes were calculated using water and salt balances (Mudgway *et al*., 1996). Objectives were to reduce the salinities by flushing permanent wetlands, and to provide a period of drying for semi-permanent wetlands. An environmental water allocation of 27 600 ML per year was available for this. It was deemed that the period of drying could be either three to four months every year or alternatively a period of one year in every five years. The option of one year every five years was selected on the basis of being more "natural" and easier to achieve through a rotation system.

Habitat Analysis Methodology

(Burgess and Vanderbyl, 1996)

Habitat Analysis Methodology was developed in Queensland, for the Water Allocation and Management Planning Initiative (Arthington *et al*., 1998), for the determination of riverine environmental flow allocations. A "panel of experts" approach, it is based on estimated flows required for the maintenance of all types of habitat. It differs from the ecology-driven approaches previously described in that it is based on meeting the requirements of habitats rather than species. Generic habitats, such as riffles, wetlands and floodplains are first identified, then the flows which will maintain those habitats are determined (Burgess and Vanderbyl, 1996). Habitat Analysis Methodology involves an examination of historical flow records to describe the pre-development flow regime, and does not include guidelines for the determination of plant water requirements (McCosker, 1998).

An adaptation of this approach for wetlands is given in Figure 10. It differs from Habitat Analysis Methodology in that the water requirements of wetland biota are specifically examined. This adaptation is compatible with ecology-driven approaches. The determination of wetland plant water regimes frequently involves the consideration of plant water requirements in terms of generic habitat types. For example, in the Gwydir wetlands, different wetland habitat types, characterised by particular vegetation communities, were considered in relation to water regime (Figure 7, Step 3; Keyte, 1994). Areas of water couch and rushes (the core wetland areas) were examined for the calculation of the quantity of water required to achieve inundation (Figure 7, Step 4a and Keyte, 1994). Young *et al.*'s (1999) Environmental Flows Decision Support System (EFDSS) (Section 5) considers different habitats of the riverine environment. These wetland habitats, based on plant communities with clonal growth, are likely to be dynamic; their distributions moving up- or down-gradient in response to water level changes (Froend *et al*., 1993).



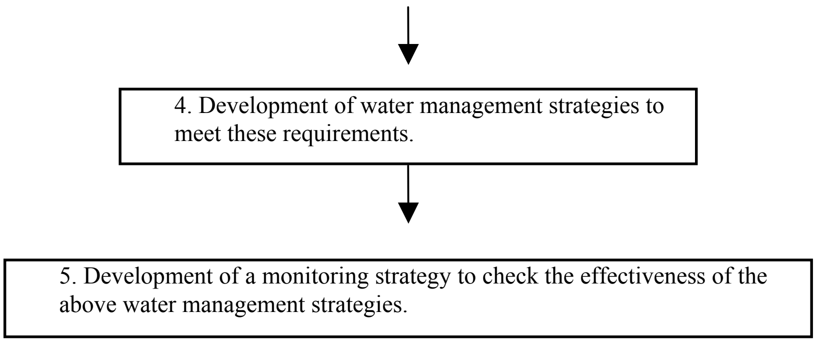


Figure 10. Adaptation of Habitat Analysis Methodology (Burgess and Vanderbyl, 1996) for wetlands.

Modelling

Environmental Flows Decision Support System (EFDSS) (Young *et al.*, 1999)

The EFDSS is a computer-based numerical model which enables the relationship between flow regimes and ecological condition to be explored. Data from computer-simulated river flows are used to drive models of environmental condition (Young, 1999). Designed for the regulated rivers of the Murray-Darling Basin, it includes the wetlands associated with rivers. A model of floodplain hydrology (Young *et al*., 1999) is included. Zones and locality types are recognised; four of the six locality types are ‘off-river;’ billabongs, wetlands, riverine lakes and floodplains, and as such fall within the scope of this study. The impact of different scenarios (modelled flow regimes) on the ecology can be examined.

The incorporation of some aspects of a hydrology-driven approach is evident as ‘natural’ and ‘current’ scenarios are always included. The ‘natural’ scenario is the conditions that would exist in the absence of regulation or diversion. It is essentially an ecology-driven approach in that it is based on information regarding the response of biota to changes in flow regime. In the case of fish and waterbirds, groups of species with common water regime requirements are defined.

Decision support systems such as this could be designed specifically for non-riverine wetlands. This approach may be useful in trade-off situations, as the effect of less than optimum water regimes on ecological condition will be demonstrated. It may be a particularly useful tool where consumptive pressure on water resources is strong as a return to pre-development water regimes is unlikely to be achievable in these situations (Young, 1999).

Conceptual modelling

Conceptual modelling involves the examination of the ecological effects of various water regime scenarios. A generalised model of the responses of amphibious, submerged and terrestrial wetland plants to altered frequency of flooding, depth or extent of flooding, duration of flooding, and variability of flooding, as well as to more permanently wet and more permanently dry conditions has been developed by Brock and Casanova (1997). This model was then used in an analysis of the likely effects of water extraction on the wetlands associated with the Paroo River (Brock, 1999). This is an example of the use of conceptual modelling.

Summary of methods

The major elements of the methods together with assessments of their respective advantages and disadvantages, are summarised in Table 2. A key disadvantage of hydrology-driven approaches is their lack of defensibility with respect to biotic conditions. Where consumptive demand for water is high, and there is either either adequate existing ecological knowledge or resources for targeted studies, ecology-driven approaches are likely to be most suitable. Multi-criteria analysis (Table 2) may be useful in the evaluation of environmental values and social and economic constraints, and in the resolution of trade-offs between different values and uses.

Table 2. Summary and assessment of methods for determining environmental water allocations for wetlands.

Approach	Method	Major elements	Advantages	Disadvantages
Hydrology-driven		Determine the pre-development water regime using any existing data and/or modelling. Attempt to restore this regime.	Does not require knowledge about the water requirements of wetland plants and animals Costs low	The biota may have changed since pre-development times due to causes not directly related to water regime; ie fire frequency, climate change. Assumes the biota have linear responses to changes in water regime (Young *et al*., 1998). This is rarely the case (Roberts *et al*., 2000) Difficult to justify the determined water regime in trade-off situations Not amenable to the development of conceptual models
	Knights and Fitzgerald (1994) Incorporates multi-criteria analysis into an approach that is primarily hydrology-driven	Describe the divergence of the modified water regime from that of the predevelopment regime using data on the relationship between water regime and habitat, ecosystem function and species data on the socio-economic impact of changes to water availability, Develop the preferred management option	Includes economic and social considerations Authors propose that it is more “workable” than ecology-driven approaches.	As above

Approach	Method	Major elements	Advantages	Disadvantages
Ecology-driven	General	Determine a water regime that will match the requirements of preferred or existing biological communities, or those which used to exist (Gippel, 1996)	Particularly useful where little pre-disturbance hydrological information is available. Explicitly aimed at the protection of identified communities/species. Directly addresses the respective values of wetlands. Allows focus to be placed on meeting the water requirements of threatened/endangered species or communities. Key hydrological elements of relevance to biota may be identified, eg hydroperiod, frequency of inundation. Where invasion of exotic species is directly related to the flow regime, the problem can be specifically addressed. The determined water regime should be defensible on ecological/biological grounds in trade-off situations. Amenable to conceptual modelling	Is dependent upon knowledge about water requirements of wetland biota. Requires a large research effort or detailed existing knowledge. However, many wetland species are widely distributed (eg river red gum), so knowledge from one wetland environmental water allocation can be utilised for others in the same region. Monitoring data (hydrological + biological) will add to the knowledge of the water regime responses of wetland biota.

Approach	Method	Major elements	Advantages	Disadvantages
Ecology-driven	Gnangara	Determine the water requirements of existing or desired plants Set environmental water requirements Check against environmental water requirements of wetland fauna Refine environmental water requirements to suit fauna if necessary	Designed to protect existing environmental values of wetlands with already disturbed hydrology, which were potentially threatened by groundwater extraction.	Requires a large research effort or a large amount of existing knowledge
	Roberts *et al*., (2000)	Determine the water requirements of existing or desired plants Set environmental water requirements	Can easily be adapted to include the water requirements of fauna Identification of surrogate species (Roberts *et al*., 2000, p.36) may enable conceptual models to be devised.	Requires a large research effort or a large amount of existing knowledge Does not address the water regime requirements of fauna.

Approach	Method	Major elements	Advantages	Disadvantages
Holistic Approach (hydrology- driven, but incorporates ecological requirements). *Restore the essential elements of the pre-development water regime in order to protect the biota*	Adaptation of Habitat Analysis Methodology (Burgess and Vanderbyl, 1996) for wetlands	An expert-panel approach. identify generic habitat types determine the water requirements of the biota of each habitat develop water management strategies to meet those requirements develop a monitoring program to check the effectiveness of the strategies	Hydrological monitoring (depth over time) in conjunction with biotic monitoring should allow the testing of : the experts' assumptions about the response of the biota to change in water regime, and the effectiveness of the water management strategies to meet the requirements Habitat-based	Is dependent upon experts' knowledge of water requirements of wetland biota. The extent to which environmental water requirements, provisions or allocations determined by expert panels are defendable in trade-off situations may vary, depending upon the extent to which documentation is provided to support the expert opinion (Growns, 1998). Is not based around explicit objectives (the implicit objective is to return the wetland to the pre-development state).

Approach	Method	Major elements	Advantages	Disadvantages
Modelling	Conceptual modelling		Focus on major habitats/ vegetation communities/ invasive species eg *Melaleuca* recruitment or survival, extent of *Typha*, etc. Incorporates water regime/ water balance Can incorporate variability	Generally requires the same knowledge/ research base as ecology-driven methods.
	Computer modelling eg EFDSS (Young *et al*., 1999)		Provides a framework for the gathering of data Should result in a high level of defensibility of the environmental water allocations in trade-off situations	Generally requires the same knowledge/ research base as ecology-driven methods. This model is specific to rivers of the Murray-Darling. New models will need to be developed for other regions/ types of wetlands.
Multicriteria analysis		List: environmental values socio-economic constraints knowledge of water requirements of fauna/flora hydrology current historical	May enable the evaluation of environmental values and social and economic constraints May be used to identify key species/ communities that are threatened by water regime disturbance, for targeted research Enables environmental water management of different wetlands to be compared, & differences justified Useful for resolving internal and external trade-offs (Figure 3, Steps 2 & 5)	Will not necessarily provide water requirements/ allocations

Critical evaluation of methods

A best practice methodology should address community aspirations, set ecological functions and ecosystem services as objectives, include objectives to enable the management to be evaluated, and not rely on a past set of ecological or hydrological conditions. The methodologies were therefore evaluated (Table 3) according to the following criteria:

- Whether community aspirations can be structurally addressed in the process of setting objectives
- Whether ecological functions and ecosystem services are set as objectives
- Whether the method can be evaluated for its performance according to set objectives
- Whether the method relies on a specified and known set of past ecological or hydrological conditions.

The Gnangara method was the only one fitting all of the above requirements, as its inclusion of seasonally drying in objectives incorporates ecological functions and ecosystem services into objectives. All three ecologically-driven methods may be evaluated according to objectives. Both the Gnangara and Roberts methods address community aspirations in the setting of objectives, through the identification of uses and values.

Table 3. Critical evaluation of methods.

Method	Have community aspirations been structurally addressed in the process of setting objectives?	Are ecological functions and ecosystem services set as objectives?	Can the method be evaluated for its performance according to set objectives?	Does the method rely on a specified and known set of past ecological or hydrological conditions?
Knights and Fitzgerald (1994) hydrology-driven resource management approach	No	No	No	Yes: hydrological
Roberts *et al*. (2000)	Yes: incorporated into uses and values in first step	No. Objectives are based on vegetation health	Yes	No
McCosker and Duggin (1993)	No	No. Ojectives are based on vegetation health and waterbird breeding	Yes	No
Gnangara method	Yes: incorporated into uses and values in first step	Yes *	Yes	No

* The method included an emphasis on maintaining seasonal drying in wetlands deemed to have historically been seasonal wetlands. This was incorporated into objectives for individual wetlands. The determination of whether a wetland was seasonal or not was based on the life histories of invertebrates. Seasonality relates to ecosystem function and could be interpreted as part of the ecological character of a wetland.

Discussion

A best practice methodology for the determination of environmental water allocations for a wetland or wetland aggregation is likely to incorporate elements of virtually all methods described here. In practice, determinations of environmental water allocations for wetlands generally depend on an assessment of pre-development and current water regimes, and the effects of altered hydrology on wetland vegetation, due to limitations of knowledge regarding vegetation water requirements (McCosker, 1998). A determination of environmental water allocations based on meeting vegetation objectives (Roberts *et al.*, 2000 methodology) could be compared against the requirements of waterbirds (see Briggs and Thornton, 1999) or other wetland fauna (see Scott and Grant, 1997; Burbidge and Kuchling, 1994). The use of objectives based on identified values and the requirements of wetland biota is likely to provide a high level of defensibility for decisions regarding environmental water allocations.

Often wetlands are considered in terms of several different zones for the determination of water regime requirements of flora and fauna. The zones may be described in terms of vegetation communities with different water requirements (McCosker and Duggin, 1993; Keyte, 1994), or as vegetated areas compared with areas of open water (eg Briggs and Thornton, 1999). This aspect of Habitat Analysis Methodology is frequently incorporated into the analysis of wetland environmental water requirements.

The means of achieving the desired water regime is dependent upon the source of the water. In the case of the groundwater-fed wetlands of the Gnangara mound, the desired water regime is set using depth criteria. Groundwater pumping is controlled in such a way that these criteria are met (WAWA, 1995). For riverine wetlands, the relationship between wetland water levels and streamflow may be determined through the analysis of streamflow data and inundated area, using either aerial photos or remote sensing. Alternately water balance calculations may be used. The desired water regime may then be achieved through the control of dam releases, the operation of regulators, or through appropriate licensing of consumptive users.

Boulton and Brock (1999) noted that management strategies for Australian wetlands must be sufficiently flexible to incorporate the temporal and spatial variability that is a major characteristic of these systems. Natural variations in climate result in variable water regimes both within and between years. As a consequence the determination of environmental water allocations for a wetland is likely to be an ongoing process requiring adaptive management. The use of adaptive ecological management, where actions are monitored and used to successively refine further management approaches, will be a particularly important strategy for wetlands where changes need to be made when climatic conditions change (Boulton and Brock, 1999).

4. FRAMEWORK FOR ENVIRONMENTAL WATER ALLOCATIONS FOR WETLANDS

Framework

The following framework (Figure 11) was developed from the review of contemporary methods and approaches (Sections 2 and 3 of this report). Elements of both the Roberts *et al.* (2000) and Gnangara (WAWA, 1995) methods have been incorporated into a stepwise approach.

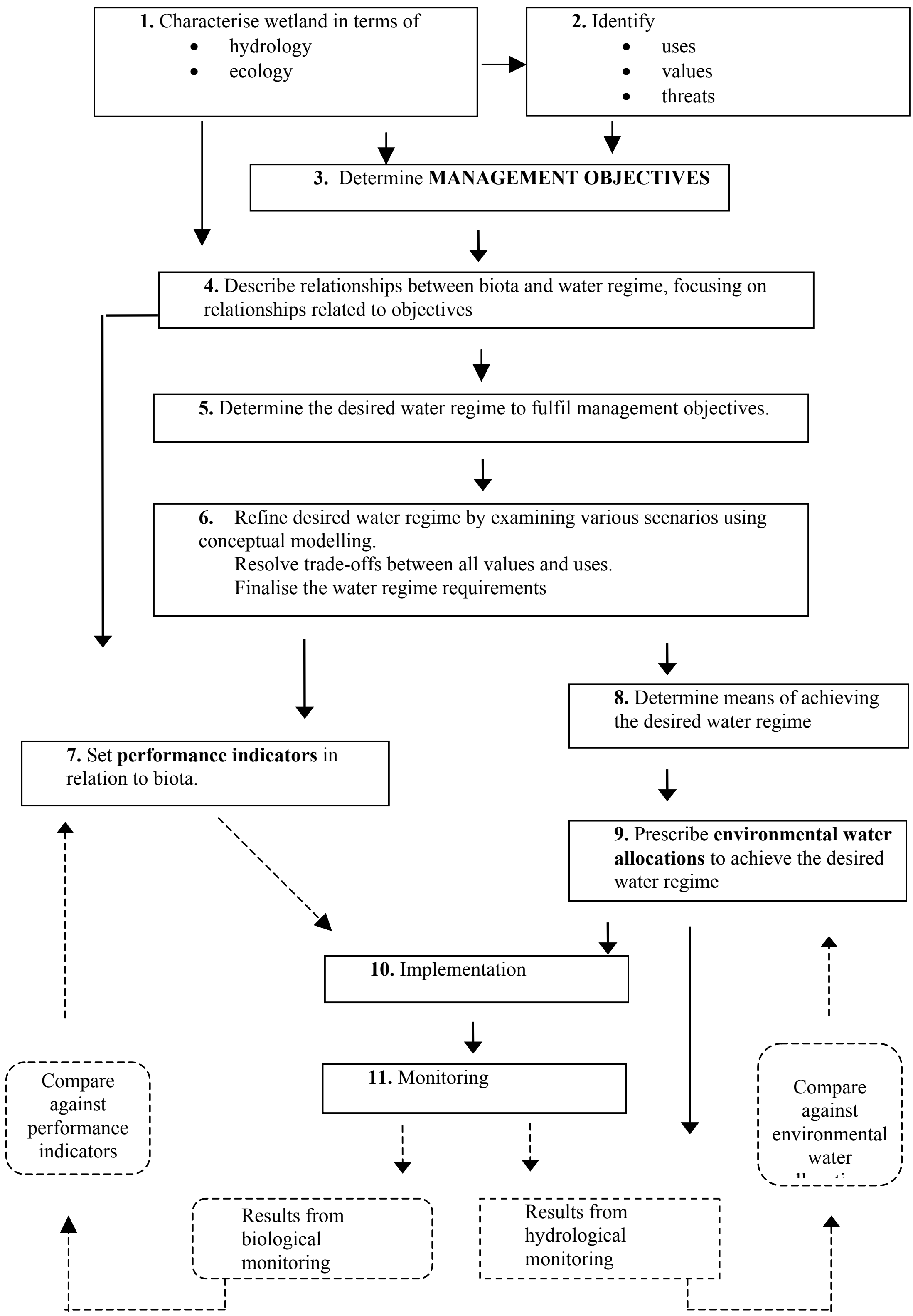

1. Characterise wetland in terms of
• hydrology
• ecology
2. Identify
• uses
• values
• threats
3. Determine MANAGEMENT OBJECTIVES
4. Describe relationships between biota and water regime, focusing on relationships related to objectives
5. Determine the desired water regime to fulfil management objectives.
6. Refine desired water regime by examining various scenarios using conceptual modelling.
Resolve trade-offs between all values and uses.
Finalise the water regime requirements
7. Set performance indicators in relation to biota.
8. Determine means of achieving the desired water regime
9. Prescribe environmental water allocations to achieve the desired water regime
10. Implementation
11. Monitoring
Compare against performance indicators
Compare against environmental water
Results from biological monitoring
Results from hydrological monitoring

Figure 11. Framework for the determination of environmental water allocations. Feedback loops are indicated by dashed lines.

Step 1. Characterisation of wetland hydrology and ecology

Step 1 involves the description of the hydrology and ecology of the wetland. Existing hydrological records are examined together with rainfall and evaporation data. It may be possible to identify the "essential elements" (*sensu* Arthington, 1998) of the pre-development water regime (such as the timing and duration of dry periods) from historical records. Alterations to the pre-disturbance water regime can be identified. Analysis of the water budget may be useful in determining human impact.

The water budget of a wetland may be examined in terms of the following equation:

$\Delta S\ (t) = P + Q_i + G_i - E - Q_o - G_o$

where

$\Delta S\ (t)$ = Change of wetland water volume over a defined period of time

P = Precipitation falling on the wetland over a defined period of time

Q_i = Surface water flowing into the wetland over a defined period of time

G_i = Ground water flowing into the wetland over a defined period of time

E = Evapotranspiration over a defined period of time

Q_o = Surface water flowing out of the wetland over a defined period of time

G_o = Ground water flowing out of the wetland over a defined period of time

(Carter, 1986; LaBaugh, 1986; Bennett and McCosker, 1994).

The examination of water budget is usually difficult due to inadequate data (Gippel, 1993). The modelling of average monthly water levels rather than average annual water levels allows the consideration of the water requirements of wetland flora and fauna.due to the greater ecological significance of the former. Gippel (1993) used a variety of estimation techniques to develop a continuous monthly model of the water level of a wetland.

Existing data for wetland flora and fauna data are compiled, knowledge gaps are identified and surveys are carried out where necessary. Surveys may be focused on responses of the biota to changing water regimes. Examples include:

- encroachment by weeds and terrestrial vegetation into areas previously characterised by wetland vegetation (see McCosker and Duggin, 1993);
- changes in recruitment of woody vegetation (eg indicated by stands of either entirely juvenile or entirely mature trees) (see Bren, 1992)
- tree deaths (see Roberts *et al*., 2000).

Wetland zones may be delineated based on vegetation communities (eg McCosker and Duggin, 1993), and the water regime of each zone described.

Descriptions of the ecology and the hydrology of a wetland form the basis of characterisation of the wetland. The ecological character is defined as:

> "the structure and inter-relationships between the biological, chemical, and physical components of the wetland. These derive from the interactions of individual processes, functions, attributes and values of the ecosystem(s)"
>
> (Ramsar web site)

Aspects of the ecological character include the intermittency, seasonality or permanency of the water regime, and the presence of particular vegetation communities and fauna. Dry phases give semi-permanent, seasonal or ephemeral wetlands their ecological character, as it affects many wetland processes (Crome, 1986, Balla and Davis, 1993, Bunn, 1999). Many wetland plants have specific requirements in terms of a dry phase, referred to as the inter-flood interval by Roberts *et al.* (2000) in relation to floodplain vegetation. In contrast, lack of drying is the the key to the ecological character of wetlands with permanent water regime such as mound springs.

Step 2. Identify uses, values and threats

Step 2 involves the identification of wetland uses, values and threats. Environmental and conservation values will be based on information collected in step 1 above. Examples include Ramsar listing, the presence of rare or endangered species, use of the wetland by migratory bird species covered by international conventions, and the relative rareness of the wetland type. Human uses and values may be related to Aboriginal significance, recreation, the appreciation of water views, grazing of lake beds and floodplains, and abstraction of water. The identification of threats is focused on those human activities which may alter the water regime.

Step 3. Determine management objectives

Objectives may include meeting obligations associated with international conventions such as the Ramsar Convention. The Ramsar Convention requires "wise use" of wetlands, and an important aspect of "wise use" is the maintenance of ecological character (Adam, 1999, Ramsar web site). A general management objective is therefore to maintain the ecological character of the wetland (defined in step 1). The objective of maintaining a wetland's 'ecological character' has some similarities with the objective of holistic approaches, that is, the identification and incorporation of the 'essential features' of the historic water regime into the modified water regime (Arthington, 1998). A difference is that 'ecological character' incorporates ecological as well as hydrological aspects. Both objectives are based on the concept that a degree of deviance from the pre-development state is acceptable within certain limits. They are compatible with the concept that ecological responses are frequently non-linear and often characterised by thresholds. This concept is generally accepted amongst wetland ecologists (Bunn, 1999).

Specific management objectives will be shaped by the identified uses, values and threats (Step 2). Management objectives may be based on vegetation (eg

Leitch, 1989, Roberts *et al.,* 2000), waterbirds (eg Leitch, 1989; Briggs and Thornton, 1999), or other fauna (eg Leitch, 1989; Burbidge and Kuchling, 1994; WAWA, 1995). Resolution of trade-offs between conflicting values may be required. For example, the demand for year-round water views may conflict with the ecological values of a seasonally dry wetland (WAWA, 1995). Peat mining proved to be incompatible with water supply, heritage and habitat values in Wingecarribee Swamp in NSW (Tranter, 1999). The separation of these first three steps in this method (Figure 11) should result in a high degree of transparency and defensibility of trade-off resolutions.

Step 4. Describe the relationships between biota and the water regime

The focus of this step is determined by the management objectives (Step 3) which require determination of wetland uses, values and threats (Step 2). Most attention will be placed on relationships between the water regime and significant communities or species; for example, if a wetland is significant due to the presence of waterbirds, the water regime requirements of waterbirds will be critical. These will include both direct water requirements (ie water regime requirements of the waterbirds) and indirect requirements (ie the water regime requirements of vegetation used by waterbirds).

For the examination of specific water regime requirements, wetland biota could be considered in terms of the following groups:

- Algae
- Submerged plants
- Emergent plants
- Trees and shrubs
- Aquatic invertebrates
- Fish

- Waterbirds
- Other fauna (wetland reptiles, amphibians and mammals)

Water regime requirements of biota may be examined in terms of the identified wetland zones (Step 1).

Water regime requirements for both maintenance and recruitment of individual species need to be considered. Lack of knowledge regarding these requirements has been identified as an impediment to the determination of environmental water allocations (Allan and Lovett, 1997; Arthington *et al*., 1998; Roberts *et al*., 2000). Targeted research programs may be required where knowledge is inadequate (eg WAWA, 1995).

Biotic and hydrological monitoring (Figure 11, step 11) after the implementation of environmental water allocations can add to the existing knowledge of the effects of different water regimes on wetland biota. In turn this information can inform management (Figure 11). This adaptive management approach has been key to the development of environmental water allocations such as those of the Macquarie Marshes (Brock, P., 1998), and is seen as necessary due to lack of knowledge (Adam, 1997).

The water requirements of wetland biota may need to be considered over large spatial scales. Habitats can be assessed as interlinked systems if examined in terms of the needs of particular fauna (eg Scott, 1997; Scott and Grant, 1997). Fauna such as platypus and water rats move between rivers and wetlands (Scott and Grant, 1997) so the water regimes of both need to be examined. Many waterbirds travel large distances and utilise habitats provided by different wetlands; it is rare for them to use one habitat for all their needs (Briggs and Lawler, 1989). Water regime management for mobile fauna will therefore not necessarily involve the provision of permanently suitable habitat at a single wetland.

Step 5. Determine the desired water regime

The desired water regime is determined using the management objectives and the assessment of the requirements of the wetland biota. Characteristics of the desired water regime of wetlands may include:

- amount (area inundated)
- depth (minimum and maximum)
- seasonality (whether inundation is permanent, seasonal or ephemeral)
- season of maximum inundation
- rate of rise and fall
- size and frequency of floods
- size and frequency of dry periods
- duration of floods
- duration of dry period
- variability

(adapted from Roberts *et al*., 2000).

Step 6. Refine the desired water regime by examining various scenarios using conceptual modelling

The use of conceptual modelling approaches such as EFDSS (Environmental Flows Decision Support System, Young *et al.*, 1999; Pitcher, 2000) may assist the determination of the desired water regime. Trade-offs between different uses and values may be facilitated by modelling approaches. Mitchell (1999) considers that adaptive management is in essence “trial and error”, and argues that the impacts of errors can be minimised if any possible unwanted outcomes, as well as intended outcomes, are identified, and contingency plans are developed to deal with adverse impacts as soon as they are manifested. Both conceptual modelling and the use of numerical models may assist in the identification and prediction of outcomes. The scenarios from conceptual modelling may be compared against the management objectives determined in Step 3. The scenario which most suits the management objectives may then be selected.

Step 7. Set performance indicators in relation to biota

Performance indicators are based on the management objectives. They are set in relation to biota, and reflect desired outcomes. They can include frequency and size of waterbird breeding events, health of vegetation, recruitment of plant species, relative abundance of particular invasive species and abundance of particular native species. They allow the success of the management strategy to be evaluated.

Step 8. Determination of the means of achieving the desired water regime

The means of achieving the desired water regime depend upon the source of the water and the nature of the water regime disturbance. Dam releases, weir manipulations, restrictions to abstraction and the use of regulators could be required. In wetlands associated with rivers, the relationship between streamflow and area inundated may be determined through the analysis of streamflow data and remote sensing or aerial photograph interpretation (eg Bennett and McCosker, 1994). Water balance calculations may be extremely useful for many wetlands.

Step 9. Prescribe environmental water allocations to achieve the desired water regime

Environmental water allocations are determined to achieve the desired wetland water regime to be met. For the groundwater-fed wetlands of the Swan Coastal Plain environmental water requirements were set in terms of frequencies of maximum and minimum depths of surface water (WAWA, 1995). Allocations for surface water dominated wetlands may involve the use of regulators, dam releases and abstraction restrictions. These allocations may be based on relationships determined in Step 8 between streamflow and area inundated or on the water balance calculations.

Step 10. Implementation

This step involves the implementation of the allocations determined in Step 9. These may be modified in extremely wet or dry years.

Step 11. Monitoring

Biological monitoring programs are planned to measure whether the performance indicators are met, while hydrological monitoring programs test if the desired water regime has been achieved. A feature of adaptive management is the viewing of management practice as an experiment, using hypotheses. Monitoring regimes are designed to test the hypotheses, and management is influenced by feedback from monitoring results (Chapman and Underwood, 1997). Over time, the data from both biological and hydrological monitoring programs should result in an increase in knowledge regarding the response of biota to changes in water regime.

PILOT STUDIES

The framework descibed in Figure 11 was applied to four wetlands (Thomsons Lake, Bool Lagoon, Lower Gwydir Wetlands and Boggomoss Springs) to test or demonstrate its application to different wetland types.

Thomsons Lake

Step 1. Characterisation of Thomsons Lake

Site Description

Thomsons Lake is a shallow semi-permanent/ seasonal wetland on the Swan Coastal Plain, approximately 34 km south of Perth (Crook and Evans, 1981). It is part of the East Beeliar chain of wetlands which are expressions of the Jandakot Mound, an unconfined aquifer. Although the dominant source of water for Thomsons Lake is groundwater, there is some surface inflow from Kogolup Lake and from a drain to the south-east of the lake which passes through constructed wetlands. The lake is characterised by both high waterbird abundance and diversity (Storey *et al*., 1993), and areas of sedge vegetation (Directory of Important Wetlands web site).

Hydrological data

The following information regarding the water regime of Thomsons Lake was examined for the purpose of this analysis:

- Rainfall data from the Bureau of Meteorology (1952-1999)
- Perth annual rainfall (1876 to 1985) (Cargeeg, *et al*., 1987, p.17)
- Depth data (m AHD) from the Water Corporation (1952-1999)
- Duration of dry periods (1962-1988) (Balla and Davis, 1993, p.38, Table 3.2)

- Rate of change per day (1974-1990) (Balla and Davis, 1993, p.41, Figure 3.1)
- Bathymetry and vegetation distributions in relation to AHD (Arnold, 1990, p.270)
- Frequency distribution of lake levels (Froend *et al.*, 1993, p.20, Figure 3.6)
- Groundwater abstraction volumes (1979-1985) (Cargeeg, *et al.*, 1987, p.40)

Description of the water regime

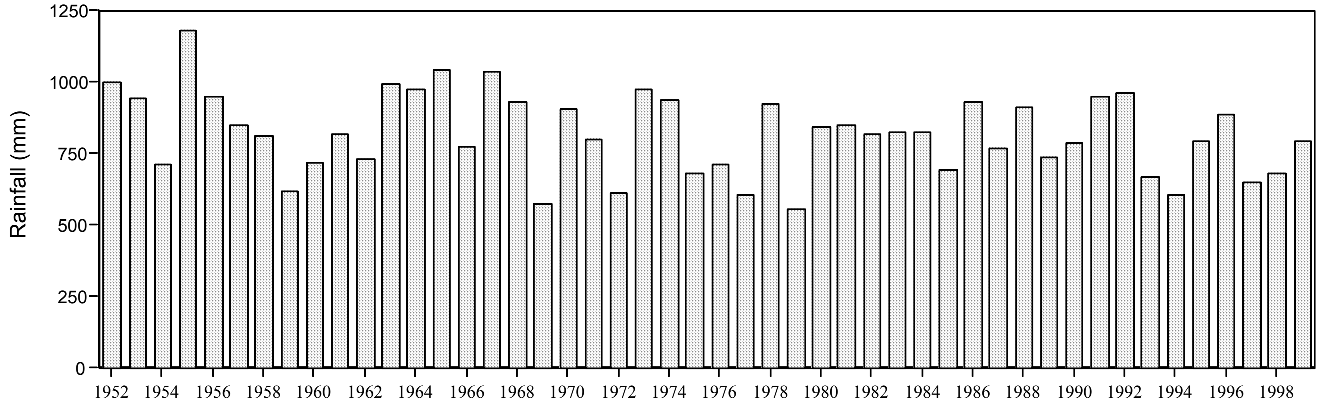
Seasonal drying occurred almost annually from the late 1970s to the late 1980s. Both prior to this period and during the 1990s drying did not occur as frequently (Figure 12). Due to the incomplete and highly variable nature of the depth data prior to 1971, it is difficult to draw firm conclusions about the nature of the historic water regime. The relatively high levels which characterised the lake's water regime between 1964 to 1978 may have been a result of excessive inundation caused by clearing of the surrounding *Banksia* woodland for cattle grazing and market gardening (Crook and Evans, 1981).

Rapid changes in water level may have become more common since groundwater abstraction began in 1979, and the frequency at which rapid changes in depths occur may also have increased (Figure 13).

Vegetation

Extensive mats of the aquatic macrophyte *Myriophyllum sp.* occur in the open water (ANCA, 1996). Above this a sedge community of *Baumea articulata*, *Typha orientalis* and *Bolboschoenus caldwelli* occurs. *Typha orientalis* became established during the 1980s and is considered to pose a threat by changing the community composition and the amount of open water (Directory of Important

Wetlands web site). Above the level of *T. orientalis*, *Baumea juncea* occurs with a few shrubs, including *Viminaria juncea* and *Acacia saligna*. At higher elevation there is a woodland of *Eucalyptus rudis*, *Melaleuca preissiana* and *Jacksonia furcellata* (Halse *et al.*, 1993) (Figure 14).


1250
1000
750
500
250
0
Rainfall (mm)
1952
1954
1956
1958
1960
1962
1964
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1972
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1976
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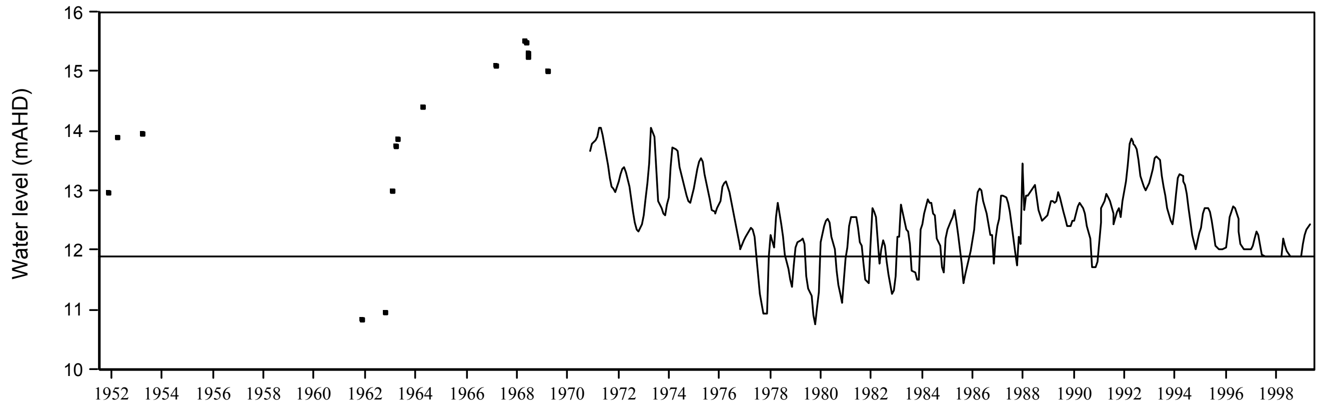
1994
1996
1998


16
15
14
13
12
11
10
Water level (mAHD)
1952
1954
1956
1958
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1962
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1970
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1974
1976
1978
1980
1982
1984
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1988
1990
1992
1994
1996
1998

Figure 12. Hydrograph with rainfall data for Thomsons Lake, WA. Data provided by the Water Corporation and the Bureau of Meteorology.

Note: The level of the lake bed is indicated on the hydrograph by a horizontal line. Data prior to 1971 were irregular and so do not show seasonal variation. From the mid-90s bores were not used for measurements, therefore after this time the level of the water table after the lake dries cannot be determined.

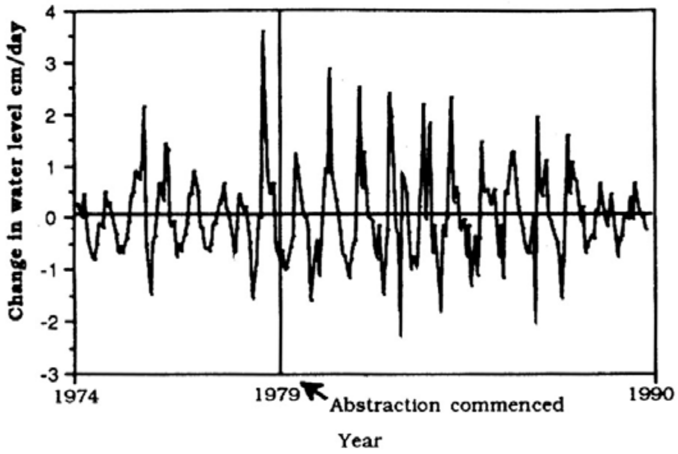

Figure 13 Rates of water level change at Thomsons Lake (from Balla and Davis, 1993, Figure 3.10, p.41)

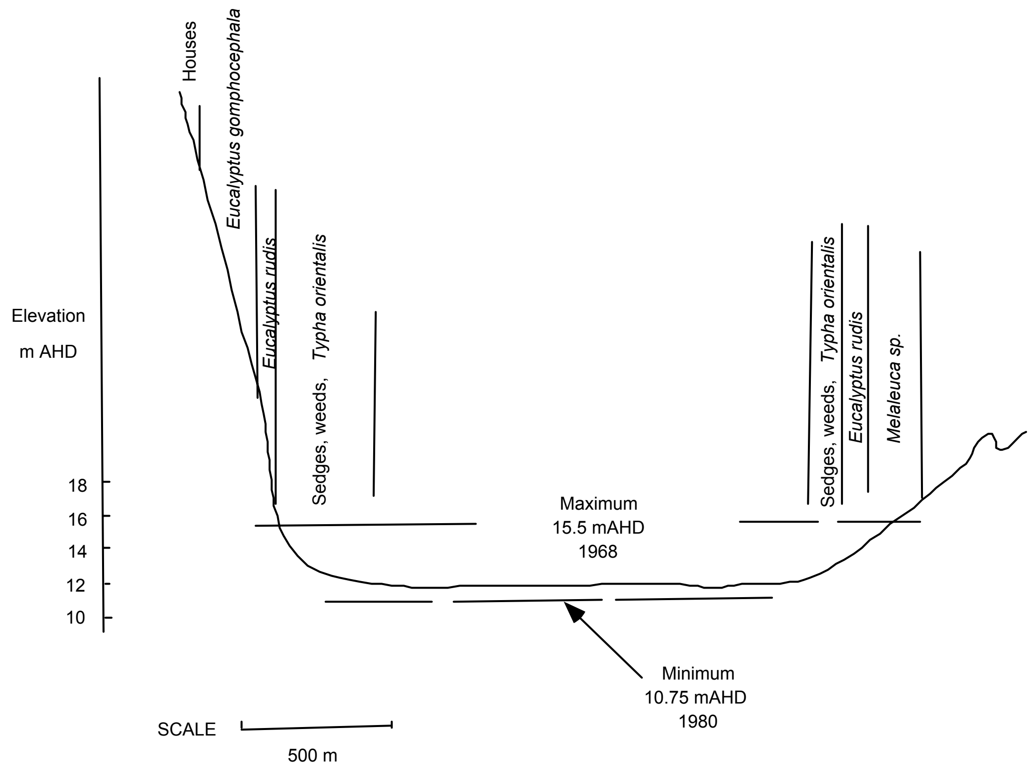

Figure 14. Bathymetry, vegetation and water level records of Thomsons Lake (adapted from Arnold, 1990, Figure 9.16, p.270)

Vegetation

Extensive mats of the aquatic macrophyte *Myriophyllum sp.* occur in the open water (ANCA, 1996). Above this, but below the usual water mark, a sedge community of *Baumea articulata*, *Typha orientalis* and *Bolboschoenus caldwelli* occurs. *Typha orientalis* became established during the 1980s and is considered to pose a threat by changing the community composition and the amount of open water (Directory of Important Wetlands web site). Above the level of *T. orientalis*, *Baumea juncea* occurs with a few shrubs, including *Viminaria juncea* and *Acacia saligna*. At higher elevation there is a woodland of *Eucalyptus rudis*, *Melaleuca preissiana* and *Jacksonia furcellata* (Halse *et al.*, 1993) (Figure 14).

Fauna

Fourteen species of migratory waders occur at Thomsons Lake. The threatened Australasian Bittern (*Botaurus poiciloptus*), which is no longer recorded regularly at other Perth wetlands, also occurs (Directory of Important Wetlands web site). Lists of waterbirds can be found at the Directory of Important Wetlands web site and in Crook and Evans (1981). Six species of wetland frogs have been recorded: *Crinia georgiana*, *Crinia insignifera*, *Heleioporus eyrei*, *Limnodynastes dorsalis*, *Litoria moorei* and *Litoria adelaidensis*. The turtle *Chelodina oblonga* has been recorded at the lake. No fish have been recorded (Directory of Important Wetlands web site).

Ecological character

The ecological character of Thomsons Lake was defined as

> *a shallow, seasonal to semi-permanent, groundwater-fed lake, with fringing sedge vegetation, which supports large numbers of waders in some years*

Step 2. Identify uses, values and threats

Uses

- Extraction of groundwater for domestic water supply for Perth occurs from the Jandakot Mound which also supports Thomsons Lake.
- The lake is used for passive recreation such as walking and birdwatching (Directory of Important Wetlands web site).

Values

Thomsons Lake is a Ramsar site and is of particular importance as a stop-over point for migratory waders. Both waterbird abundance and species diversity are high compared with other wetlands of the Swan Coastal Plain (Storey *et al*., 1993), and it is important locally as a refuge for the threatened Australasian bittern (*Botaurus poiciloptilus*) (Directory of Important Wetlands web site). The importance of an appropriate water regime for waterbirds is both direct, as many have specific habitat needs in terms of water depth, and indirect, as the extensive sedge beds constitute important habitat for some waterbirds. The sedges themselves have particular water regime requirements.

Identified threats to the water regime of Thomsons Lake

Threats to the lake's water regime include both groundwater extraction and excessive inundation caused by clearing and urbanisation (Directory of Important Wetlands web site). The threat of excessive inundation mitigates the effect of groundwater extraction, however the overall effect has been estimated to be a reduction in the groundwater levels on the Jandakot Mound of between 0.10 and 1.10 m (Balla and Davis, 1993). In the future an expected increase in urbanisation on the Mound could possibly result in excessive inundation becoming a problem. Urban drainage may cause short-term water level fluctuations (see Figure 13). A proposal to drain land east of Thomsons Lake for housing development was subject to Environmental Protection Authority restrictions due to concern for the integrity of the lake's water regime (EPA, 1990; Directory of Important Wetlands web site).

Wetland vegetation communities of the Swan Coastal Plain are considered to be dynamic, moving up- and down-gradient in response to increased or decreased inundation (Froend *et al*., 1993). However the shallow and essentially flat-bottomed nature of Thomsons Lake (Figure 14) means that a permanent reduction in groundwater levels would pose a threat to its ecological character. A relatively small reduction in groundwater levels would lead to a considerable reduction in the amount of open water.

Qualitative assessments of alterations to water budget elements are listed below (Table 4). Attempts to produce a quantitative water budget have been unsuccessful due to difficulties accessing adequate drainage data (Krasnostein, pers. comm.). As a result, the extent to which human impacts on the water regime mitigate against each other could not be determined. The overall direction of change in the water regime as a result of human activity (ie. groundwater abstraction vs land clearing) is therefore unclear.

Table 4. Processes which may alter aspects of the water budget of Thomsons Lake.

Water budget element	Processes at Thomsons Lake which could alter elements of the water budget	Nature of alteration
P Precipitation	Climate change. Rainfall has been below average since the early 1970s (Cargeeg *et al*., 1987)	Reduced
Q_i Surface water inflow	Possibly increased from drain from south-east (which is cleared, primarily agricultural land (ANCA, 1996)). Water from this drain enters the wetland after passing through constructed wetlands. These wetlands were constructed to mitigate against increases in nutrient loads. The wetlands are bypassed at times of very high flow. Reduced rainfall (above) may also result in a reduction of surface run-off	Possibly increased
G_i Groundwater inflow	Could be reduced as a result of groundwater extraction	Possibly reduced
E Evaporation/ transpiration	May be affected by climate change and the extent/ health of vegetation	Possibly reduced
Q_o Surface water outflow	n/a	
G_o Groundwater outflow	Dependent upon the level of the groundwater table	

Step 3. Determine management objectives

As a Ramsar wetland, a suitable general management objective is

To protect against decline in the ecological character of the site.

A specific management objective, based on the identified values, is

To protect the site's habitat value for migratory waders.

The water regime of Thomsons Lake is currently managed by the Water Corporation to reduce the possible negative impacts of groundwater extraction and drainage of nearby areas for urban development. The existing management objective is

"*to protect the ecological character of the lake and, in particular, its importance as a waterbird habitat*" (EPA, 1990, p.4).

This objective addresses obligations associated with the Ramsar status of the site. Management is aimed at maintaining both the natural seasonality of the water regime, with lower water levels in summer, and the effect of annual rainfall variations on the lake water levels (EPA, 1990).

Step 4. Describe the relationships between water regime and wetland biota

Water requirements of wetland vegetation

Table 5 lists general qualitative requirements of the wetland plant species of Thomsons Lake. These include adaptations to seasonal drying, and relatively shallow water for the submerged aquatic plant *Myriophyllum sp.*

Table 5. General water regime requirements of vegetation

Type	Species	General Water Regime Requirements
Aquatic macrophyte	*Myriophyllum sp.*	Requires water that is not excessively deep (Balla and Davis 1993)
Emergent macrophyte	*Bolboschoenus caldwelli*	Requires seasonal drying: becomes established below sedges as the lake dries (Halse *et al.,* 1993).
Trees	(*Eucalyptus rudis* and *Melaleuca preissiana*)	Degraded by prolonged flooding (>2 years). Where water levels fall over a long period of time, recruitment of young *Melaleuca preissiana* occurs at a lower elevation (Froend *et al*., 1993).

The water depth requirements of four emergent macrophyte species are listed below (Table 6). These species generally occur around the fringes of Thomsons Lake (Figure 14). A decrease in water levels such as occurred between 1979 and 1991 may lead to their encroachment towards the centre of the lake. Sedge vegetation in 1987 did in fact cover a greater area of Thomsons Lake than it did in 1963, which was a wetter year (Figure 12) (Froend *et al*., 1993, maps Appendix 1). In 1992, a wet year, water levels were very high, and the area occupied by sedges was much reduced in the following year as a consequence (Davis, pers. obs.). A long-term lowering in water levels would result in less open water habitat and an increase in sedge habitat. However large fluctuations in water levels between wet and dry years may be considered as part of the natural variability of the lake's water regime. These fluctuations result in variability in the area of sedge habitat.

Table 6. Water depth requirements of emergent macrophytes

Species	Range of Depths of Occurrence (Froend *et al.*, 1993)	Mean Annual Depth (Chambers *et al*., 1995)
Bolboschoenus caldwelli		+0.3 to - 0.2 m
Baumea articulata	Minimum - 1.0m Maximum + 1.0m	+/- 0.4 m
Typha orientalis	Minimum - 1.0m Maximum + 1.0m	+0.1 m to - 0.3 m

Baumea juncea	+0.2 m to -0.3 m

Water Requirements of Wetland Fauna

Vertebrates

Waders require shallow areas and the long-toed stint requires seasonally exposed mud flats. Therefore excessive inundation could potentially be a problem. The large areas of sedges and mud flats may` be critical as habitat for waders; maintaining a suitable water regime for the maintenance of these habitats should meet the requirements of waterbirds. Sudden increases in water level, due to urban drainage, and sudden decreases due to groundwater abstraction may adversely impact frog populations and aquatic invertebrates (Table 7).

When evaluating the habitat requirements of the vertebrates of Thomsons Lake, it is important to consider that the more mobile vertebrates may utilise the entire chain of the Beeliar wetlands. As a whole, this group of wetlands provides a much higher variety of habitats than does Thomsons Lake alone (Crook and Evans, 1981). In particular, nearby Kogolup Lake has a permanent water regime and is used by waterbirds when Thomsons Lake dries up (Rod Smith, Birds Australia, pers. comm.). Mobile vertebrates include waterbirds and the turtle *C. oblonga*. *C. oblonga* can travel overland long distances, although in doing so many are killed on the roads (Bush *et al*., 1995). The predator-proof fence which now surrounds Thomsons Lake may prevent the movement of some non-flying fauna such as turtles.

Table 7. Water regime requirements of wetland vertebrate fauna.

Type	Species	Water regime
Waterbirds	Long-toed Stint (*Calidris subminuta*)	Require exposed mudflats: only appear when these are present (Directory of Australian Wetlands web site)
	Waders (general)	Shallow water levels
	* Australasian bittern (*Botaurus poiciloptilus*) and Little bittern (*Ixobrychus minutus*)	Require tall sedges (Directory of Australian Wetlands web site)* *
	Musk duck (*Biziura lobata*)	Require deep permanent water (Frith, 1957: Braithwaite and Frith, 1968).
	Blue-billed duck (*Oxyura australis*)	Require deep permanent water (Frith, 1957: Braithwaite and Frith, 1968).
Frogs	*Limnodynastes dorsalia* and *Litoria adelaidensis*	Survival of embryos within egg masses may require an absence of sudden increases/ decreases in water levels, as the eggs are attached to vegetation and float on the water surface. The embryos may need to remain on the surface of the water to be both well-oxygenated and wet. Changes in depth which result in either the drying of the egg masses or their inundation (and subsequent de-oxygenation) may be detrimental (Seymour and Roberts, 1991; cited in Wilkins, 1993)
	Heleioporus eyrei	Water level increases between March and May may be detrimental to breeding success: this species lays eggs in burrows (Roberts and Main, 1993; cited in Wilkins, 1993).
Fish	None present (ANCA, 1996)	
Turtles	*Chelodina oblonga*	This species has two nesting periods (September-October and December-January) (Clay, 1981). May require the presence of water in December/January for the second nesting period, as turtles only eat when open water is present, aestivating when the wetlands dry during summer.
Other reptiles	Insufficient data	
Mammals	Bandicoots	Dense fringing vegetation

(Species List: Crook and Evans, 1981)

* Threatened species

* * See Table 6 for water regime requirements of *Baumea articulata* and *Typha orientalis*, the most abundant tall sedges.

There appear to be few animal species which require permanent water for survival. Exceptions include the musk duck and the blue-billed duck. Musk ducks were recorded in each decade between 1954 to 1979 (Crook and Evans, 1981) but are not mentioned in the Directory (Directory of Important Wetlands web site). A loss of this species could be a result of the reduced water levels. The shift from the deeper, permanent water regime which characterised the lake prior to 1978, to the current shallower, seasonal or semi-permanent water regime may have resulted in a reduction in the abundance of diving ducks and an increase in the abundance of waders.

Invertebrates

Adult insects with aquatic larvae require healthy vegetation for resting sites. Some, including adult damselflies, require macrophytes for egg-laying sites. Therefore the maintenance of a water regime which will be suitable for macrophytes is of importance also for the maintenance of invertebrate habitat values. The aquatic invertebrate fauna of the Swan Coastal Plain wetlands are considered to be adapted to seasonal drying. The requirements of aquatic invertebrates should be met if seasonal wetlands do not dry out before December each year, and if rates of wetland drying do not exceed 0.02 m day^{-1} (Balla and Davis, 1993).

Nuisance Species

Increased depth may result in a shift from a system dominated by macrophytes to one dominated by phytoplankton (Balla and Davis, 1993). Cyanobacterial blooms may result, however cyanobacteria may be favoured by the mixing conditions which are typical of relatively shallow depths. Shallow lakes exposed to strong winds conditions (as Thomsons is) often experience diurnal or semi-diurnal cycles of complete mixing and secondary stratification, which favours cyanobacteria over other phytoplankton (Bailey and Hamilton, 1997). The phytoplankton of Thomsons Lake was found to be dominated by cyanobacteria between August and November, 1994 (Bailey and Hamilton, 1997) a time when the the lake was relatively deep (Figure 12).

A decrease in water levels may favour *Typha orientalis* while an increase in permanence could lead to the establishment of *Gambusia holbrooki* (Table 8).

Table 8. Nuisance/pest species that may be favoured by changes to the water regime.

Nuisance/pest	Water regime changes favourable
Cyanobacterial blooms	Excessive depth leading to the death of *Myriophyllum sp.* beds (Balla and Davis, 1993).
Typha orientalis	Shallower regime
Introduced fish *Gambusia holbrooki**	Increased permanence

* Although not recorded at the lake this species colonises most wetlands with a permanent water regime on the Swan Coastal Plain and so there is a high possibility that it will occur in Thomsons Lake if the regime becomes permanent.

Step 5. Determination of the desired water regime

The water regime requirements of the biota of Thomsons Lake and bathymetry and hydrological data were used to develop a conceptual model (Step 6, Figure 11). This was developed to assist in the process of determining a suitable water regime.

Step 6. Refine the desired water regime using a conceptual model

Conceptual model

Scenario 1. Decreased water levels, seasonal water regime (Figure 15).

An overall decrease in water levels would result in a shift of the fringing vegetation communities down-gradient (Froend *et al*., 1993). As the wetland has a relatively flat bed and steep sides, and the sedges and *Typha* occur where the land begins to rise out of the basin (Figure 14), reduction of water levels below a certain point could lead to a spread of the sedge and *Typha* vegetation across the bed of the lake. This would be associated with a loss of habitat for the aquatic *Myriophyllum sp*. (which supports a productive invertebrate fauna) and a loss of seasonally exposed mudflats, which are important for the long-toed stint, a migratory wader (Directory of Important Wetlands web site). Additionally, a reduction in water levels would be associated with recruitment of the wetland trees down-gradient of their present distributions. This is already occurring for *Melaleuca preissiana* at nearby Banganup Lake (Froend *et al*., 1993). If water levels decreased over time, sedges may take over the areas now characterised by open water and mud flats, leading to a loss of habitat for waders. With a further loss, *E. rudis* and *Melaleuca sp.* would take over the bottom of the basin.

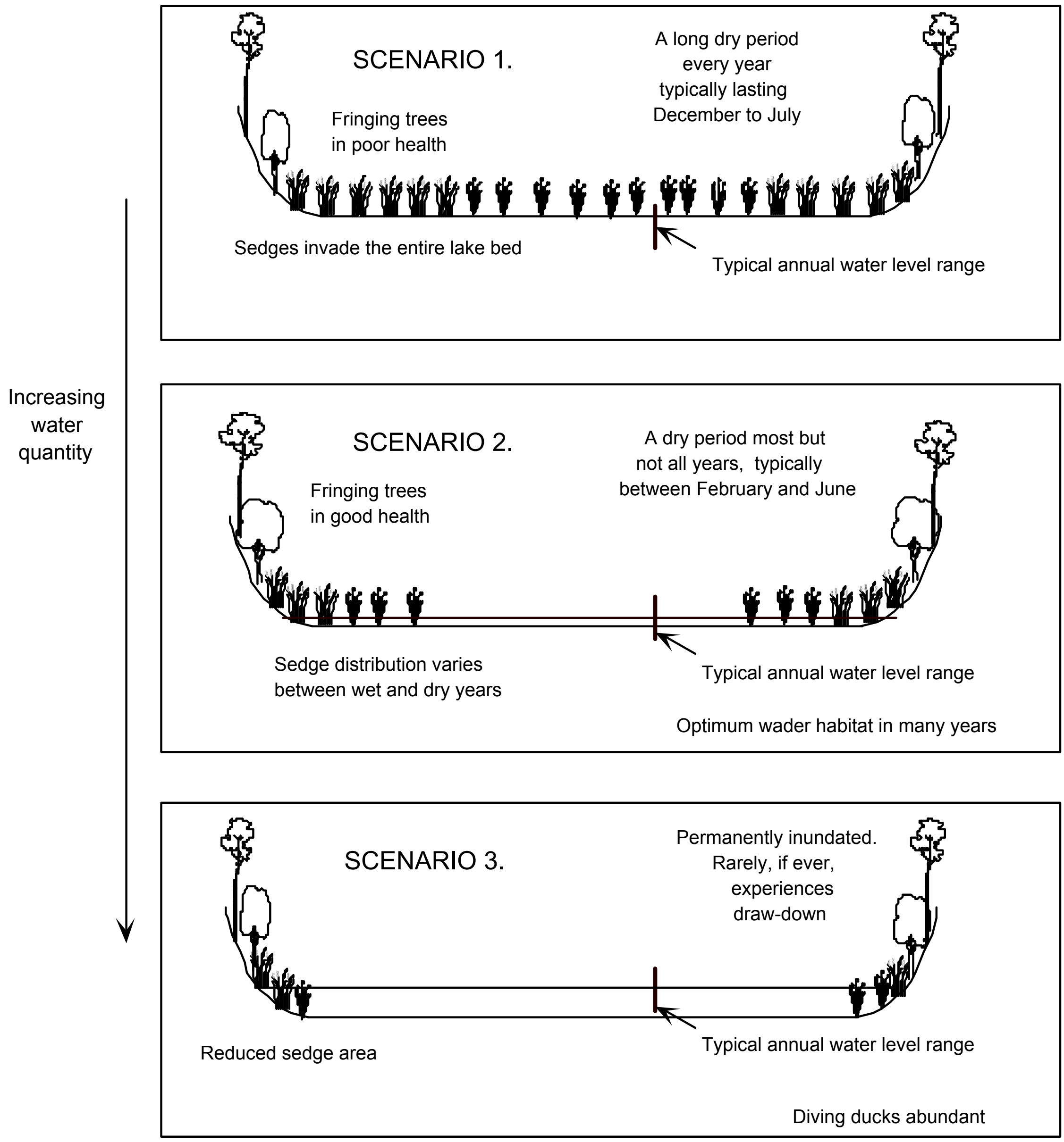

Figure 15. Conceptual modelling: scenarios describing wetland response to changing water regime (Thomsons Lake).

Scenario 2. Seasonal or semi-permanent water regime: water levels intermediate between those of scenarios 1 and 3 (Figure 15).

Wader habitat will be optimum if water levels are between approximately 11.5 and 12.5 m AHD (equivalent to depths between 0.3 m below the sediment and 0.7 m above) (Scenario 2, Figure 15). Higher water levels than this would result in a reduction of both wader habitat and the extent of sedge beds (Scenario 3, Figure 15); while lower overall water levels may result in an invasion of the entire lake bed by sedges (Scenario 1, Figure 15).

The long-toed stint (*Calidris subminuta*) occurs at Thomsons Lake when mudflats become exposed in summer/ autumn (Directory of Important Wetlands web site). This would occur only under scenario 2. This migratory species is protected by international agreements (Storey *et al*., 1993). The highest count, recorded in the summer of 1991, represented at least 1% of the probable national population of this species (Directory of Important Wetlands web site). This was a year when the lake dried (Townley *et al*., 1993). The required habitat of this species, exposed mudflats, only occurs seasonally in relatively dry years. Exposed mudflats would cease to occur if the water regime became permanent, or the wetland became excessively inundated.

Scenario 3. Deeper water levels, permanent water regime (Figure 15).

An increase in water levels could lead to deaths of *Myriophyllum sp.* beds and possibly deaths of the lower *E. rudis* and *Melaleuca sp.*, although these could re-colonise at a higher gradient (Arnold, 1990; Froend *et al.,* 1993)**.** A severe contraction of the sedge and *Typha* habitat could result (Figure 14). The most abundant waterbirds under this scenario are likely to be ducks and piscivorous birds. Waders would be less abundant, as would the threatened Australasian Bittern, which requires sedge habitat (Table 7). Diversity and abundance of invertebrates may be reduced by the reduction of macrophyte habitat and the establishment of conditions suitable for *Gambusia holbrooki* (Table 8). This may in turn reduce waterbird abundance. Deeper water levels may satisfy a possible alternative management objective of providing landscape amenity in the form of year-round open water views. However, if the increase in water level were to be associated with algal blooms as a result of a shift from a macrophyte-dominated system to a phytoplankton-dominated system, the amenity value would be reduced.

Scenario 4. Rapid water level fluctuations due to influence of drainage water.

Rapid water level fluctuations may negatively impact the breeding success of the frogs *Limnodynastes dorsalia* and *Litoria adelaidensis* (details Table 7). Some aquatic insects may not be able to complete their life cycles before the lake dries. Waterbirds such as coots, with nests attached to vegetation may be negatively impacted by rapid changes in water levels.

Desired water regime

The water regime of Scenario 2 satisfies the management objectives best. Inter-annual rainfall variation will mean that Scenarios 1 and 3 occur after successions of very wet or dry years. Scenario 4 may occur as a result of increased urbanisation.

Step 7. Performance indicators

Performance indicators could be defined in terms of relative areas of various habitats. Inter-annual variation would have to be allowed for; for example, large-scale reduction in the area of *Typha* in wet years, and increases in dry years. This variability due to climate could be accommodated by wording the performance indicators in a similar manner to the water level criteria:

> "The area of sedge vegetation is not to increase/decrease by more than a determined percentage for a certain number of years per decade, or for more than a certain number of consecutive years".

Additional performance indicators could be based on the breeding success of waterbird and frog species identified in the conceptual model as threatened by excessive water level fluctuations (Scenario 4).

Step 8. Determine the means of achieving the desired water regime

The desired water regime could be achieved by setting environmental water requirements in terms of water levels, allowing for inter-annual variation due to climate variability. Human impacts such as groundwater extraction, urban development and drainage could be modified in order to meet these requirements. This has been the approach used in the management of Thomsons Lake's water regime (WAWA, 1992).

Step 9. Set environmental water allocations to achieve the desired water regime

Existing criteria were first examined to determine their sense not clear in this context.

Existing criteria for the management of the water regime of Thomsons Lake

WAWA's operational criteria for the management of abstraction in terms of the water level of Thomsons Lake are:

"groundwater abstraction must not result in water levels falling between 10.8 and 11.3 m AHD more than once in any ten year period"

(WAWA, 1992, Section 3.5.3).

This criterion is compatible with scenario 2 of the conceptual model (Step 5).

Table 9. Relationship between criteria water levels in mAHD and water depths.

Water level in m AHD	Approximate depth of water in the middle of the lake
10.8	1.0 m below sediment surface of the lake bed

11.3	0.5 m below sediment surface of the lake bed
11.8	Water at the sediment surface of the lake bed. Lake bed saturated but not inundated.

Suitability of the water level criteria (WAWA, 1992)

The minimum water level criteria for management is 10.8 m AHD (WAWA, 1992). This equates to the minimum level required for the health of emergent macrophytes. The point at which the water table is approximately at the surface of most of the lake bed occurs at 11.7 m AHD (Table 9) (Arnold 1990, p.269 Figure 9.15). When the water depth is at 10.8 m AHD, the water table is approximately 1.0 m below the ground level. According to Townley *et al*. (1993) this is the point at which the capillary rise of water can no longer reach the roots of emergent macrophytes (Table 10). *Baumea articulata* and *Typha orientalis*, the most abundant emergent macrophytes at Thomsons Lake, occur in the zone where the level of the water table varies between 1.0 m below and 1.0 m above ground level (Froend *et al.,* 1993). The minimum water level criteria of WAWA (1992) should adequately protect the extensive sedge areas (Table 10). The other criteria, that the level not fall between 10.8 and 11.3 m AHD more than once every 10 years due to abstraction (WAWA, 1992), results in the water table not falling below 0.5 m of the sediment surface more than once every 10 years. This should also protect the health of the emergent vegetation, as the optimum water level for *B. articulata* and *T. orientalis* is + / - 0.1 m above the lake bed (Froend *et al*., 1993) (Table 10). This should in turn ensure the protection of fauna habitat, including waders and invertebrates.

Short-term water level fluctuations

The issue of increased short term water level fluctuations is not covered by WAWA's (1992) criterion. This has the potential to negatively impact invertebrate, frog and waterbird populations (Scenario 4, conceptual model). A maximum rate of change of 0.02 $m.day^{-1}$ has been included as a criterion for wetlands of the Gnangara Mound (WAWA, 1995), on the basis of the requirements of aquatic invertebrate communities (Balla and Davis, 1993). This criterion could be incorporated into the general criteria for the management of Thomsons Lake.

Table 10. Water regime criteria in relationship to depth and water regime requirements of wetland vegetation and fauna.

Criteria (WAWA, 1992) Water levels in m AHD	Effect of criteria in terms of the lake's water regime.	Match with water requirements of biota
WAWA (1992): Groundwater abstraction must never result in water levels falling below 10.8 m AHD. (Water levels are artificially maintained to meet this criteria).	The water table should never fall more than 1 m below the lake surface*.	Townley *et al*., (1993): This is the point at which emergent macrophytes can no longer access water. Matches the lowest water level that *Baumea articulata* and *Typha orientalis* can survive.
WAWA (1992) Groundwater abstraction must not result in water levels falling between 10.8 and 11.3 m AHD more than once every 10 years.	The water table should not fall in the range of 0.5 to 1.0m below the surface of the lake bed more than once every 10 years**.	Preserves the health of sedge beds, and therefore their extent.
WAWA (1992) Minimum water level not exceed 11.8 m AHD more than once every 10 years.	Preserves seasonal drying in 9 out of 10 years.	Seasonal drying is linked to increased productivity of aquatic invertebrates, which should result in large numbers of waterbirds (Crome, 1988). The preservation of the natural variability of the water regime may be important in the maintenance of fringing vegetation (Brock and Casanova, 1997). Preservation of the natural seasonality is likely to be critical for the health of the fringing trees, which include *Eucalyptus rudis* and *Melaleuca preissiana* (Froend *et al.,* 1993). Seasonal drying allows for the exposure of mudflats in summer/autumn, which is required by the Long-Toed Stint (a migratory wader) (Directory of Important Wetlands web site). Seasonal drying should reduce the potential for *Gambusia holbrooki* to colonise and achieve high densities, and result in an aquatic invertebrate community typical of seasonal wetlands.

*With an annual difference between maximum and minimum water levels of 1.5 m (from hydrograph in Townley *et al*., 1993 Figure 4.1.7 p89), the maximum water level attained annually should not fall below 1.0m.

** With an annual difference between maximum and minimum water levels of approximately 1.5 m, the maximum water level attained annually should not fall below 0.5 to 1.0m more than once every 10 years.

Steps 10 and 11. Implementation and Monitoring

Biological monitoring regimes should be designed to test performance indicators related to the area of sedge habitat and waterbird and frog breeding success. Biological monitoring should also incorporate an invertebrate monitoring program. Hydrological monitoring should include daily depth measurements to indicate rates of change of depth as well as actual depths.

Conclusion

A lack of historical hydrological data for Thomsons Lake means that the management of the water regime cannot be based on an attempt to reinstate the regime which existed prior to development. WAWA's (1992) management objective, based on the maintenance of ecological character and the protection of waterbird habitat, reflects the ecological values and Ramsar status of the site. The methodology allowed a suitable water regime to be determined based on the requirements of the desired and/or existing wetland flora or fauna.

WAWA's (1992) criteria appear to meet the water regime requirements of the sedge habitat whilst also maintaining suitable water levels and a seasonal/ semi-permanent water regime to meet the requirements of waders. They do not address the threat of increased short-term water level fluctuations. Additional criteria addressing this issue should be incorporated into the current criteria. A monitoring program should ideally incorporate daily water level monitoring and a biotic monitoring program focussed on performance indicators. These should be based on the identified changes to flora and fauna communities identified in the conceptual model.

Bool Lagoon

Step 1. Characterise the wetland

Hydrology

Location and Bathymetry

Bool Lagoon lies in the south-east of South Australia, and comprises thee interlinked basins (Figure 16).

Figure 16. Bool Lagoon (from Brownlow *et al.,* 1994, p.1376). Inflow occurs via Mosquito Creek, and outflow occurs via the outflow channel.

Water regime

The water regime is artificially manipulated as the wetland is used as an equalisation basin for flood mitigation. It now acts as a sump for a catchment of 1215 km^2. In the past it was filled from the overflow from Mosquito Creek during winter, but most of the creek flows bypassed the lagoon. The water regime is more permanent now than it was in the past. Most of the wetland now dries out approximately once every two years (ANCA, 1996). It could therefore be characterised as semi-permanent. There is a gradient of permanency within the wetland; Hacks Lagoon is the deepest and generally contains water all year round, with a depth range of 0.3-1.40 m (Brownlow *et al.*, 1994).

Source

Bool Lagoon receives water also naturally as part of a regional drainage scheme. Water tables in the area are rising (ANCA, 1996). In terms of a water budget, surface water flowing in to the wetland has increased and groundwater flowing in may have increased as a result of the rising water table.

Depth

Average depth is 1 m, and the maximum recorded is 1.5 m (ANCA, 1996). The mean maximum depth is 0.94 to 1.09 m (Denton and Ganf, 1994).

Existing management of the water regime

Water levels are now managed for a draw down period when necessary for the benefit of vegetation (ANCA, 1996).

Ecology

Flora

Threatened species include *Baumea rubiginosa* and *Rumex bidens* (ANCA, 1996). Dominant vegetation is shown in Table 11.

Table 11. Dominant flora of various zones of Bool Lagoon (ANCA, 1996).

Zone	Dominant species
Main basin	*Triglochin procera*
Lagoon edge reedbeds	*Phragmites australis* *Typha domingensis*
Lagoon edge rushbeds	*Baumea articulata* *Baumea juncea*
Tussock sedgeland	*Gahnia filum* *Gahnia trifida*

Wet herblands on mudflats around lagoon margins	*Schoenus nitens*
Grassland	*Distichlis distichophylla* *Sporobolus virginicus*
Tussock grassland	*Poa labillardieri* *Gahnia filum*
Woodlands in the south east corner of the main basin	*Melaleuca halmaturorum*

Fauna

The Directory lists seventeen threatened species of waterbird and fourteen species of migratory waders. Other fauna include frogs, native and introduced fish, the eastern snake-necked tortoise (*Chelodina longicollis)* and the water rat (*Hydromys chrysogaster*) (ANCA, 1996).

Ecological character

Bool Lagoon is a semi-permanent wetland with a diverse riparian flora, including a stand of *Melaleuca halmaturorum,* which provides important habitat for waterbirds.

Step 2. Identify uses, values and threats

Uses

Bool Lagoon Game Reserve is usually opened for duck hunting for several mornings per year, dependent upon conditions (Directory of Important Wetlands web site).

Values

Bool Lagoon is listed as a Ramsar site (Directory of Important Wetlands web site; Ramsar site 322). The wetland is of importance for waterbirds and of national importance for colonial nesting birds (ANCA, 1996). It is an important drought refuge for waterbirds, and provides breeding habitat for waterbirds (Directory of Important Wetlands web site). Much of the surrounding area has been drained for agricultural purposes.

Threats

Recruitment of *M. halmaturorum* has been negatively affected by the increased permanence of the water regime (Denton and Ganf, 1994).

Step 3. Determine management objectives

General

To protect against decline in the ecological character of the site.

Specific

1. To protect the site's habitat value for migratory waders and rare and endangered waterbirds.

2. To preserve the existing vegetation distributions.

The general objective relates to the site's Ramsar listing. The specific objectives relate to the identified value of the site for waterbirds, and the identified threat to the *Melaleuca* woodland, respectively.

Step 4. Describe relationships between biota and water regime

Flora

The health of *Melaleuca halmaturorum* juveniles is negatively impacted where floods exceed six to nine weeks. The dominant stand at Bool Lagoon was found to be restricted to mature individuals. Germination was observed to occur, but seedlings failed to become established. An experiment confirmed that juvenile trees were adversely affected by flooding (Denton and Ganf, 1994). The lack of juveniles in the stand of *M. halmaturorum* therefore appear to be a result of the increased depth and permanence of the water regime. This is a long-lived species, with a lifespan of more than 100 years (Denton and Ganf, 1994). The increased permanence of the water regime appears to have negatively affected *Baumea arthrophylla* and positively affected *Triglochin procerum* (Table 12).

Table 12. Water regime requirements of wetland plants of Bool Lagoon, and effects of the altered water regime.

Species	Type	Water regime requirements	Affect of altered water regime
Melaleuca halmaturorum	Tree	Juveniles cannot tolerate inundation of more than 6 to 9 weeks (Denton and Ganf, 1994)	Recruitment no longer occurs
Baumea arthrophylla	Emergent aquatic	Suited to seasonally fluctuating water levels (Rea and Ganf, 1994)	Became less abundant: now only occurs in the south-west of the wetland (Rea, 1992 cited in Denton and Ganf, 1994)
Triglochin procerum	Semi-emergent aquatic		Invaded deeper areas (Rea, 1992, cited in Denton and Ganf, 1994)

Fish

The eggs of western carp gudgeon (*Hypseleotris klunzingeri*) are vulnerable to desiccation, as are those of the dwarf galaxias (*Galaxias pusilla*). However, juveniles and adults of the dwarf galaxias (*Galaxias pusilla*) can survive in swamps which may be dry for up to 5 months (Beck, 1985, cited in Koehn and O'Connor, 1990).

Frogs

The frog *Limnodynastes peronii* occurs at Bool Lagoon and is considered to require permanent water (Cogger, 1996).

Mammals

The abundance of water rats may be favoured by permanent inundation (Scott and Grant, 1997). Breeding occurs in spring and summer; flooding during this time may result in some mortality of young but this effect may be offset by the increased food availability.

Waterbirds

Waterbirds which inhabit and breed in Bool Lagoon have specific water regime requirements (Table 13), and will therefore be affected by water regime management. Complete drying on an annual basis may negatively affect breeding of intermediate egrets and little black cormorants (Crome, 1988, Table 13), while if the annual dry phase regularly lasts more than two months great egrets breeding will be negatively impacted (Briggs *et al*., 1994, cited in Scott, 1997, Table 13). Complete drying will negatively impact musk ducks and blue-billed ducks (Table 13, Frith, 1957). However, for other ducks, complete drying of the wetlands is likely to result in large breeding events in subsequent floods (Crome, 1988, Table 13). The movements and breeding of many ducks (such as pink-eared ducks) are strongly influenced by weather. These species travel large distances to exploit wetlands with suitable conditions (Frith, 1957).

Table 13. Water regime requirements of waterbirds.

Species/ Group	Requirements
Great egret (*Egretta alba*)	Breeding requirement: minimum duration of flooding is 10 months (Briggs *et al*., 1994, cited in Scott, 1997)).
Intermediate egret (*Egretta intermedia*) and Little black cormorant (*Phalacrocorax sulcirostris*)	At Booligal, NSW, were found to breed best when the swamps had been filled for a long time. These species are fish-eaters (Crome, 1988)
Ducks (general)	Breed in large numbers in floods after complete drying out of swamps (Crome, 1988).
Musk duck (*Biziura lobata*) Blue-billed duck (*Oxyura australis*)	Require permanent deep water (Frith, 1957). Favoured by the stable conditions found in irrigation drainage swamps.
Grey teal (*Anas gibberifrons*)	Prefers rising water levels (Frith, 1957)
Pink-eared duck (*Malacorhynchus membranaceus*)	For breeding requires residual flood waters which are drying up. Movements and breeding are dominated by weather

(Frith, 1957).

Waterbird use of wetland trees

The stands of *M. halmaturorum* at Bool Lagoon are important for ibis (LWRRDC, 1997) and may also affect the habitat value of the wetlands for maned ducks and spoonbill (Table 14). The survival of the stand of *M. halmaturorum* may be important for waterbird habitat values.

Table 14. Waterbird use of trees.

Waterbird	Tree use
Ibis	Nest in the old stands of *Melaleucas* at Bool Lagoon (LWRRDC, 1997b)
Spoonbills	Sometimes nest in outer branches of large trees (Simpson and Day, 1993)
Maned duck (*Chenonetta jubata*)	Often perch in trees (Simpson and Day, 1993)

Step 5. Determine the desired water regime to fulfil management objectives

The alteration of the water regime from seasonal to permanent which occurred with irrigation development appears to have resulted in ecological change, the most obvious being the lack of recruitment of *M. halmaturorum*. The existing fauna includes species adapted to seasonal water regimes, as well as species which require permanent water. Some of the species requiring permanent water, such as musk ducks and blue-billed ducks, are typical of irrigation drainage swamps (Frith, 1957).

The desired managed water regime would include periodic draw-down to allow the recruitment of *M. halmaturorum*. Denton and Ganf (1994) suggest that draw-downs for this purpose need only occur approximately once every 10 years. This would satisfy the second specific management objective, regarding the preservation of existing vegetation distributions. Draw-downs would benefit duck breeding. The breeding of great egrets would be protected by including periods of inundation greater than 10 months, achieved either by draw-down occuring less frequently than annually, annual draw-down of brief duration, or draw-downs not resulting in the drying of the deeper Hacks Lagoon. The retention of water in Hacks Lagoon would retain the value of the wetland as a drought refuge for waterbirds and would allow the survival of any wetland fauna which require permanent water. This would satisfy the first specific management objective regarding the habitat value of the wetland for waterbirds. The general management objective would be also be satisfied, as the ecological character of the site has been defined as a "semi-permanent wetland, with diverse riparian flora, including a stand of *M. halmaturorum*, which provides important habitat for waterbirds."

Step 6. Refine the desired water regime by examining various scenarios using conceptual modelling

Scenario 1: Permanent water regime

Under this scenario, natural recruitment of *M. halmaturorum* would not occur except at the higher elevations (Denton and Ganf, 1994). The reduced area of *M. halmaturorum* woodland would directly negatively impact ibis populations (LWRRDC, 1997b) and possibly also other waterbird species (Table 14). One alternative is the mass planting of established saplings of *M. halmaturorum* (Denton and Ganf, 1994). Disadvantages of this alternative include the cost and the possible continued adverse effects on other species. While the adverse effects of the altered water regime on this long-lived tree species have been identified, effects of the altered water regime on other species may not be as obvious.

The resultant very stable water regime is likely to be associated with reduced duck breeding (Table 13, Crome, 1988).

Scenario 2: Managed draw-downs most years, with complete drying of the wetland

If draw-down occurred in most years, natural recruitment of *M. halmaturorum* could occur more frequently. The area occupied by *Triglochin procerum* would be reduced, possibly to be replaced by *Baumea arthrophylla*. The value of the wetland as a drought refuge to waterbirds would be reduced or lost if complete drying was to occur frequently. This is a concern as wetlands in much of the surrounding area have been lost (Step 2, Values). Some fauna which may have benefited by the increased permanency of the water regime (eg musk duck, blue-billed duck, some species of frogs and fish) while others may be lost. Abundance of fish-eating waterbirds such as the intermediate egret and the little black cormorant would be reduced. If the hydroperiod was generally less than 10 months, breeding of the great egret may be negatively affected.

Scenario 3: Occasional managed draw-downs characterised by incomplete drying (water to be retained in Hacks Lagoon).

Denton and Ganf (1994) argue that species diversity may best be preserved by a managed water regime that is "adaptable" rather than "fixed", that is, a water regime that incorporates inter-annual variability. They suggest that water levels be manipulated approximately once every 10 years to allow the occasional recruitment of *M. halmaturorum*. In the summer of 1993-4, low water levels were achieved by manipulating the regulator gates, to facilitate *M. halmaturorum* recruitment (Denton and Ganf, 1994). This would have few negative impacts on other species; fish and frogs requiring permanent water could survive in Hacks Lagoon. Large duck breeding events could occur after the infrequent managed draw-down.

Refined desired water regime

Scenario 3 (described above) may best preserve the identified values of this wetland, in particular waterbird habitat values associated with its Ramsar status.

Step 7. Set performance indicators

Performance indicators could be based on successful *M. halmaturorum* recruitment, waterbird breeding, and waterbird abundance and species present.

Step 8. Determine the means of achieving the desired water regime

Regulator gates at the outlet allow manipulation of the water regime (Denton and Ganf, 1994).

Step 9. Prescribe environmental water allocations to achieve the desired water regime

Environmental water allocations could be set based on occasional manipulation of the water level (approximately once every 10 years) to achieve summer levels low enough to allow recruitment of *M. halmaturorum*. Flexibility could be incorporated into the allocations, based on climate variability and the health of previous cohorts of *M. halmaturorum* juveniles. The allocations should also deal with a possible change towards greater permanency and increased depth which may result from the rising water table. If this occurs greater intervention may be required.

Steps 10 and 11. Implementation and Monitoring

Hydrological monitoring should be based on frequent depth measurements. More detailed hydrological measurements would allow a water balance to be calculated, and the risk posed by rising water tables could be assessed. Biological monitoring should include monitoring of the health of *M. halmaturorum* juveniles, waterbird use, waterbird breeding, and the presence of other fauna such as frogs, tortoises and water rats.

Lower Gwydir Wetlands

Step 1. Characterise the wetland

Hydrology

The Lower Gwydir wetlands are semi-permanent terminal wetlands of the Gwydir River (Keyte, 1994). They comprise floodplain wetlands of two major streams of the Gwydir River, the Gingham Watercourse and the Lower Gwydir Watercourse. The hydrology of the wetlands has been altered by the Copeton Dam, weirs, and regulators which divert water for irrigation, stock and domestic use (Keyte, 1994).

Ecology

Vegetation

McCosker and Duggin (1993) have defined the wetland in terms of management units. The hydrology and vegetation communities of the units most affected by alterations to hydrology are indicated in Table 15.

Table 15. Vegetation communities at the Gingham Watercourse most threatened by altered water regime (McCosker and Duggin, 1993).

Unit	Hydrology	Vegetation communities
Low floodplain	Flooding frequency less than that of the Watercourse Unit	Open coolabah woodlands (*Eucalyptus coolibah*) with an understorey of river cooba (*Acacia stenophylla*) and lignum (*Muehlenbeckia florulenta*)
Watercourse	Prior to the completion of the Copeton Dam, subject to regular inundation	Dominant vegetation is water couch (*Paspalum distichum*) and ribbed spike rush (*Eleocharis plana*) meadows. Stands of dead coolabah trees River cooba and lignum

Fauna

These wetlands provide an important resource for waterbirds on a regional scale as their flooding is not always synchronous with flooding of other

Murray Darling Basin wetlands such as the Macquarie Marshes or the Narran Lakes (Directory of Important Wetlands web site). The wetlands are significant for the large numbers of breeding waterbirds that have been recorded (Ramsar web site). Abundance, species diversity and breeding of waterbirds have declined. The abundance of colonial nesting birds (cormorants, herons and egrets) is reported to have declined, as has the abundance of waterfowl, large rails and brolga (Debus, 1989, cited in Keyte, 1994). This has been at least partly attributed to the reduced quantity of water entering the wetlands (Keyte, 1994). A successful large breeding event occurred in the summer of 1999, however after the introduction of new water sharing rules (Nickson, 1999). There is anecdotal evidence that abundance of water rats, frogs and red-bellied black snakes has declined (Keyte, 1994).

Ecological character

The wetlands are of a terminal riverine wetland type, ecologically significant for their large area of water couch and ribbed spike rush meadows, and their habitat value for waterbirds.

Step 2. Identify uses, values and threats

Uses

Two major land uses that affect the wetland are grazing and irrigation for cotton-growing (Directory of Important Wetlands web site). Grazing occurs in the Ramsar site and in wetland outside the Ramsar site, and relies on flooding for the promotion of pasture growth. This is adversely affected by river regulation and the transfer of unregulated flows for irrigation (McCosker, 1994). Some of the wetland area outside the Ramsar site has been cleared for cereal cropping and cotton-growing.

Values

Ecological

Ecological values of the wetlands include their habitat value for waterbirds and the large area of water couch (*Paspalum distichum*) and marsh club-rush (*Bolboschoenus fluviatilis*).

Economic

The wetlands are situated on very productive grazing land, and represent a drought refuge for stock (Keyte, 1994).

Threats

The over-riding threats to the wetlands is a reduction in the frequency and magnitude of flooding, resulting in a reduction of the quantity of water reaching the wetlands. There has been a 70% reduction in the occurrence of flows large enough to flood the Gingham and Lower Gwydir watercourse wetlands. The consequences include a serious and continuing contraction of reed beds, and weed invasion into water-couch and spike rush meadows (Table 16, Keyte, 1994).

Table 16. Nature of alteration to water regime and effect on vegetation at the Gingham Watercourse (McCosker and Duggin, 1993).

Unit	Alteration to hydrology	Affect of altered hydrology on vegetation
Low floodplain	Reduction in medium and moderate floods since river regulation	Invasion of lippia (*Phyla canescens*) River cooba and lignum under stress as a result of insufficient flooding.
Watercourse	Reduction in the frequency and duration of flooding.	Spread of lippia, especially on land subject to irregular and short duration flooding. Contraction of water couch and ribbed spike rush meadows during the last 10 years as a result of a reduction in the frequency and duration of flooding. Dead coolabah trees. The deaths have been attributed to prolonged inundation during the 1950s floods.

Step 3. Determine management objectives

General

To protect against further decline in the ecological character of the site.

Specific

1. To protect the site's habitat value for waterbirds, with particular reference to the amount of waterbird breeding.

2. To reduce the area of weeds such as lippia.

3. To maintain the health of native vegetation.

4. To maintain current vegetation distributions, or where possible, reverse the incursion of terrestrial vegetation into core wetland areas which has occurred since the completion of the Copeton Dam.

Step 4. Describe relationships between biota and water regime

The reduction in the frequency of small to medium floods (as a result of diversion for irrigation) is considered responsible for the displacement of aquatic and semi-aquatic vegetation with terrestrial vegetation, and the invasion of weeds including lippia (*Phyla canescens*). These effects may be accelerated by grazing (Bacon *et al*., 1992, cited in Keyte, 1994).

Estimates of the water requirements of the dominant plant species have been made (Keyte, 1994, shown in Table 17). These are based on the estimated water regime that occurred in each wetland community before river regulation.

Table 17. Estimates of flood frequencies required by dominant plant species (Keyte, 1994, using data from Craig *et al*., 1991 and Rankine and Hill, 1979).

Wetland type	Dominant species	Flood frequency estimates	Flood duration estimate	Type of flood event

Core wetland	*Bolboschoenus fluviatilis*	once per year	30-180 days	Freshes, minor floods
Watercourse	Water couch and ribbed spike rush meadows.	1 in 1-2 years	30-180 days	Minor/moderate floods
Intermittent wetlands	River cooba/ lignum	1 in 3-7 years	30-120 days	Moderate/major floods
Floodplain	Coolabah	1 in 10-20 years	less than 30 days	Major floods

Fauna

Maintenance of the health of lignum and river cooba is important for the long-term maintenance of waterbird populations (Keyte, 1994). Water birds may require longer inundation periods for breeding than the periods required for vegetation health. Briggs and Thornton (1988) suggest minimum inundation periods of 5-10 months for the management of river red gum wetland water regimes for waterbird breeding. This allows species such as darters, cormorants, herons, egrets, spoonbills and Australian white ibis to breed. These species require relatively long inundation periods, while ducks are able to breed successfully with shorter inundation periods. Minimum inundation periods of 5 to 10 months, therefore, allow the breeding of a large number of waterbird species.

Step 5. Determine the target water regime

The desired water regime for each wetland vegetation type is indicated by the estimated water requirements of the dominant plant species (Table 17). Longer durations than those required by plants may enhance waterbird breeding; these may be achieved in high rainfall years rather than every year.

Minimum flooding requirements have been calculated to meet the plant water requirements of the Gingham Watercourse wetlands (McCosker and Duggin, 1993). Volumes of water have been determined to deliver flow events in the categories of freshes, minor floods, moderate floods and major floods for various wetland vegetation types (core wetland, water couch, river cooba and coolabah, respectively).

Step 6. Refine the desired water regime by examining various scenarios using conceptual models

Scenario 1: Current situation.

Scenario 2: Meeting vegetation requirements; increased frequency of inundation, minimum duration.

- healthy native vegetation,
- limited waterbird breeding except in unusually wet years

Scenario 3: Longer duration of inundation.

- healthy vegetation,
- large waterbird breeding events.

Step 7. Set performance indicators in relation to biota

Performance indicators should relate to:

- waterbird breeding events
- waterbird abundance
- waterbird species diversity
- weed abundance
- vegetation health with specific reference to trees (due to their habitat value for birds)
- area of water couch and spike rush meadows

Step 8. Determine the means of achieving the desired water regime

Estimates of water volumes required to achieve and maintain inundation have been made using a water budget, for both wet and dry antecedent conditions (McCosker and Duggin, 1993). The means of achieving the desired water regime would involve the resolution of trade-offs with other water users, due to the over-allocation of water for consumptive uses.

Step 9. Prescribe environmental water allocations to achieve the desired water regime

Environmental water allocations would need to incorporate the natural seasonality and variability of inundation.

Steps 10 and 11. Implementation and Monitoring

Water depth monitoring programs would be designed to measure the frequency and timing of inundation, Depth measurements would need to be taken within each wetland vegetation community. Biological monitoring programs would be designed to measure the performance indicators.

Boggomoss Springs

Step 1. Characterise the wetland

Site Description

The site is located 20 km north-east of Taroom and lies within the Fitzroy catchment in Queensland, in the Brigalow Belt South bioregion. It consists of artesian springs scattered over an area of approximately 400 ha (Directory of Important Wetlands web site).

Hydrology

The springs arise from the Great Artesian Basin and flow permanently. There is variation in flow, some of which is related to seasonal factors (Directory of Important Wetlands web site). The water depth of the wetland is 0.05-0.1 m.

Ecology

General

The permanently saturated nature of the springs provides a habitat markedly different from that of the surrounding region. The flora also differs from that of other artesian springs (Directory of Important Wetlands web site).

Vegetation

The plant community of the springs is rare (Directory of Important Wetlands web site), and there are species of uncertain taxonomic status.

Fauna

An undescribed snail species occurs in the springs (Directory of Important Wetlands web site).

Ecological character

Permanent springs fed by artesian water, with little-known wetland animal and plant species, many of which are likely to be dependent upon the permanent flow of water to the springs for their survival.

Step 2. Identify uses, values and threats

Uses

Landuses of the area include grazing and broadacre farming. The springs are an important water source for livestock (Directory of Important Wetlands web site).

Values

Ecological

The Boggomoss Springs are a good example of active artesian springs, a rare habitat (Directory of Important Wetlands web site).

Cultural

Artesian springs generally have significant Aboriginal cultural value (Reyenga *et al*., 1998).

Economic

Economic values of the site are associated with grazing and agriculture, while the artesian water is of value for stock and domestic use (Directory of Important Wetlands web site).

Threats

Aquifer drawdown through high usage of artesian water in the Great Artesian Basin.

The proposed Nathan Dam could result in the flooding of some of the springs.

(Directory of Important Wetlands web site).

Step 3. Determine management objectives

General

To protect against decline in the ecological character of the site.

Specific

To protect against decline in flow.

(This could be considered a general management objective for all artesian springs of the Great Artesian Basin).

To protect the Boggomoss Springs from hydrological alterations associated with the Nathan Dam.

Step 4. Describe relationships between biota and water regime

Where little information exists concerning the water regime requirements of flora and fauna of artesian springs, it could be assumed that at least some species require permanent water, as the water regime of the springs has been permanent. As many artesian spring species are endemic (Reyenga *et al*., 1998), the reduction of habitat associated with any decline in flow could conceivably endanger endemic populations. The water regimes of some of the springs are also threatened by flooding by the proposed Nathan Dam (Directory of Important Wetlands web site). If the springs were flooded in this way the hydrology and hence water quality and quantity would be completely altered.

Step 5. Determine the desired water regime

The desired water regime would be characterised by:

- no loss of aquifer pressure, and
- no flooding of springs associated with the proposed Nathan Dam.

Step 6. Refine the desired water regime by examining various scenarios using conceptual modelling

Ecological effects of the following scenarios could be explored:

Scenario 1: Maintenance of present aquifer pressure and spring flows. No flooding associated with the Nathan Dam.

Scenario 2: Reduced aquifer pressure leading to the extinction of some of the springs.

Scenario 3: Reduction in aquifer pressure leading to the complete extinction of the springs.

Scenario 4: Flooding of some of the springs by the proposed Nathan Dam.

Step 7. Set performance indicators in relation to biota

Performance indicators for Boggomoss Springs, and for artesian springs generally, could perhaps be related to population sizes of wetland flora and fauna.

Step 8. Determine the means of achieving the desired water regime

The Great Artesian Bore Rehabilitation Project is a joint Federal and State Government Initiative aimed at the reduction of water wastage (Queensland Department of Natural Resources web site). A reduction of approximately 140 megalitres a day has been achieved through the installation of control valves and the use of piping rather than open drains. Bore rehabilitation efforts could be focussed more on the area where recharge occurs for the springs.

Step 9. Prescribe environmental water allocations to achieve the desired water regime

In the case of artesian springs, initiatives such as the Great Artesian Basin Rehabilitation Project may be adequate to control aquifer drawdown. This solution differs from the allocations of other types of wetlands in that it is large-scale rather than being aimed at individual wetlands

Steps 10 and 11. Implementation and Monitoring

Hydrological monitoring

Monitoring of aquifer pressure and flow at the Springs would indicate whether the large-scale management strategy of the Great Artesian Basin Rehabilitation Project is adequate.

Biological monitoring

Monitoring should be aimed at the estimation of the population sizes of artesian spring species.

5. OPPORTUNITIES AND LIMITATIONS

Introduction

Limitations and opportunities for implementing environmental water allocations vary according to the nature and degree of human impact on the water regime, and the source of the water. They are therefore discussed in terms of broad groups of wetlands. Further details are shown in Table 18. The presence of physical structures such as dams, weirs, irrigation channels and levee banks may limit the ability to deliver environmental water allocations. Other limitations are related to the relatively large-scale problems such as rising water tables and the consumptive demand for water. The ability to determine appropriate water allocations is frequently limited by knowledge regarding both the pre-development water regime and the requirements of biota. Significant opportunities for environmental water allocations exist where abstraction occurs and is characterised by a large amount of wastage (eg unregulated artesian bores), and in isolated wetlands where water regimes may be manipulated relatively easily. These limitations and opportunities are explored in more detail below for groups of wetlands.

Riverine wetlands affected by excessive water extraction

Water regimes of many riverine wetlands (both terminal and floodplain) of the Murray-Darling Basin are severely affected by upstream abstraction of water. Examples include the Lower Gwydir wetlands, Narran Lakes, the Great Cumbung Swamp, the Macquarie Marshes and the Barmah Forest. Limitations to the provision of environmental water for these wetlands include the demand for water for consumptive purposes, and over-allocation of water for consumptive purposes. The delivery of large floods is limited by legal liability. In addition, the presence of dams and other regulatory structures such as levee banks restricts the ability to return these wetlands to the pre-development water regime. There is also often a lack of data regarding pre-development water regimes. For these reasons it has been argued that rehabilitation may represent a more achievable management goal for these wetlands than the restoration of the historic water regime (Roberts *et al.*, 2000). A certain level of change in wetland biota may be inevitable.

The Narran Lakes in New South Wales are adversely affected by upstream abstraction in Queensland. This is an example of a potential political limitation of the management of wetland environmental water allocations.

While environmental water allocations for these riverine wetlands may be associated with an economic cost to irrigators (due to a reduction in water allocated to consumptive uses), they are likely to be associated with economic benefits to graziers. This is because the increased flooding frequencies resulting from environmental water allocations benefit floodplain pastures. Excessive extraction for irrigation negatively affects grazing values as well as conservation values. Areas of agreement and conflict between the views of graziers and irrigators have been examined in terms of management of water resources of Macquarie Marshes (Brock, P., 1996). Interestingly, it was found that despite differences there was consensus that the Marshes should be maintained in at least their present (1996) condition.

A review of the social and economic costs and benefits of irrigation can be found in Morrison (1999).

Barmah-Millewa Forest

Large dam releases are considered to be an environmentally suitable solution for the Barmah-Millewa Forest, but the associated socio-economic costs of this are considered too high (Leitch, 1989). Water management is therefore carried out with the use of engineering structures to efficiently deliver water to where it is needed (Barmah-Millewa Forum and MDBC, 2000). Management difficulties associated with the location of the forest in two states is addressed by the existence of the Murray-Darling Basin Commission. The negotiation of trade-offs between various stakeholders is likely to be made easier by the creation of the Barmah-Millewa Forum.

Riverine wetlands threatened by increased permanence due to irrigation drainage water and/or river regulation

There are often opportunities to manipulate the water regimes of individual small or isolated wetlands made permanent as a result of irrigation drainage water or river regulation. Seasonal drying can be restored through the use of flow regulators, with environmental benefits and minimal costs. Examples include Bool and Hacks Lagoon (irrigation drainage) and Lake Woolpolool on the Chowilla floodplain (river regulation). (Details are included in the Literature Review, Section 2).

Great Artesian Basin (artesian springs)

Aquifer drawdown in the Great Artesian Basin threatens both conservation values and the consumptive use of water, as it causes the reduction or cessation of flow from bores as well as springs (Reyenga *et al*., 1998, Qld Department of Natural Resources web site). Efforts to reduce wastage therefore have social and economic benefits in addition to environmental benefits. There may be scope to target springs which are of particular importance due to their endemic fauna. Efforts to reduce wastage could be focussed on the recharge areas of these springs in an effort to avoid the extinction of their flow.

Wetlands impacted by alterations to drainage associated with agriculture

The effect of drainage of wetlands for agricultural development in Queensland's Wet Tropics is the direct loss of wetlands. Other threats to wetland water regimes as a result of agriculture include altered wetland hydrology due to drainage from adjacent agricultural land (Tasmania) and the deliberate drainage of a wetland in an attempt to improve the drainage of nearby pasture (Logan Lagoon, Tasmania) (Directory of Important Wetlands web site). In the case of these wetlands there appears to be a direct conflict between agricultural and pastoral landuse and conservation values associated with wetlands.

Cape Range subterranean wetlands, Western Australia

Flow in these wetlands may be threatened by groundwater extraction for town water supply (Hamilton-Smith *et al*., 1998, Directory of Important Wetlands web site). Expansion of the township and of tourism may lead to an increase in water use which may threaten flow to these wetlands.

Wetlands of the Western Australian wheatbelt threatened by excessive inundation (eg Lake Toolibin)

Wetlands of the Western Australian wheatbelt are threatened by excessive inundation caused by rising water tables resulting from the clearing of deep-rooted perennial native vegetation. Associated problems are salinity and water-logging. Both salinity and excessive inundation negatively impact wetland flora and fauna. Limitations to the ability to reduce excessive inundation of wetlands of these wetlands are generally associated with the very large-scale nature of the problem. Solutions are likely therefore to be very expensive. However, attempts to address salinity issues, such as tree-planting, will have the effect of reducing excessive inundation of these wetlands.

Wetlands of the Swan Coastal Plain (general)

Wetlands of the Swan Coastal Plain are potentially affected by excessive groundwater extraction. The reduction of evapotranspiration associated with clearing for urbanisation however mitigates the effect of groundwater extraction. As the increased exploitation of surface water is associated with other environmental costs, an increase in Perth's population without a reduction in per capita water usage will negatively impact these wetlands. There is however a relatively large knowledge base regarding the water requirements of wetland vegetation and aquatic invertebrates and the hydrology of these wetlands due to a targeted research program carried out in the late 1980s and early 1990s (Kite *et al*., 1994). A large percentage of these wetlands have already been lost through filling and draining for urban development.

Twin Swamps (Swan Coastal Plain, groundwater fed)

Opportunities for managing individual wetlands of the Swan Coastal Plain are similar to those for small riverine wetlands. The water regime of Twin Swamps is managed to meet the requirements of the endangered western swamp turtle (*Pseudemydura umbrina*). Groundwater is pumped into Twin Swamps to extend the hydroperiod. This approach will no longer work if the groundwater table falls too far.

Desert soaks and gnamma holes of Western Australia with water regimes potentially adversely affected by feral camels

The permanent nature of many desert soaks and gnamma holes is threatened by camels. Trampling by camels may damage the vegetation of desert soaks, which could lead to the greater exposure of the water surface, resulting in their drying up (Dragon Tree Soak, ANCA, 1996). Camels drink some gnamma holes dry (Gibson Desert Gnamma Holes, ANCA, 1996). Cost is a limitation to protecting these wetlands from the potentially significant alteration to their water regimes by camels. This could be achieved by either reducing camel numbers or in some cases by the fencing off of small wetlands.

Wetlands of the Australian Alps threatened by alterations to drainage

Alpine wetlands are threatened by alterations to drainage caused by walkers (Davies Plain, Kosciusko Alpine Fens, Bogs and Lakes, Mount Buffalo Peatlands, etc), stock (Caledonia Fen) and four-wheel driving (Davies Plain)

(ANCA, 1996). Limitations to the protection of the water regimes of these wetlands are those associated with the cost of education campaigns, signs, the re-routing of walking tracks, and fences to exclude stock. Hydrological research may be required to determine the extent of the threats to the water regimes of the wetlands.

Table 18. Limitations and opportunities for implementing environmental water allocations for wetlands.

Region	Type of wetland	Source of water	Nature of threat to wetland water regime	Limitations	Opportunities	Examples
Murray Darling Basin NSW, Vic, SA, Qld	Riverine terminal wetlands	Surface water dominated. River	Reduced quantity of water (reduction of certain flows) due to abstraction and regulation Increased permanency in parts (eg near irrigation channels).	There is frequently an over-allocation of water for consumptive purposes, and a high demand for water for irrigated agriculture. Environmental water allocations to wetlands are associated with economic costs to irrigators. Lack of data regarding pre-disturbance water regime. Legal limits to the delivery of large floods Political boundaries rarely coincide with catchment boundaries, making management difficult. eg the Narran Lakes of NSW: significant upstream extraction occurs Queensland.	These wetlands are generally located in south-eastern Australia, where work has been done of wetland plant water requirements. Many of these wetlands have management plans with environmental water allocations. Many sites are Ramsar-listed (eg Lower Gwydir wetlands, Narran Lakes). Environmental water allocations to wetlands are associated with economic benefits to graziers. The existence of the Murray-Darling Basin Commission should facilitate coordination of management.	Lower Gwydir wetlands Narran Lakes Macquarie Marshes Great Cumbung Swamp

Region	Type of wetland	Source of water	Nature of threat to wetland water regime	Limitations	Opportunities	Examples
Murray Darling Basin NSW, Vic, SA, Qld	Floodplain wetlands of SE Australia	Surface water dominated. River (bank overflow).	Reduced quantity of water (reduction of certain flows) Increased permanency in parts. Increased water in summer threatens moira grass plains of the Barmah-Millewa Forest (Atkins, 1993)	River regulation, diversion, abstraction, flood mitigation Legal limits to the delivery of large floods In the case of the Barmah-Millewa Forest, difficulties associated with its location on the boundary of two states (NSW and Victoria), ie, two jurisdictions.	A methodology has been developed for the determination of plant water requirements for these wetlands (Roberts *et al*., 2000). In the case of the Barmah-Millewa Forest, the stakeholders are represented through the Barmah-Millewa Forum, making trade-offs potentially easier. The existence of the Murray-Darling Basin Commission should facilitate coordination of management.	Barmah-Millewa Forest
Murray Darling Basin and elsewhere	Small or isolated riverine wetlands affected by irrigation drainage water, or river regulation.	Surface water dominated. Irrigation drainage water, or water from regulated streams.	Increased permanency		Regulators are often present, facilitating management of water levels. There is some information regarding the water requirements of species adversely affected by excessive inundation (Denton & Ganf, 1994)	Bool and Hacks Lagoon SA Lake Woolpolool, Chowilla floodplain SA

Region	Type of wetland	Source of water	Nature of threat to wetland water regime	Limitations	Opportunities	Examples
Great Artesian Basin (NSW, QLD, SA)	Artesian springs	Artesian water	Aquifer drawdown due to extraction from bores. Artesian pressure and discharge rates have declined (Queensland Department of Natural Resources web site)	Aquifer flow in the Great Artesian Basin crosses State political boundaries (Qld, NSW, SA) Improvements in artesian pressure resulting from the Great Artesian Basin Project could be slow. Before they are achieved some springs could become extinct, along with any endemic fauna, ie, response time or lag.	The Great Artesian Basin Project is a joint Federal and State Government initiative (Queensland Department of Natural Resources web site) There are opportunities for reducing water wastage (the Great Artesian Basin Rehabilitation Project). Preservation of the resource for consumptive use by reducing wastage does not conflict with conservation values.	Elizabeth Springs Aramac Springs Lake Eyre Mound Springs Boggomoss Springs

Region	Type of wetland	Source of water	Nature of threat to wetland water regime	Limitations	Opportunities	Examples
Queensland coast (Wet Tropics)	Wetlands of the Wet Tropics impacted by alterations to drainage associated with agriculture (especially sugarcane production)	Various; riverine plus local catchment run-off	Alterations to wetland hydrology due to drainage from adjacent agricultural land. Drainage of wetlands for agriculture.	Conflicts between conservation values and agricultural practices (drainage) There are no Ramsar-listed sites		Herbert River Floodplain wetlands Innisfail area wetlands Russell River wetlands Tully River/Murray River Floodplains Wyvuri Swamp
Tasmania	Wetlands impacted by alterations to drainage associated with agriculture	as above	Lake water levels affected by water use for agriculture (Little Waterhouse Lake) Logan Lagoon is threatened by drainage for the purpose of improving soil drainage on nearby pasture	Conflicts between conservation values and agricultural and pastoral values/uses		Little Waterhouse Lake Logan Lagoon
Western Australia	Subterranean karst wetlands	Groundwater	Reduced flow due to groundwater extraction	Pressure on the water resource for town water supply	There has been a large amount of research interest in the endemic cave fauna	Cape Range subterranean wetlands

Region	Type of wetland	Source of water	Nature of threat to wetland water regime	Limitations	Opportunities	Examples
Western Australia	Wetlands of the WA wheatbelt	Groundwater	Excessive inundation due to rising water table related to clearing of native vegetation	The problem is large-scale in nature. Solutions are likely to be large-scale and expensive	Pumping Planting deep rooted perennial vegetation in strategic locations Efforts to address salinity issues will also ameliorate excessive inundation	Lake Toolibin Coyrecup Lake Yealering Lakes System
Western Australia	Wetlands of the Swan Coastal Plain (general)	Groundwater	Reduced water levels and alterations in variability associated with groundwater abstraction Increased levels associated with effects of clearing.	Threats to wetland water regimes (abstraction for Perth's water supply and hydrologic alterations resulting from clearing) are likely to increase with increasing population. The alternative to groundwater abstraction, increased exploitation of surface water resources, also has environmental costs.	The hydrologic effect of groundwater abstraction (lowering of the water table) mitigates against the hydrological effect of clearing (rising water table). Potential water-saving opportunities may exist. A knowledge-base exists regarding ecological response to water regime due to a targeted research program carried out in the early 1990s based on wetlands of the Gnangara Mound	Gnangara mound lakes Jandakot mound lakes (these include the Ramsar sites Thomsons Lake and Forrestdale Lake)

Region	Type of wetland	Source of water	Nature of threat to wetland water regime	Limitations	Opportunities	Examples
Western Australia Twin Swamps (Swan Coastal Plain)	Groundwater-fed	Groundwater	Hydroperiod (period of inundation) in some years was too brief to enable the endangered western swamp turtle (*Pseudemydura umbrina*) to survive and reproduce.	The solution (pumping groundwater into the wetland) will not be successful if the groundwater table falls significantly	The hydroperiod was able to be extended by pumping in groundwater.	Twin Swamps
Desert east/north-east Western Australia	Desert soak and surrounding permanent swamp	Groundwater	Camels damage vegetation. This could potentially lead to the exposure and consequent drying out of the wetland	Cost of excluding camels or reducing camel population	The wetland is relatively small (5 ha total, 1 ha main water area) so fencing may be an option Reducing camel numbers may benefit other ecosystems	Dragon Tree Soak
	Gnamma holes	Surface run-off	Camels occasionally drink gnamma holes dry	Cost of excluding camels or reducing camel population	Reducing camel numbers may benefit other ecosystems	Gibson Desert Gnamma Holes
Australian Alps (ACT, NSW, Vic)	Bogs, wet heath, lakes, fens	Snow melt, direct precipitation, groundwater (springs)	Trampling by walkers and stock, and 4-wheel driving may result in the alteration of drainage lines	Cost of education, fencing, signs	Education campaigns	Caledonia Fen, Davies Plain, Kosciusko Alpine fens, bogs and lakes, Mount Buffalo Peatlands, Rock Flats

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