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Riverine and Wetland Salinity Impacts — Assessment of R&D Needs

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Boxes

Glossary

avifauna	the birds of a given region
charismatic	capacity to influence or impress people
DECORANA	a statistical package used in pattern analysis
detrital	composed of detritus
detritus	particles of dead organic matter, often finely divided suspended in water or lying on the bottom
water drawdown	fall in water level due to abstraction
epiphyton/epiphytes	the biofilm occurring on plants. Epiphytes can be plants or animals that grow attached to plants, using them as support rather than as a direct source of organic matter
fecundity	the power of an animal species to multiply rapidly; the number of eggs produced by an individual or species
ionic	characterised by the presence of electrically charged atoms or other chemical species
lotic	pertaining to, or characterised by, running water
macrophytes	aquatic plants large enough to be seen with the naked eye, represented in freshwaters by submerged, floating and emergent forms
mesosaline	moderate levels of salinity
oligosaline	low levels of salinity
periphyton	the plants and animals attached to submerged surfaces such as rocks, plant stems etc., also known as *Aufwuchs*
potable	fit for drinking by humans
taxa	groupings of related species (singular: taxon) used in the classification of plants and animals
ephemeral lake	a short-lived lake created by recent rain or inflow
terminal lake	a lake with no outlets
trophic	pertaining to nutrition and position in the food chain or web
TWINSPAN	a statistical program used in pattern or cluster analysis

Executive summary

The salinisation of land in Australia as a result of human activities is a significant problem for agricultural production, infrastructure and terrestrial biodiversity. The process also affects rivers and wetlands but its impacts on these environments have received less attention.

Recognising this, the Land and Water Resources Research and Development Corporation (LWRRDC) commissioned a scoping review of available information. The aims were:

- to identify the current status of knowledge on the impacts of salinisation on rivers and wetlands,
- to identify the management and other implications of current research, and
- to identify R&D gaps.

This report represents the outcome of this scoping review.

The principal impacts of salinisation of inland waters include:

- loss of aquatic biodiversity;
- negative changes to vital ecosystem processes such as primary productivity;
- nutrient cycling/spiralling, and decomposition;
- breakdown of food-web structure;
- a decrease or loss of aesthetic, amenity, recreational and other values;
- loss of wetland and riverine habitat;
- decrease in water quality; and
- overall environmental degradation.

Secondary salinisation, as it is known, is a result of the disturbance to the hydrological cycle brought about by the replacement of native deep-rooted perennial vegetation with annual crops and pastures. This development of agriculture has resulted in increased groundwater recharge, rising watertables and consequent mobilisation of salts naturally stored in the soil profile. Rising saline groundwater can directly impact wetlands or enter streams through groundwater seepage. Salt brought to near the soil surface can also be transported to streams by surface run-off or interflow. Saline discharges, for example from irrigation enterprises, can also be made directly to wetlands or streams.

The region most affected by salinisation to date is south-west Western Australia. However, extensive salinised areas also exist in South Australia, Victoria and New South Wales. All these states anticipate a substantial expansion of the problem, and some areas in Queensland and Tasmania are also at risk.

The environmental costs of salinisation in terms of loss of biodiversity and ecological assets is likely to be very high but are intrinsically difficult to quantify.

The impact of salt on the freshwater biota is complex, diverse, extensive and inevitably negative. The sensitivity to salt differs between different groups of the biota so that accurate predictions of the impact for particular groups is difficult. The extent of knowledge of the sensitivity to salt is different for different groups, but overall is inadequate.

The detailed findings and recommendations of this review are as follows:

Aquatic environmental impacts of salinisation

- Representatives from all biological communities, particularly macroinvertebrates (detritivores, predators and herbivores) and plants (diatoms/algae, macrophytes and riparian vegetation) are salt sensitive. As a result, any deleterious effects to particular taxa are likely to translate into broader ecosystem processes, such as primary productivity, decomposition, nutrient spiraling/recycling, and the flow of energy and material through trophic webs. Such processes define ecosystems and underpin their fundamental health and integrity.
- Exposure to salinities of between 1,000 and 2,000 mg/L for even short periods is likely to have significant deleterious effects on biological communities in lowland streams, rivers and associated wetlands and, as a result, impact on important ecosystem processes. More subtle sublethal and indirect effects are likely to occur at salinities below this. However, there are insufficient data to

assess either the likelihood, extent or magnitude of such changes.

- Species diversity is significantly reduced as salinity increases, with more salt tolerant but less diverse taxa likely to become dominant.
- For temporary wetlands, the concentration of salts as water evaporates results in the exposure of biological communities to increasing salinities. Although flooding river water or groundwater may initially be of low salinity, final salinities may be four to five times initial ones, because of evaporation. In addition, combinations of high water temperatures and salinities during summer result in low concentrations of dissolved oxygen. Such low levels of oxygen, coupled with increasing bacterial respiration of organic material would further contribute to oxygen depletion. An observed decrease in pH is of concern, particularly if widespread in poorly buffered wetland systems. The more acidic conditions would undoubtedly prove harmful for the biota, in some cases more so than changing salinities.
- The plant community (micro-algae and macrophytes) contains a range of species sensitive to small increases in salt concentration, including both lethal and sublethal effects. A concentration of 1,000 mg/L is sublethal; for some species, lethal effects become evident at 2,000 mg/L. The decline in macrophyte biomass has several significant repercussions:
  - reduction in plant cover causing changes in the light regime and subsequent shift towards a more phytoplankton-dominated system and algal blooms;
  - loss of food and breeding habitat for waterbirds, fish and lower, support levels of the food web (eg. insects and yabbies);
  - reduction in concentration of dissolved oxygen, resulting in fish kills, adverse effects on decomposition and denitrification, liberation of phosphorus from sediments and production of noxious tastes and odours.

  Such synergistic effects will compound, resulting in significant loss of ecosystems of high conservation and public amenity value.
- Significant loss of abundance (biomass) in many invertebrate taxa reduces food availability for other taxa, including fish and waterbirds, and confounds impacts on in situ carbon/nutrient processing.
- As salinities increase over the drawing-down period, significant increases in abundance of more salt tolerant fly species, including some mosquito and chironomids (midges), are likely to occur.
- Macroinvertebrates in wetlands consist of a diverse community that include species sensitive to small increases in salinity. Significant reductions in species diversity have been observed at a salinity of 800 mg/L. Sensitive taxa include cladocerans, gastropod snails, some hydrophylid water beetles, aquatic weevils, dragonflies, some damsel-flies and some dipteran fly species.
- Increasing salinity up to 5,000 mg/L significantly reduces the abundance of all major taxa, including water beetles, crustaceans, and dipteran flies, that emerge from flooded wetland sediments 12 months later. No gastropod snails emerged. Such long-term effects are significant given that such over-wintering communities are the first animals to emerge after the wetland floods and are likely therefore to represent the initial processes involving detrital material, and underpin later community development. This later community develops as a more diverse secondary wave of insects and bird consumers arrive in the wetland.

Knowledge gaps

- Current knowledge is insufficient to make informed statements concerning the extent and magnitude of likely impacts of increasing salinity in riverine and wetland ecosystems.
- Few studies have examined community changes in either wetlands or rivers subjected to increasing salinity.
- There is a significant lack of knowledge of fundamental processes affecting ecosystem structure and function in riverine and wetland systems. Lack of basic knowledge prevents reasonable predictions of the likely salinity effects to riverine and wetland ecosystems.
- The relative contributions of phytoplankton, epiphytes and macrophytes to net primary production in wetlands or as food source for various consumer categories, are not known.
- There has been little, if any, interaction between groundwater hydrologists and biologists/ecologists examining salinity effects in aquatic systems. The absence of such interdisciplinary research is seen as an impediment in assessing the potential environmental effects of salinisation of aquatic systems.
- A review of salinity tolerance data indicates that, although some information on the sensitivity to increased salt concentrations of certain river and stream dwelling animal and plant species is available, there is little information on the effects of salinity on possible sensitive life-history stages, behavioural responses, and of sublethal effects.
- There is a dearth of information on the effects of salinity on communities of plants and animals and their interactions. Deleterious effects on certain important taxa (so-called, keystone taxa) or groups of taxa (eg. micro-algae) in a community are likely to have more significant effects on ecosystem processes, such as production or the decomposition of organic matter, than effects on other groups.

- It is difficult to predict the effects of increased salinity on lowland systems given the lack of detailed biological information. Little is known in the way of either animal and plant community structure in lowland rivers and streams, or how communities vary in space and time. Even less is known about the extent and magnitude of interactions between particular animal taxa or plant/animal functional relationships. Vital ecosystem processes within lowland streams and rivers are poorly understood and require elucidation.
- General biological knowledge of Australian wetlands is extremely poor. In only a few cases, for example, is it known what plants and animals live in wetlands apart from the obvious charismatic species. This lack of basic census information is the legacy of years of neglect by governments and researchers. This basic omission has been repeatedly cited as undermining informed opinion and management decisions.
- Despite obvious links between groundwater intrusion and salinisation of wetlands and rivers, a poor understanding of the dependence of wetlands systems on groundwater exists.
- Changes in salinity over time in relation to drawdown events and flushing are rarely monitored yet they are likely to be critical to any understanding of processes.
- There is little information on how important leaching and flushing are in re-setting salinity levels, ie. what the impacts of hydrological practices on salinity in wetlands are, especially given that wetland and river systems are increasingly being regulated.
- There is minimal information on the rehabilitation of wetlands and rivers following salt impacts.

Implications for research and management

- As a matter of urgency, the effects of salinity on the base of the food web, periphyton/epiphyton productivity and detrital processing, should be quantified in some representative streams and wetlands.
- Longer-term studies should be undertaken to elucidate and quantify the effect of increasing salinity at an ecosystem level in rivers and wetlands. These studies need to examine effects on temporal and spatial variation in rates of primary production, decomposition, organic matter processing and nutrient cycling over a range of different wetland and riverine types.
- Broader interdisciplinary studies involving biologists, hydrologists, hydrogeologists and engineers should be encouraged and supported to examine and quantify interactions between groundwater intrusion, salinisation of rivers and wetlands, and associated ecosystem responses.
- Pre-existing biological survey data and related stream and groundwater salinity data from a variety of impacted streams and wetlands should be collated and analysed to provide some baseline biophysical data and potential hazard maps of types of systems at risk.
- Studies should be undertaken to examine and quantify the connections between salinity catchment hydrology and wetland/riverine catchment hydrology.
- Existing studies examining environmental flows should be expanded to incorporate salinity, groundwater flows and groundwater salinity.
- Studies should be undertaken that link engineering options to ameliorate salinity problems with biological/environmental outcomes. The potential conservation or ecological improvement with engineering costs should be identified.
- Studies should be undertaken to quantify the effects of rapid salinity increases (eg. resulting from overland flow, pulses of salt water moving down a stream) on biological communities in a variety of different riverine and wetland systems so as to identify effects and possible generic responses.
- Broadscale surveys of wetlands should be undertaken to examine, validate and quantify the extent of any correlations between increasing salinity and pH changes in wetlands.
- Researchers and managers should be encouraged to work together on large-scale field experiments to quantify salinity effects per se before and after management intervention.
- Changes in salinity over time in relation to drawdown events and flushing should be monitored.
- Studies should be instituted to determine the importance of leaching and flushing in re-setting salinity levels, ie. determine the impact of hydrological practices on salinity in wetlands, especially given that the management of wetland and river systems are increasingly involving regulation.
- Studies should be undertaken to elucidate the relationships between drawdown, flushing and salinity levels in a variety of wetlands.
- Studies should be undertaken to quantify the effects of various management practices on wetland and riverine health as measured by community structure, biodiversity and ecosystem processes.
- Long-term studies should be set up to determine how long it takes community or ecosystem change in streams and rivers subjected to increasing salinisation.
- Given that salinity is intricately linked to environmental water flows, studies should be undertaken to determine the amounts of water required to maintain wetland systems in the face of increasing salinisation.
- The implications, in terms of environmental degradation, of transporting or temporarily holding saline wastewater in rivers and wetlands needs to be clearly offset against the short-term benefits gained.

- The distance that saline water is moved through natural drainage systems should be minimised.
- Saline water should not be directed to a wetland that cannot be easily and frequently flushed.
- Catchment level management plans need to have protection of wetlands and rivers as a primary objective.
- Where appropriate methods involving replanting with deep-rooted species and increased efficiency of on farm water use should be used to arrest the rise in saline groundwater in preference to surface and sub-surface drainage.
- Wherever possible saline water should be disposed of on the farm or in the region of its origin.
- Until reliable data exist to suggest otherwise, where release of saline water into natural systems is unavoidable, salinity levels of the receiving waters must be maintained at less than 1,000 mg/L.
- Negative as well as positive effects of management strategies designed to protect riverine and wetland systems from salinisation must be considered when developing a management plan.

Introduction

Background to this review

Salinisation is an increase in the concentration of total dissolved solids in water and soil. Land and water resources can be salinised naturally by physical and chemical processes, referred to as **primary salinisation**, or by human activities, referred to as **secondary salinisation** or, often simply as **salinisation**. Major secondary salinisation problems exist in many semi-arid and dry areas of the world, with an estimated 950 M ha (an area slightly greater than the land mass of Australia) now affected by salt. Like land resources, water resources are also affected by salinisation following human activities. The main causes of aquatic salinisation in surface water systems are accelerated saline groundwater seepage, or overland flow across saline affected land or discharges of irrigation return flows. The volume of water resources affected by salinisation and salt loads, as well as the relative contributions of natural and human-induced sources, are not known. In almost all countries with major land salinisation, salinisation of streams, rivers and wetlands are a major problem. These countries include Australia, Argentina, China, the Commonwealth of Independent States (former Soviet Union), India, Iran, Iraq, South and Northern Africa, Thailand and the United States of America.

The severity of economic, social and environmental damage caused by this problem although undoubtedly extensive, is not known.

It is estimated that Australia has 29 M ha of naturally saline land (Williamson 1990) of which salt marshes, salt lakes and salt flats—important ecosystems in their own right (Williamson 1990)—cover 14 M ha. Secondary salinisation has developed in little more than 200 years, that is, since settlement by Europeans and the introduction of agriculture and domestic grazing animals. It is now arguably one of, if not the most, important land and water resource problem. Every State is now affected by salinity problems to some degree, in most cases in association with other major land and water degradation impacts. Large areas of land and aquatic resources of New South Wales, Victoria, South Australia, the Murray–Darling Basin and Western Australia are now significantly degraded by salt. There are concerns held by senior resource managers and researchers that the problem is not only increasing in severity but that land and water resources in Queensland and Tasmania will also be affected.

Attempts to estimate the impact of secondary salinisation so far have been largely based on the economic costs associated with loss of agricultural production, although it is recognised that additional costs associated with social and environmental degradation are likely to be significant. However conservative, such estimates of economic costs are considered so significant that in Victoria and Western Australia, for example, secondary salinity is regarded as **the most significant** land resource issue.

To lessen economic, social and environmental impacts and costs of secondary salinisation, a range of management strategies have been or are being developed at all three levels of government, ie. Federal, State and local. Significant variation between States exists in planning, and developing strategies, and the States are at different stages in their implementation. Understandably, an important aim in management plans is to reduce the impact of salinity on agricultural production. However, policy initiatives are designed both to lessen subsequent impacts on aquatic systems, and, in some cases, protect and rehabilitate riverine and wetland ecosystems. Even so, resource managers are presently required to make policy and management decisions on salinity based on little information about the ecological impacts on rivers and wetlands. Recognising this, the Land and Water Resources Research and Development Corporation commissioned a scoping review of available scientific and management information.

Review objectives

1. To identify the current status of knowledge of the national salinity situation in terms of its environmental impacts on riverine and wetland condition and health and related management issues

2. To identify the scale, scope and management implications of current research work being undertaken on identifying and quantifying the effects of increasing salinity on riverine and wetland health
3. To identify critical R&D gaps and associated management implications of environmental effects of increasing salinity on riverine and wetland health.

Scope of the review

The significance of secondary salinisation is made more complex because it is strongly correlated with many other forms of land degradation that impacts on aquatic systems; for example, erosion and sedimentation, increasing inputs of nutrients and other pollutants and flow regulation. Salinity effects per se, therefore, rarely occur in isolation. Increasing salinisation of land and aquatic environments is one feature of a far broader landscape degradation having both synergistic and complementary components. Notwithstanding this, this review focuses upon:

- **the effects of salinity itself on the biology and management of wetlands and riverine systems, and incorporating a comprehensive analysis of all biotic groups.**

However, as appropriate, we have attempted to describe how this focus fits into the broader changes brought about by salinity per se and the concomitant effects of landscape changes driving salinity.

Process of the review

This review has been carried out by a small team who consulted widely with senior resource managers at both regional, state and federal levels and senior scientific researchers.

The process involved the following steps:

- a collation of (i) the national and international scientific literature pertaining to impacts of secondary salinisation on aquatic systems, (ii) appropriate federal and state government and regional policy documents and research reports concerned with managing the salinity problem, and (iii) reports and conference abstracts documenting salinity research from research/funding organisations;
- a extensive review of this information;
- taped, face-to-face interviews of key researchers and managers across the country and all currently or recently involved with secondary salinity, either examining its impacts on biota and eco-processes in riverine or wetlands systems, or its management at regional, state or federal level;
- discussions with aquatic biologists and ecologists;
- preparation of a draft review for critical examination and feedback by reviewers selected by LWRRDC; and
- preparation and submission of final review.

The assistance provided by all those contacted and subsequently involved is gratefully acknowledged. Any transcription errors in the information given by them or its interpretation are our responsibility.

Practitioners interviewed:

- Dr Margaret Brock, University of New England
- Mr David Buntine, Department of Natural Resources and Environment, Victoria
- Dr Bruce Chessman, Department of Land and Water Conservation, NSW
- Dr Jenny Davis, Murdoch University, WA
- Dr Ray Froend, Edith Cowan University, WA
- Associate Professor George Ganf, University of Adelaide
- Dr Fred Ghassemi, Australian National University
- Dr Stuart Halse, Department of Conservation and Land Management, WA
- Ms Anne Jensen, Department of Environment and Natural Resources, SA
- Dr Kay Morris, Monash University
- Mr Danny O'Neill, Department of Natural Resources and Environment, Victoria
- Dr Greg Raisin, Department of Land and Water Conservation, NSW
- Dr Nick Schofield, Land and Water Resources Research and Development Corporation
- Dr Peter Terrill, Murray–Darling Basin Commission
- Dr Bill Walker, Australian National University
- Dr Glen Walker, CSIRO Water Resources
- Professor Bill Williams, University of Adelaide

Each was contacted by letter and invited to participate in the study. A copy of the template of 14 questions to be used to direct interviews was also included. With the permission of each interviewee, each interview was recorded and a subsequent transcript produced. Verification of answers, opinions, and comments as transcribed was sought from each interviewee, following the production of a summary of opinions. This summary formed the basis of our subsequent analysis and production of the review of opinions.

Environmental costs of secondary salinisation

The impact and associated costs of secondary salinisation are mostly seen in terms of land degradation and decreases in water quality leading to economic loss of agricultural productivity and damage to domestic, commercial, community or government infrastructure. Impacts to the environment, although normally acknowledged as significant in most publications, have yet to be adequately quantified.

At a qualitative level, it is generally acknowledged that impacts due to secondary salinisation will result in:

- **decline of native vegetation;**
- **loss of nesting sites and decline in bird populations;**
- **loss of food sources for wildlife populations;**
- **increased soil and wind erosion;**
- **loss of wetland habitat;**
- **reduced biodiversity in streams, rivers and wetland ecosystems; and**
- **loss of water quality for the environment.**

Such impacts will lead inevitably to:

- **loss of aesthetic and amenity value of these habitats;**
- **loss of recreational and tourism opportunities;**
- **damage to state/national parks and wildlife sanctuaries; and**
- **decline in the value of the national heritage and national estate.**

Such assertions are largely based on intuition and on observations of land and water ecosystems already significantly impacted due to land degradation, including salinisation. However, such visible impacts have normally resulted from high salinity, for example, and are largely irreversible.

At present there is no national consensus on the extent and magnitude of the impacts of secondary salinisation on the environment in terms of critical concentrations (acute or chronic impacts), spatial and temporal effects of exposure, and habitats, biota, and ecosystem processes most at risk. There are also at present no national estimates of environmental damage as a component of the economic cost of salinity.

Impact on aquatic biodiversity: salt sensitivity of biota

In this part of the review we provide a comprehensive overview of the current status of information on the environmental effects of secondary salinity in terms of its impact on the aquatic biota, and consequently loss of biodiversity. It is preceded by the following boxed sections which provides additional information on the origin and physiological adaptations of freshwater organisms that account for observed salinity effects.

Origins of freshwater biota and physiological adaptations

Differences in origin explain many anomalies of structure and habit encountered in the freshwater biota. For example, some insects are only aquatic during certain stages of development (eg. dragonflies, with aquatic juveniles and terrestrial adults terrestrial) and many have to breathe air (eg. water bugs and water beetles), reflecting their ancestral terrestrial lineage. Life evolved in a primeval sea about 3,000 to 4,000 million years ago. Simple life-forms gave rise to the complex organisms that colonised freshwater environments. Some forms invaded and successfully colonised dry and others stayed aquatic. Of the latter, comparatively few, perhaps via swamps, estuaries or brackish waters, eventually reached fresh water. Their descendants comprise the *primary aquatic plants and animals* which make up most of the present flora and fauna of wetlands, ponds, lakes, streams and rivers. In addition, representatives from widely differing groups of land plants and animals re-colonised the aquatic environment. These secondarily aquatic organisms include higher water plants, aquatic insects, mites and spiders, and some water snails (predominantly, pulmonate gastropods).

The general distribution of the freshwater biota and their likely origins are summarised by Hutchinson (1967). This distribution has been influenced by a long evolutionary history of physiological adaptations to a wide range of salinities including mechanisms for osmotic regulation (Krogh 1939; Beadle 1943, 1957, 1959; Robertson 1960; Potts and Parry 1964). The changes have mostly developed against a background of large differences between the salinity of the environment and that of the cytoplasm or body fluids of the aquatic organism concerned.

Physiological adaptations of aquatic plants and animals to salinity

Plants and animals have adapted to live in a wide range of aquatic environments, including fresh waters (rivers, streams and wetlands), saline lakes and wetlands, estuaries and the oceans. To achieve this, organisms have developed a range of physiological mechanisms and adaptations to maintain the necessary balance of water and dissolved ions in their cells and tissues. Knowledge of the extent and the ability of freshwater plants and animals to do this is also extremely important in any consideration of their sensitivity to increased environmental salinity levels.

Box continued on next page

Physiological adaptations of aquatic plants and animals to salinity — cont'd

In the following boxed sections, we briefly review the basic principles of physiological adaptations in freshwater plants and animals, and in simple terms seek to answer the two questions: How is salt lethal to aquatic plants and animals? What sublethal effects are caused by increased salinity? More specific information on each of the biological groups reviewed is contained in the relevant sections that follow. In simple terms, high salinity is lethal to freshwater plants and animals because the cells of the organism have either a lack of water or an excess of ions or both and this results in a range of toxic effects.

Osmotic relationships

The movement of water across a cell membrane is controlled by the process of *osmosis*. Cell membranes are selectively permeable in that water can pass freely, in either direction, through the membrane, while most solute ions (eg. sodium, potassium) and molecules (eg. urea, other organic molecules) must be actively transported. Water molecules flow through the cell membrane to keep the ionic concentration on both sides equal; this is called *osmotic flow*, and the force required to oppose the osmotic flow is the osmotic pressure. The more concentrated the solution, the greater the tendency of water to move into it and the higher the osmotic pressure of the solution. Animal physiologists generally use the term osmotic pressure (or osmotic potential), while plant physiologists prefer the term water potential. A fundamental difference between the two is that osmotic pressure is a function of solute concentration only, while water potential is also a function of pressure.

When the cell and its external medium have the same osmotic pressure, the two are said to be iso-osmotic. In this case, there is no net movement of water molecules in either direction. For example, a solution of 9,000 mg/L sodium chloride is iso-osmotic to the cells of humans and other mammals, and red blood cells placed in 9,000 mg/L sodium chloride will neither shrink nor swell. However, if the red blood cells are transferred to a more concentrated sodium chloride solution, they lose water to the surrounding medium and therefore shrink. The solution is said to be *hyper-osmotic* to the cell. On the other hand, if the cells were transferred to a less concentrated sodium chloride solution, water would start to diffuse into the cell which would then swell and eventually burst. In this case, the surrounding medium is now *hypo-osmotic* to the cell.

While the selectively permeable membrane of a cell enables water to diffuse freely across it, this is not the case for most solutes dissolved in the cytoplasm (ie. internal medium of the cell) or the extracellular fluid (ie. the solution external to the cell). Here, the solutes are *actively transported* into and out of the cell to regulate the solute concentration and thus maintain the integrity of the living cell. There is a number of mechanisms by which this energy-demanding process occurs (Wallace et al. 1986). The physiological relations between the tissues of aquatic organisms and the external environment are of two kinds. In the case of the Protozoa, small algae and small, simple multicellular organisms (eg. *Hydra*), the cells are for the most part in direct or very close contact with the water, and the control mechanisms are concerned with the regulation of ion and water exchange directly between the cell interior and the external medium. On the other hand, in the large multicellular animals such as annelid worms, molluscs, Crustacea, insects and fish, most of the living tissues are bathed by a body fluid which acts as an intermediary and 'buffers' the effects of the normal environmental fluctuations. The control of exchange between body fluid and external surroundings is often performed by a relatively few specialised cells situated on the body surface and in the gut and excretory organs.

Plants

Plant cells differ from those of animals in having a rigid cell wall, as well as having a large vacuole which can develop high osmotic pressure because of the high concentrations of salts, sugars and other organic compounds stored in it. In a normally functioning plant cell, water diffuses into the vacuole causing it to distend and press against the cell wall.

Box continued on next page

Physiological adaptations of aquatic plants and animals to salinity — cont'd

Plants — cont'd

Such a condition is known as turgor. Turgor can be maintained only when the water potential of the soil or surrounding solution is more positive than that of the plant cells (Wallace et al. 1986). If this plant cell was then placed into a high salinity solution (ie. hypertonic medium), it would tend to lose water to the surroundings and the cell membrane would tend to shrink away from the cell wall. This non-turgid condition adversely affects the functioning of the plant and the plant will eventually die. Plants are often divided into two broad groups in terms of their response to salinity; *non-halophytes* are those species that achieve their best growth in fresh waters and whose growth is reduced as salinity increases, and *halophytes*, which are those plant species that are salt-tolerant. Non-halophyte plants grown in soils or water with high salinity generally suffer either reduced growth or death, caused by either (or both) toxic effects due to an excess of ions in their cells, or water deficit due to difficulties in extracting water from the surrounding medium (Greenway and Munns 1980).

Animals

The ability of an animal species to regulate optimal internal osmotic concentrations against external gradients determines the salinity tolerance of the species. Good regulators are *euryhaline*, while poor regulators are *stenohaline* or *osmoconformers*. In addition, some species exhibit tissue tolerance, ie. body fluid concentrations may vary widely without the physiological impairment that would be caused in most species. The concentration of ions in the body fluids of most freshwater invertebrates is significantly lower than in their marine invertebrates, but still usually well above that of the external medium. This leads to a tendency for water to be gained by osmosis and for ions to be lost by diffusion. The animal counters these tendencies by excreting urine and actively taking up ions. Freshwater organisms are therefore hyper-osmotic regulators. In contrast, organisms in saline environments are hypo-osmotic regulators, generally excreting only small amounts of urine and possessing a range of mechanisms to exclude salt. Vertebrates often possess additional mechanisms for either excluding or handling excess salt.

Impacts on biodiversity

Earlier debate concerned, not so much whether increasing salinity will impact on the freshwater biota but rather the extent of the impact, given the high salinity of environments that some organisms had been exposed to over geological and historical time and thus adapted to. Some argued that some aquatic Australian fauna and flora were pre-adapted to increasing levels of salinity because of the likely salinity fluctuations of their aquatic environments they had evolved in. This is likely to be the case for some plants and animals, and indeed evidence for such tolerance exists within some groups (see section on salt sensitivity). However, extreme care in extrapolating such arguments is needed in assessing impacts to riverine and wetland ecosystems. The **rate** at which hydrological equilibria have been disrupted since European settlement, the **concentrations** that biota are now exposed to, and the wide geographical extent of such disruption inevitably results in the exposure of freshwater ecosystems to rapidly increasing salinities, likely to be well in excess of pre-adaptive flexibility. Further, as discussed elsewhere in this report, the salinity problem has been exacerbated by other environmentally degrading landscape processes that impact on aquatic systems such as water extraction/flow regulation, increasing levels of nutrients, and sedimentation. Such multifactorial impacts, many synergistic in influence (for example, the toxic effects of salinity are affected by lowered dissolved oxygen, and such shifts in oxygen concentration will in turn influence the form of nutrients available and their concentration) will cause a raft of significant deleterious effects on aquatic biota, with increasing salinity simply a major contributor. Available evidence is given below.

Salinity effects on different taxonomic groups

Hart et al. (1989, 1991) conducted an extensive and critical review of the available scientific information (scientific literature and government reports) on the possible biological effects of increasing salinisation on the freshwater biota. The review considered in detail the lethal and sublethal effects of salinity on individual species within the following groups of aquatic organisms: microbes (mainly bacteria), microalgae, macrophytes (vascular plants), riparian vegetation, invertebrates, fish, amphibians, reptiles, mammals and waterbirds.

Their review highlighted a general lack of data worldwide on the sensitivity of freshwater plants and animals to increases in salinity. While there were some useful laboratory and field data on lethal and sublethal effects of increased salinity on particular species, such information was limited because it only covered short-term, acute effects, and a relatively small number of test species (mostly adults) had been investigated. Very few studies were identified that investigated lethal or sublethal effects on possibly more sensitive life stages.

In addition to laboratory data, their review relied heavily on field survey data from within Australia, where the presence or absence of particular species had been noted and qualitatively correlated with salinity. Such presence/absence data take no account of the general viability of the population as in many cases no data on abundances were recorded. The use of such data for determining salinity tolerance was acknowledged as questionable; however, it does provide a comprehensive list of individual aquatic taxa and records the ranges of salinity within which they have been collected.

One repeated pattern shown by the review by Hart et al. (1989) is that within each category of biota there exists a large range of salt sensitivities, with some 'freshwater' species within the group (admittedly few) being found over a large range of field salinities. This pattern also existed at lower taxonomic categories. For example, within the water beetles, 74 different taxa were listed: of these, 24 were found in salinities up to 5000 mg/L, 13 up to 10,000 mg/L, eight in salinities greater than 20,000 mg/L. Furthermore, within five different species of the same genus, *Stenopriscus*, three were found at salinities less than 1,000 mg/L, one was found at 5,000 mg/L, and one was found at 51, 020 mg/L.

- **Such variation makes it difficult to predict, with confidence, broad response patterns within particular groups. This underlines the danger of extrapolating generalised responses for broad taxonomic categories**

Since 1989, notwithstanding some progress in attempts to close the gaps identified by Hart et al. (1989), there still exists little information on the biological and environmental effects of increasing salinity to freshwater systems. As a result, most of the major conclusions of Hart et al. (1989, 1991), in our opinion, are still relevant. With this in mind, we have included below the original conclusions for each taxonomic group from Hart et al. (1989). These are shown below with the text italicised. Pertinent research since 1989 has then been reviewed and used to develop, modify or refine these conclusions. Our subsequent comment or revised conclusions are then shown in bullet-pointed bold text.

Microbial community

Bacteria play important roles in aquatic ecosystems. They affect the mineralisation of organic matter, recycling of major nutrients, transformations of pollutants and the flow of energy and material through the trophic web. They interact with both the abiotic and living (biotic) components of wetlands, streams and lakes. Because of the complexity of these relationships and the possibility for synergistic interactions, the only certain way to know what effect low-level salinisation may have is empirically to study bacteria in the affected system. Such studies should focus on processes rather than individual bacteria.

It appears that small changes in salinity may have little deleterious effect on microbial processes of importance to freshwater ecosystems. Because of the ability of freshwater bacteria to adapt to small changes in salt content and the replacement of freshwater types with otherwise similar salt water bacteria, the bacterial community as a whole may be able to compensate.

This review revealed a scarcity of studies which explicitly examine the effects of small increases in salinity on microbes in fresh water ecosystems. The current review has been unable to identify any new studies.

There have been numerous studies of microbes in estuaries and coastal oceans; however, few of these have actually examined salinity per se as the dominant factor in ecosystem interactions. This is partly due to the difficulty in separating the effects of salinity differences from those caused by large changes in organic matter supply, suspended load, current velocity and other characteristics that also occur when fresh water and salt water meet. This problem is especially relevant in applying the results of these studies to salinity increases in freshwater ecosystems, where increased concentrations of predominantly, sodium chloride, is the only major variable.

There may be differences in the effects caused by low level continuous inputs of salt and pulsed inputs, if the frequency of the pulses does not allow the community time to adapt.

Significant impacts could occur if salt inputs interact with physical factors to create situations affecting important functional groups of bacteria. This could occur in wetlands with low flushing rates where evaporation could increase the salinity, and stratification could occur favouring bacteria with different dominant metabolic pathways causing large shifts in benthic microbial metabolism.

- **We are not aware of any additional research since 1989 that has examined the effect of salinity on microbial communities that would lead us to disagree with the original conclusions of Hart et al. (1989, 1991).**

Micro-algae

There is little information on the salt sensitivity of micro-algae.

Recent work on the effect of salinity on diatom communities has focused on the diatom flora of natural salt lakes. Even so, many useful insights are provided by this research. Blinn (1993, 1995) reported that salinity is an important variable in the distribution of saline lake diatoms. He reported that the greatest diatom diversity was found in habitats with conductivities less than seawater and with an ionic composition similar to marine environments. Blinn (1995) presented the results of a survey of 19 lakes of varying salinity in Western Victoria. He found that as salinity rose, species number and diversity fell. For example, Pink Lake (262 mS) had only seven diatom species, while Lakes Elingamite and Purrumbete (3.7 mS) had over 100 diatom taxa.

Blinn (1993) developed a conductivity index which provides a relative numeric scale to evaluate various diatom taxa along conductivity gradients. This index was used to rank the various diatom taxa in the salt lakes of Western Victoria according to their association with ionic strength (Blinn 1995). Taxa such as *Navicula erifuga, Fragilaria capucina* var. *radicans, Navicula cincta, Nitzschia palea, Nitzschia frustulum, Rhopalodia musculus, Navicula communis, Navicula pusilla, Rhopalodia gibberula* and *Amphora coffeaeformis* are considered to be most tolerant of habitats with high salinity. In contrast, species *Rhopalodia gibba, Gomphonema parvulum, Navicula pygmaea, Amphora avalis, Diatoma tenue, Navicula pupula* and *Nitzschia amphibia* are considered to be less tolerant of elevated salinity.

Based on a cluster analysis of the conductivity index, Blinn (1995) found that selected diatom taxa displayed four major groupings. The least tolerant group were found at conductivities less than 20 mS. The next two groups were found at conductivities of 75 mS and 100 mS. A fourth group was considered the most euhaline as its taxa occurred over the full range of conductivities—from 1.5 to 262 mS. Blinn (1995) also identified several species whose distribution was correlated with a suite of ions including Na^+, K^+, Mg^{2+} and Cl^-. As the concentration of these ions increased, the numbers of Rhizosolenia eriensis fell whilst the numbers of *Navicula cincta, Navicula erifuga* and *Stauroneis wislouchii* rose. Some species also showed significant positive Pearson correlations with specific ions. *Navicula cincta* and *Navicula erifuga* were positively correlated with Na^+ and *Fragilaria capucina* var. *radicans* and *Nitzschia palea* were positively correlated with Cl^-.

Although salinity appears to be the factor determining community structure, other factors may be involved. For example, there is a notable difference in the salinity tolerance of two varieties of *Cocconeis placentula* (*lineata* and *euglypta*). The former invades waters with relatively high salinities (>70 mS) while the latter is restricted to waters with conductivities <10 mS (Blinn 1993; 1995). Differences in the distribution of these two varieties may result from differences in their association with specific substrata rather than salinity tolerance alone. Lowe (1974) indicated that *Cocconeis placentula* var. *euglypta* is primarily epiphytic while no specific substrate was given for *Cocconeis placentula* var. *lineata*. The dramatic decrease in species richness and abundance of vascular plants with increasing salinity (Hammer and Heseltine 1988) may be the limiting factor for *Cocconeis placentula* var. *euglypta* in saline lakes.

We conclude:

- **As salinity rises, the number and diversity of diatom species falls**
- **Selected diatom taxa fall into three categories of salt sensitivity: less than 20 mS includes the most sensitive, 75–100 mS includes those of intermediate tolerance and 100–262 mS includes the most tolerant.**
- **Diatom taxa are correlated with ionic composition or suites of ions including Na+, K^+, Mg^{2+} and Cl^-.**
- **Certain diatom taxa may be lost from a system as a result of their association with specific substrata rather than from salinity increase. The decrease in species richness and abundance of vascular plants with increasing salinity may be the limiting factor**

Macrophytes

A large proportion of macrophytes found in Victoria are salt sensitive, with salinity increases up to around 1,000–2,000 mg/L expected to result in lethal effects.

Field studies show that diversity of macrophyte species decreases as salinity levels increase.

The research emphasis to date has been on understanding the adaptations of halophytes to elevated salinity rather than the effect of salinity on non-halophytes.

There has been little study of the biology or ecology of macrophytes and microalgae in Australian rivers and streams.

There is a range of salt sensitivities amongst the species making up a macrophyte community.

Sublethal effects may lead to the gradual disappearance of the more sensitive species from a community.

Warwick and Bailey (1998) exposed *Potamogeton tricarinatus* grown from tubers and the seedlings of *Triglochin procera* to 2 g/L and 6 g/L NaCl immediately after turion and seed emergence and 34 days after emergence. Plants of *P. tricarinatus* exposed to 2 and 6 g/L immediately after emergence were reduced in size, with plants exposed to 6 g/L developing leaves having submerged leaf-type morphology. Delaying NaCl exposure for 34 days post-emergence for *P. tricarinatus* caused catastrophic leaf loss and a reduction in new leaf emergence at both salinities. In contrast, *T. procera* grew at a steady rate. No difference was apparent between plants exposed to salt after 0 or 34 days. There was some effect of 6 g/L NaCl on rate of leaf gain throughout the experiment and on dry weight after 80 days.

Warwick and Bailey (1997) demonstrated that the freshwater macrophytes *Amphibromus fluitans*, *Potamogeton tricarintus* and *Triglochin procera* exhibit very different patterns of ion accumulation in their leaves. *A. fluitans* excluded Na^+, maintained the lowest concentration of Na^+ and Cl^- of the three species and maintained low concentrations of Na^+ in the younger leaves relative to the older leaves. *P. tricarinatus* was unable to regulate its Na^+ and reached saturation of uptake at an external NaCl concentration of 2 g/L; similar Na^+ concentrations were observed in leaves of all ages. The absence of a leaf age gradient may be attributable to a capacity to absorb Na^+ from the water column directly into the leaves irrespective of age. *T. procera* took up the largest amount of Na^+ and in approximate proportion to the outside concentration although it maintained low concentrations of Na^+ in the younger leaves relative to the older leaves. *T. procera* may be capable of absorbing Na^+ into leaf vacuoles which could be balanced by a high concentration of a compatible solute such as proline in the leaf cell cytoplasm.

In both *A. fluitans* and *T. procera*, the ratio of Na^+/K^+ was lower in younger leaves than in older leaves. *A. fluitans* and *T. procera* are both capable of growing as emergent macrophytes, in contrast to *P. tricarinatus*, which cannot and, therefore, may have leaf cuticles which prevent desiccation when growing out of the water column and retard uptake of solutes when in the water column. If Na^+ and Cl^- can only be taken up via the roots, then there is a capacity for selection of K^+ over Na^+ and the transport of K^+ to the youngest leaves.

James and Hart (1993) found a range of salt sensitivities measured in terms of height and number of shoots/leaves produced with *P. tricarinatus* being the most sensitive followed by *M. crispatum*, *E. acuta* and *T. procera*. A progressive depression of growth rate and plant size was observed for each species with increasing salinity above 1,000 mg/L. The onset of depression of growth rate occurred more quickly the higher the salinity the plants were exposed to. Both sexual and asexual reproduction were blocked in *M. crispatum* at salinities greater than 1,000 mg/L.

Warwick and Bailey (1997) found that in terms of growth and leaf demography, *P. tricarinatus* was the most severely affected of the species they investigated. It showed significantly reduced dry weight and leaf size at 6 g/L salt along with a reduction in leaf appearance rate and an increase in leaf death. *T. procera* was not as severely affected although leaf size was reduced at 6 g/L salt. *A. fluitans* was not affected by a salinity of 6 g/L.

We conclude that:

- **A large proportion of submergent macrophytes found in SE Australia are salt sensitive, with increases up to about 1,000–2,000 mg/L likely to result in lethal effects for some species. Sublethal effects will occur at lower salinities.**
- **The vigour of aquatic plants is reduced at levels less than lethal salinities.**
- **The range of salt sensitivities amongst the species of a macrophyte community probably reflect differences in morphology and the physiology of ion uptake.**

Riparian vegetation

Many of the higher plants associated with wetlands and lowland rivers are salt sensitive. The available data indicate that adverse effects will occur at salinities above 2,000 mg/L for a number of aquatic plant species found in Victoria. It is likely that sublethal effects are operating below this level, but the extent is unknown.

The salinity tolerance of non-halophyte plants depends largely on their capacity to exclude sodium chloride either by limiting sodium chloride uptake through osmoregulation, or by accumulating, but then compartmenting the sodium chloride (this latter strategy may be combined with the synthesis of organic solutes to maintain osmotic equilibrium).

Large variations in salt sensitivity occur between species and between populations and individuals of the same species from different locations. For a particular plant species, the populations growing in freshwater environments tend to be more sensitive to salinity increases than those growing in slightly saline environments.

Salt sensitivity can differ between the seeds and seedlings of an individual species. This may reflect different environmental salinities encountered at various life stages (eg. germination, seedling stage and maturity).

Increasing salinity and waterlogging can act synergistically in affecting plant growth—for waterlog-tolerant plants, salinity interferes with the plant's adaptive mechanisms to waterlogging.

Few of the experimental studies reported in the literature distinguish between lethal and sublethal effects on plants. Often short-term studies give salt tolerance limits or ranges, but fail to explain precisely what these mean, especially in terms of plant recovery or longer-term adverse effects. For example, sublethal salinity effects, below a designated (short-term) tolerance range for a particular species, may prove deleterious in the longer term. There is increasing evidence showing that long-term responses to salinity might be due to factors quite different from those affecting growth in the short term.

Difficulties arise in assessing salt sensitivity of plants because of different experimental methodologies used and the different sources of seed tested. The latter often results in markedly different salt sensitivities being found for the same species by different researchers.

Many of the data used in this section to rank salt sensitivity of plant species are derived from studies oriented towards reclamation of salt-affected land. Considerable caution is needed in extrapolating these data to predict the salt sensitivity of extant native vegetation.

In view of the potential for substantial variations in sensitivity to salt depending upon the origin of the plant species, and the inherent problems in extrapolating data, experimental trials similar to those described by Clemens et al. (1983) and van der Moezel and Bell (1987), should be undertaken prior to any discharge of saline wastewater to wetland or lowland river systems. Seed should be collected from plant populations within the area to be affected and should be selected from a range of riparian, littoral and aquatic species.

Bell and Froend (1990) monitored the change in survival, growth and vigour of tree species growing on the bed and margins of Lake Toolibin, an ephemeral lake of the Northern Arthur system in the central Western Australian Wheatbelt. Lake Toolibin is comparatively fresh but is increasingly influenced by secondary salinisation and unnaturally prolonged inundation. They demonstrated the sensitivity of temporary lake species to the combined stresses of increased flooding duration and salinity. *Eucalyptus rudis* and *Melaleuca strobophylla* are trees of the lake margins where soil salinity was 0.3%. These two species were the most sensitive to the combination of increasing secondary salinity and prolonged periods of inundation, and showed the greatest mortality, greatest reduction in vigour, and smallest growth increments. *E. rudis* has previously been shown to be adversely affected by increasing periods of soil saturation (Froend et al. 1987)

Bell and Froend (1990) found that *Casuarina obesa* was not as severely affected as species growing at the margins of Lake Toolibin. Although areas of high *C. obesa* mortality exist, over most of the lake bed the increase in stress apparently still lies within the limits of tolerance of the mature trees. *C. obesa* has been shown to be highly tolerant of salinity and waterlogging stress (van der Moezel et al. 1988). Populations of *C. obesa* in the middle areas of the lake, which had the highest soil salinity (0.07%) of any of the populations, showed increased mortalities, decreased vigour and reduced growth compared to populations of *C. obesa* in areas of the lake with more favourable conditions; *C. obesa* was not affected by longer periods of inundation.

Mensforth and Walker (1996) have demonstrated that *Melaleuca halmaturorum* is able to survive in saline areas fringing frequently waterlogged areas such as permanent wetlands and temporary swamps through a combination of environmental processes and physiological adaptations. This species has a deep and extensive root system able to adjust root water uptake to take advantage of available water sources. During the summer, the plant uses saline groundwater in response to salinisation (and hence unavailability) of surface soil water. *M. halmaturorum* is able to take up water from saline substrates by maintaining a low leaf water potential. At the end of winter, water is taken from a combination of groundwater and rainfall near the soil surface.

In an investigation of *Eucalyptus camaldulensis* trees growing at two sites on the banks of Punkah and Chowilla creeks, two permanent creeks on the Chowilla anabranch system of the Murray River, Thornburn et al. (1994) showed that the trees sometimes derive only 50% of their water from the creeks. The rest is derived from the more saline soil waters and groundwaters. The average salinity of the groundwater was 4,000 mg/L at Chowilla Creek and 28,000 mg/L at Punkah Creek. They suggested that use of soil water or groundwaters might benefit the red gums because it would buffer the response of the trees to changes in creek flow and salinity that occur naturally (eg. during droughts) or for anthropogenic reasons. Uptake of soil water would also provide nutrients.

Mensforth et al. (1994) investigated the water sources of *E. camaldulensis* ranging in distance from 0.5 to 40 m from Punkah and Chowilla creeks. The creeks had a conductivity of 0.8 dS/m and the underlying groundwaters values ranging from 30–50 dS/m. Trees greater than 15 m from the creek used no stream water. They used groundwater in the summer and a combination of groundwater and rain derived surface-soil water (0.05–0.15m depth) in the winter. They suffered water stress at conductivities > about 40 dS/m, about –1.4 Pa. Trees adjacent to the Chowilla Creek used stream water directly in the summer but may have used stream water which had flooded the soil profile in the winter. *E. camaldulensis* appears to be partially opportunistic in the source of water it uses.

Thorburn and Walker (1994) investigated the water sources of *E. camaldulensis* at three sites on the Chowilla floodplain with varying exposure to stream water, all underlain by moderately saline groundwater. Water uptake patterns were a function of the long-term availability of surface water. Trees with permanent access to a stream used some stream water all of the time. However, water from soils or the watertable frequently made up 50% of the water used by these trees. Trees beside a temporary stream had access to the stream 40–50% of the time (depending on the level of the stream). No more than 30% of the water they used was stream water when available. However, stream water use did not vary greatly whether trees had access to the stream for two weeks or 10 months prior to sampling. Trees at the third site only had access to surface water during a flood. These trees did not change their uptake patterns during 2 months inundation compared to dry times, so were not utilising the low salinity flood water. Trees beside the temporary stream appeared to change their water use efficiency in response to the availability of surface water. *E. camaldulensis* at the study site may not be as vulnerable to changes in stream flow and water quality as previously thought.

Thorburn and Walker (1994) concluded that generally stream water is not as important for *E. camaldulensis* as previously thought. Therefore, changes in river flow patterns and salinity will not necessarily be detrimental to trees. However, the time scale over which *E. camaldulensis* responds to change in stream conditions is unknown. Tree health may be directly linked to river hydrology as groundwater depth and salinity are affected by changes in river or stream flow. Increases in groundwater depth and/or salinity will reduce uptake of groundwater (Thorburn et al. 1994) and increase water stress on trees (Mensforth et al. 1994).

We conclude that:

- **Some riparian species have extensive root systems in contact with several different sources of soil water. They are able to adjust water uptake to take advantage of the less saline source(s) as they become available at different times of the year. Such species may not be as detrimentally affected by changing salinity as originally thought.**

Invertebrates

Invertebrate species appear to be amongst the most sensitive of the freshwater animals to increases in salinity, with adverse effects likely to occur in some species at salinities in excess of 1,000 mg/L.

The available data suggest that the most sensitive invertebrate animals are from three groups: simple multicellular organisms, insects and molluscs. Toxic effects would be expected to occur in the simple multicellular organisms (eg. Hydra *sp., flatworms) with quite small increases in salinity, given their lack of complex osmoregulatory structures and their small size. Within the insects, some groups (eg. water bugs, beetles and dipteran flies) are expected to be quite tolerant of salinity increases, while other groups (eg. stoneflies, some mayflies, some caddisflies, some dragonflies and certain water bugs) will be sensitive to even minor increases in salinity. The limited data available suggest that some mollusc groups, particularly pulmonate snails, are quite sensitive to increasing salinity.*

The crustaceans appear to be the most salinity tolerant of the invertebrates. However, in this group as in others, there are individual species that are quite salt sensitive.

There are some serious limitations in the available information base relating to the effects of salinity on invertebrates, including:

- *a general lack of data for many groups;*
- *a limited amount of laboratory tolerance data, and that which are available are biased towards salt tolerant species;*
- *much of the available data are based on field observation of presence or absence of species. There is rarely an assessment of whether the population is viable;*
- *a lack of data from which to assess the salinity tolerance of the various life stages; here a knowledge of the tolerance of eggs would be useful;*
- *a lack of information from which to assess the ecological relevance of laboratory-based salinity tolerance data.*

Recent experimental work by Bailey (1998) in which salinity was artificially increased for wetland invertebrates demonstrated a significant reduction in invertebrate species diversity as assessed by five separate diversity indices including 'number of taxa'. The lowest concentration at which a significant reduction was observed was 800 mg/L, as assessed by the Shannon index.

Recent work by Williams et al. (1990, 1991), Bunn and Davies (1992), Hammer et al. (1990), Bailey et al. (1993–96) and Gallardo and Prenda (1994) largely supports the above conclusion. Williams et al. (1991) and Bunn and Davies (1992) both reported lower than expected occurrence of insect taxa in a number of rivers subject to salinisation in South Australia and Western Australia. In particular, both studies suggested that certain species of mayflies, stoneflies, caddisflies, megalopterans, mecopterans, and neuropterans may be particularly sensitive to salinity. Other groups either absent or rare in samples included oligochaetes, leeches, turbellarians and non-estuarine bivalve molluscs. Vertessy (1994), Marshall

(1996) and Bailey (1998) demonstrated that the abundance of the gastropod snail, *Ferrissia tasmanica*, a species found in lowland rivers of Victoria, was significantly reduced at a salinity of 2,000 mg/L after only four days of exposure. The crustacean community, dominated by cladoceran species, found in a temporary floodplain wetland in central Victoria, were shown to include the most sensitive of invertebrates when salinity increased from 400 mg/L to 5,000 mg/L over a six month period. Abundance was reduced by 77 to 99%. Other sensitive groups from this wetland community included certain water beetles (Hydrophilidae), aquatic weevil beetles (Curculionidae), dragonflies (Anisoptera), gastropod mollusc (*Isidorella newcombi*), and certain Ceratopogonidae, Stationyidae and Tanypodinae (Diptera).

Bailey (1998) has produced a database of invertebrate salt sensitivity for species associated with riverine and wetland environments within Australia.

Taylor (1994) reported significant sublethal effects for increasing salinity on growth, fecundity and age-dependent mortality in two species of gastropod snails, *Isidorella newcombi* and *Lymnaea* sp., found in wetlands, central Victoria. Individuals, although consuming similar amounts of food, grew slower and produced lower numbers of egg masses of significantly smaller size than did the controls. Additionally, juvenile snails were significantly more sensitive to salt than adults. The work of Vertessy (1994), Marshall (1996), Taylor (1994) and Bailey (1998) have gone a little way in addressing the absence of experimental manipulation of salinity in examining invertebrate sensitivity. Their results have revealed that common invertebrate inhabitants of both lowland streams and temporary wetlands contain species highly sensitive to even low and moderate increases of salinity.

We conclude that:

- **As a group, aquatic invertebrates contain species that range from the most sensitive to the most tolerant taxa. Adverse effects are likely to occur for some species at salinities in excess of 800 mg/L.**
- **Each taxonomic division of the invertebrate phyla contains species that are highly sensitive to increases in salinity. Using such broad categories as Insecta and Crustacea is generally unhelpful. A more extensive statistical examination of the available database compiled by Bailey should be undertaken to identify any hierarchical grouping of species/taxa based on their 'sensitivity'. A broader type of classification is likely to prove useful to resource managers when attempting to predict salinity effects on biodiversity within a stream, river or wetland.**
- **Although many species of crustacean are found over a considerable range of conductivities, some individual crustacean species are no less sensitive than other groups.**
- **Little information on the salt sensitivity of invertebrate groups, both lethal and, particularly, sublethal effects exists. There are serious limitations in the information that does exist, in particular:**
  - **many of the data are based on field observation of presence/absence of species. There is rarely any indication of whether populations of the species are viable;**
  - **few laboratory tolerance data, particularly those examining any potential synergism between salinity and, for example, temperature or dissolved oxygen are available;**
  - **information on sensitive life stages, eg. eggs or juveniles is generally lacking.**

Fish

Adult Australian freshwater fish species appear to be quite tolerant of salinities up to around 10,000 mg/L.

The least tolerant Australian species known appears to be the sooty grunter, based on the inability of its sperm to fertilise eggs when the salinity is over 8,000 mg/L. The most tolerant species is the Lake Eyre hardyhead, which has been found at salinities of 145,000 mg/L in Israel (Lotan 1971), and Cyprinodon variegatus, *which has been recorded at 142,000 mg/L in North America (Simpson and Gunter 1956).*

The small amount of information available on sensitivity of critical life stages of fishes to salinity suggest that larval stages may be more sensitive than adult stages. Fish eggs appear to be relatively tolerant of salinity increases.

Studies on the entire life cycle, or preferably on the most critical life stages, of important fish are needed. The sperm viability test is rapid and simple, and may provide a conservative indication of a species' salinity tolerance.

There is little information available on the sublethal effects of salinity on fishes. These may include shifts in abundance and distribution, or behavioural responses (eg. breeding). There is a need for more research in this area.

There have been no studies on Australian species to test the different effects (if any) on growth due to constant compared with fluctuating salinity increases. Evidence is available showing that acclimated fish species are more tolerant of salinity than unacclimated individuals.

Virtually all information on salinity tolerance in fishes is derived from field observations or laboratory tests where the solutions contain predominantly sodium chloride. The effects of other ions have received little attention.

In an Australia-wide context, future salinity tolerance studies would be best directed at the primary division fishes, Neoceratodus forsteri, Scleropages jardini, Scleropages leichardti, *and* Lepidogalaxias salamandroides, *these being the ones least likely to be tolerant of elevated salinities. At present, only* Lepidogalaxias *(Salamanderfish) occurs in an area where dryland salinity is a problem, but all could conceivably be exposed to increased salinity in the future, particularly as a result of saline discharges.*

Preliminary results from O'Brien (1996) have suggested that eggs exposed to elevated salinities immediately upon fertilisation (pre-water-hardened eggs) may be more sensitive than eggs several hours after fertilisation (water-hardened eggs). Pre-water-hardened eggs of Macquarie perch and trout cod both showed significant reductions in survival when placed in saline test solutions ranging from 1,500–6,000 μmhos/cm and 6,000 μmhos/cm, respectively. No eggs survived test solutions of 6,000 μmhos/cm. The level causing a 50% reduction of hatching for Macquarie perch and trout cod were 2,900 and 5,100 μmhos/cm, respectively. O'Brien's (1996) preliminary results, using respiration rate and blood osmolarity effects, suggested that elevated salinity causes stress to some species at levels commonly observed in some salt affected environments.

We conclude that:

- **Fish eggs appear more sensitive to elevated salinity immediately after fertilisation.**
- **Increasing salinity may cause sublethal stress in Macquarie perch and trout cod.**

Amphibians, reptiles and mammals

Amphibians

No data currently exist on the salinity tolerance of adult Australian frogs. Overseas laboratory studies suggest that adult frogs should be able to tolerate salinities up to ca. 10,000 mg/L, but only for limited time periods.

There have been no Australian studies, and very limited overseas investigations, of the effects of salinity on egg masses or tadpoles, both of which could be more sensitive.

Tadpoles and egg masses may be sensitive indicators of the biological effects of salinity in wetlands, and appear worthy of special investigation.

Main (1990) investigated the salt sensitivity of frogs and tadpoles of the western Australian burrowing frog, *Heleioporus albopunctatus*, at preferred/selected breeding sites. Deposition of salt in the soil and decay of vegetation has destroyed many breeding sites of this frog throughout the wheatbelt of Western Australia (Main 1990).

Reptiles

Freshwater tortoises are the reptiles most at risk from salinity increases in lowland rivers and wetlands.

Overseas studies have shown that turtle species with salt-secreting glands can tolerate estuarine environments. At least one Australian species of Australian freshwater tortoise is known to possess functional salt glands.

This indirect evidence suggests that Australian freshwater tortoises may be able to cope with salinities up to 5,000 mg/L provided they possess functional salt glands.

Mammals

Australia's only strictly freshwater mammal is the platypus. No information exists on its salinity tolerance.

- We are unaware of any studies examining the effects of increasing salinity on freshwater amphibians, reptiles or mammals.

Waterbirds

Salinity tolerance varies greatly between different waterbird species.

Many species of waterbird are able to feed in saline waterbodies, but must have freshwater nearby to drink.

There is evidence of low breeding success for some waterfowl species when salinity increases above 3,000 mg/L, possibly due to the poor ability of hatchlings to osmoregulate.

Water birds are directly dependent upon macrophytes (for food, nesting and cover) and invertebrates (for food). Both these groups are likely to be adversely affected at salinities well below those causing direct effects on water birds per se.

Botero and Rusch (1994) have recently examined temporal changes in wetland use by Blue Winged Teal in Columbia and Costa Rica. There, freshwater wetlands have been shown to be significant winter feeding areas for this species but some are impacted by changing environmental conditions, particularly a decrease in vegetation and a simplified invertebrate community structure. Surveys of feeding and nesting behaviour at all wetlands were carried out periodically from 1980 to 1989 and revealed significant changes in diet and nesting intensity at the Cienaga Grande wetlands, Columbia. Changes in food availability were cited as the explanation of the differences in diet between 1982 and 1988. Although not quantified, aquatic plants such as water lily and busy pondweed abundant in 1982 and important to blue-winged teal, disappeared as salinity levels increased over a large area of Cienaga Grande over the next five years.

The ability of the red-necked phalaropes, *Phalaropus lobatus*, to switch prey under conditions of changing prey abundance at Mono Lake, California, was tested in order to predict the potential effects of continued water diversions there on migratory waterbird populations (Rubega and Inouya 1994). Mono Lake is a saline lake. Freshwater diversions have caused a drop of 12.2 m in lake-level resulting in a doubling of lake salinity, and a substantial decrease in the abundance of one of the two major prey items, the soft-bodied larvae of *Ephydra hians* (dipteran fly). The other major prey item, *Artemia monica* (hard-bodied brine shrimp), showed no adverse population effects as salinity levels increased. Red-necked phalaropes could not switch prey because they are incapable of surviving on a diet of just the hardier of the two invertebrates. Individual birds fed only *Artemia* lost weight rapidly until death ensued, or until they were offered another prey. Such data show that a marked preference for one prey may indicate important physiological limitations in some waterbirds, and also indicate that strong prey preferences of migratory birds can, and probably should, be taken into account in determining the likely impacts of salinisation on prey species, especially where initial prey diversity is low.

Knowledge gaps for freshwater ecosystems: inadequacy of current information

- There is an acute scarcity of studies which explicitly examine the effects of small increases in salinity on microbial species in freshwater ecosystems.
- There is an inadequate knowledge base for accurate assessment of whether micro-algae are affected by increasing salinity.
- There has been little study of the biology or ecology of macrophytes and microalgae in Australian rivers and streams.
- There are few data on either sublethal effects on growth, physiological or community responses in macrophytes.
- Few published experimental studies distinguish between lethal and sublethal effects in plants. Often short-term studies give salt tolerance limits or ranges, but fail to explain precisely what these mean, especially in terms of plant recovery or longer-term adverse effects. For example, sublethal salinity effects, below a designated (short-term) tolerance range for a particular species, may prove deleterious in the longer term. There is increasing evidence showing that long-term responses to salinity might be due to factors quite different from those affecting growth in the short term.
- There are some serious limitations in the available information on the effects of salinity on invertebrates, including:
  - a general lack of data for many groups;
  - a limited amount of laboratory tolerance data, with those available biassed towards salt tolerant species; many available data are based on field observations of presence or absence of species. There is rarely an assessment of whether the population is viable;
  - a lack of data from which to assess the salinity tolerance of the various life stages; here, a knowledge of the tolerance of eggs would be useful;
  - a lack of information from which to assess the ecological relevance of laboratory-based salinity tolerance data.
- The little information available on the sensitivity of the critical life stages of fish to salinity suggests that larvae may be more sensitive than adults. Fish eggs appear to be relatively tolerant of salinity increases.
- Studies on the entire life-cycle, or preferably on the most critical life-stages, of important fish are needed. The sperm viability test is a rapid and simple test, and may provide a conservative indication of a species' salinity tolerance.
- There is little information available on the sublethal effects of salinity on fish. These effects may include shifts in abundance and distribution, or behavioural responses (eg. breeding). There is a need for more research in this area.
- There have been no studies on Australian species to test the different effects (if any) on growth following constant compared with fluctuating salinity increases. Evidence indicates that acclimated fish species are more tolerant of salinity than unacclimated individuals.
- Virtually all information on the salinity tolerance in fish is derived from field observations or laboratory tests where the solutions contain predominantly sodium chloride. The effects of other ions have received little attention.
- No data currently exist on the salinity tolerance of adult Australian frogs. Overseas laboratory studies suggest that adult frogs should be able to tolerate salinities up to ca. 10,000 mg/L, but only for limited time periods.
- There have been no Australian studies, and limited overseas investigations, of the effects of salinity on egg masses or tadpoles, both of which could be more sensitive than adults.
- Tadpoles and egg masses may be sensitive indicators of the biological effects of salinity in wetlands, and appear worthy of special investigation.
- We have no information to assess if freshwater reptiles or the platypus are either directly affected by increasing concentrations of salt or indirectly, by way of reduced food availability, particularly of invertebrate prey.

Research needs and recommendations

Biota

- Available salt sensitivity data be collated and subjected to more rigorous statistical examination to identify possible patterns or trends in salt sensitivity.
- Studies focus on salt sensitivity in the field situation and use longer term experimental protocols.
- Collaboration between regional managers and research staff be encouraged to (i) allow large field settings, and (ii) provide information for adaptive management.

Micro-algae

- As a matter of urgency, some baseline estimates of micro-algal sensitivities to changes in salinity be obtained. Studies including surveys in affected areas, glasshouse experiments, and field manipulations are needed.

Macrophytes

- Salinity tolerance ranges be determined in the field for important salt-sensitive aquatic plant species. Priority be given to comparisons between emergent and submergent macrophytes and stream and wetland species, examining the effects of both different concentrations and exposure times.
- Greenhouse experiments be used to identify rapidly the sensitive life-stages of macrophytes, eg. seeds, juvenile plants, vegetative and sexual stages and both lethal and sublethal effects.
- Studies be undertaken to investigate community level changes. The water sources of plants need to be known so that the effect of hydrological changes on wetland vegetation can be predicted and management strategies developed.
- Since macrophytes from a wide array of aquatic systems show a range of sensitivities to changing salt and rivers and particularly wetlands differ in dominant macrophyte species and macrophyte community structure, studies be undertaken to examine the feasibility of developing a macrophyte sensitivity model. The purpose of this would be to provide the basis for a handbook for managers, and so provide appropriate information and guidelines for particular macrophytes concerning critical concentrations and exposure times thus minimising damage to a particular macrophyte and wetland type and indicating restoration potential.

Macroinvertebrates

- Because each taxonomic division of invertebrates contains species that are highly sensitive to salinity, and broad categories (eg. insects, crustaceans) are generally not useful, a more extensive statistical examination of the available data base compiled by Bailey be undertaken to identify hierarchical groupings of species/taxa based on their 'sensitivity'. A broader type of classification is likely to prove useful to resource managers when attempting to predict salinity effects on biodiversity within a stream, river or wetland.
- A handbook of salt sensitive invertebrates be developed.
- More experimental work be undertaken on sublethal effects of increasing salinity. Of particular concern are the effects of salinity on growth, feeding and fecundity.
- An examination of macroinvertebrates be conducted on a catchment-wide scale within salt affected areas, especially a comparative examination of impacted and non-impacted streams and wetlands in the same or similar catchments. Close association with researchers and regional groups would facilitate such projects.

Fishes, amphibians, reptiles, mammals and waterbirds

- Nationally, future salinity tolerance studies would be best directed at the primary division fish, *Neoceratodus forsteri*, *Scleropages jardini*, *Scleropages leichardti*, and *Lepidogalaxias salamandroides*, as the species least likely to be tolerant to salinity. At present, only *Lepidogalaxias* occurs in an area where dryland salinity is a problem, but all could be exposed in the future, particularly as a result of saline discharges.

- The salt sensitivity of frogs, particularly egg masses and tadpoles, and of reptiles and the platypus be determined as a matter of urgency. A lack of data on such 'charismatic' species and national icons is a significant gap in knowledge.
- The indirect effect of salinity increases on waterbirds be investigated.

Impacts on aquatic ecosystem: effects on riverine and wetland communities and processes

In this section we focus on the possible changes to riverine and wetland ecosystems as a result of salinisation. We first examine groundwater interactions with river and wetland ecosystems. We then review studies that have examined salinity effects to community structure in these systems, and then speculate on effects to ecosystem processes. As before, this discussion is preceded by boxed text which provides additional information on Australian aquatic ecosystems; the types of ecosystems present, their biological communities and characteristic ecosystem processes.

Australian aquatic ecosystems

Australia is the driest inhabited continent. It has the lowest percentage of rainfall as run-off, the lowest amount of run-off, the least amount of water in rivers, and smallest area of permanent wetlands. The continent is divided into 12 drainage basins. The Western Plateau drainage division, which covers 32% of the continent, produces almost no run-off, and a further 17% does not drain into the ocean. Some 65% of the continent's mean annual run-off occurs in the northern drainage divisions, which currently is not impacted by salinity.

Australia has the world's most variable rainfall and streamflow and its streams and rivers have moderate to high natural turbidity and salinity (McMahon et al. 1992, Williams 1982). The Murray–Darling River system is Australia's largest, draining about one-seventh of the continent. It ranks with the world's large rivers in terms of length and catchment area, but has much lower annual discharge than these and this has been significantly affected by regulation. The chemistry of inland waters differs from most waters elsewhere, often being dominated by sodium chloride rather than calcium or magnesium bicarbonates (Williams 1982). Groundwater resources are extensive, with the Great Artesian Basin underlying 22% of the continent. Its quality is variable, ranging from fresh to highly saline. Its distribution, particularly that of water within it of potable quality, has largely determined the inland development of human settlement and agriculture. However, the rate of extraction has been increasing and in some aquifers extraction is greater than recharge. The generally arid climate and ancient, well-weathered landscape mean that mainland Australia has relatively few permanent and freshwater lakes. Lakes on the mainland are often shallow, temporary and exhibit a range of dissolved salt concentrations. Many inland lakes are naturally highly saline. Inland waters include all water inland of estuaries, both in surface features like streams, rivers, lakes, wetlands and reservoirs, and subsurface features as groundwater.

Australia's inland surface waters can be broadly divided into a number of different categories, each with its own characteristics. Two broad classifications exist: running waters (lotic systems) such as streams and rivers, and standing waters (lentic systems) for example ponds, lakes, billabongs swamps, and marshes.

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What is a wetland?

Wetlands can generally be viewed as ecotones, ie. transitional zones between well-defined terrestrial habitats and deepwater aquatic ones. They are intermediate areas between wet and dry habitats and have a wide variety of different forms and special characteristics influenced by unique hydrological regimes. They are known by a variety of names including swamps, bogs, marshes, fens, billabongs, ponds, lakes, coastal lagoons and estuaries (Mitsch and Gosselink, 1993).

Given such variety in form, longevity and location, definitions are difficult. The International Union for the Conservation of Nature and Natural Resources (IUCN) proposed the following broad definition under the Ramsar Convention:

> *... areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt including areas of marine water, the depth of which at low tide does not exceed 6 meters.*

The recent Wetlands Policy of the Commonwealth of Australia (1997) and the Scoping Review for the National Wetlands R&D Program (Bunn et al. 1997) restricted their working definitions of wetlands by excluding, in large part, main in-channel elements of permanent rivers and streams and certain coastal marine habitats. We follow this precedent here.

Characteristics of wetlands

Australian wetlands are characterised by large variations in hydrological regime (Lake 1995). As a consequence, many wetlands are temporary with water-levels changing throughout the year and between years. Such variation may be predictable, as in the case of flooding or rainfall, or unpredictable, as in the case of droughts. As a result, many **wetlands** may exist as **'drylands'** for considerable periods. Such variation makes it difficult not only to define wetlands but also to appreciate the nature of threats and land-use issues associated with wetland management.

Wetlands can be associated with in-channel flow from a fine-grained stream network, flooding and groundwater. The water balance in wetlands is affected by the natural processes of rainfall, run-off and evaporation, together with human modification of the local environment and land-use practices within the catchment. Broadly, it is acknowledged that permanent and semi-permanent wetlands receive most of their water from local and regional run-off and groundwater. Those that are intermittently wet are more often supplied by rain or flood waters. However, the relationships are poorly understood, particularly those between the wetland and groundwater. Most wetlands have some form of interchange with the groundwater (Hatton and Evans 1998). The exceptions are perched wetlands where the wetland sits well above the groundwater and only receives surface water (Mitsch and Gosselink 1993).

Wetlands are therefore shallow, standing waterbodies that may contain water permanently (eg. many billabongs), seasonally or only rarely in particularly wet years. The water quality in wetlands ranges between fresh and saline, although this report is primarily concerned with freshwater wetlands (salinity < 3,000 mg/L). Wetlands are characteristically less than 5 m deep and have widely varying sizes and shapes. The boundaries are often not clearly defined because the water-level changes annually. All wetland are characterised by the dominance of water regimes on their vegetation, wildlife and soils. They usually contain true aquatic plants (macrophytes) and provide important habitats for invertebrates, fish, waterbirds, reptiles, amphibians and mammals.

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Characteristics of wetlands — cont'd

Australia has a wide variety of wetlands, many having unique features and of high ecological value. Numerous species of birds, fish, amphibians and other aquatic life depend on them as habitats for their survival (McComb & Lake 1990). National inventories of wetlands were developed in 1985 (Paijmans et al. 1985; ANCA 1993), and listed the various types and their locations. The Ramsar Convention lists 567 wetlands of international significance, 40 in Australia (Phillips 1993).

Although significant wetlands are theoretically protected by various levels of reservation within National Parks and World Heritage Areas, on a national scale wetlands are not well-protected from human impacts. Often viewed as wastelands, many have been filled, drained, reduced in area or have had their unique character substantially changed by nutrient enrichment or sediment inputs. For example, 89% of wetlands in the Murray–Darling Basin have been lost due to drainage. In coastal New South Wales, 75% of original wetlands have been lost, and a similar percentage from the Swan Coastal Plain in Western Australia have been filled or drained. In Victoria, wetlands have been reduced by more than 70%, while in South Australia drainage has reduced wetlands in the south-east to 11% of their former area. Clearly, wetlands are among the most threatened environments in the country (Bunn et al. 1997).

Types of wetlands

A large variety of wetlands exist throughout Australia and thus in areas that are currently affected by salinisation. They range from shallow depressions filled for only short periods during wet years, to permanent marshes and billabongs. Depending on their geographical location, wetlands have their own unique biological communities. For example, water-tolerant eucalypts, such as river red gum and swamp gum, are characteristic of the intermittently wet lowland areas in Victoria, South Australia and Murray–Darling Basin, with cumbungi, reeds and rushes (*Juncus, Phragmites* and Typha) often dominating the littoral zone. In the few remaining wetlands in the wheatbelt of Western Australia, swamp she-oaks and paperbarks (*Casuarina* and *Melaleaca*) as well as *Banksia* and some *Acacia* occur.

A rich aquatic flora may develop in the semi-permanent and permanently inundated areas. Significantly, temporary wetlands can become areas of enormous productivity (primary as well as secondary) following inundation, with rapid growth and dense coverage of macrophytes. Such locations are often important breeding and feeding grounds for migratory waterbirds and native fishes.

For the purposes of this report, the following classification system for freshwater wetlands has been used (after Hart et al. 1989):

(a) **Flooded river flats:** these include the many areas of agricultural land that become inundated after heavy rains and floods. Water may be retained for periods from a few days to several months.

(b) **Freshwater meadows:** these include shallow (up to 0.3 m) temporary (less than 4 months duration) waterbodies that may be dominated by herbs, sedges, paperbarks (*Melaleuca* spp.), red gums or lignum, and commonly occur on grazing land.

(c) **Shallow freshwater marshes:** these are generally less than 0.5 m deep and persist for up to 8 months per year, drying out in mid/late summer and filling again in winter; they may be dominated by herbs, sedges, cane grass, paperbarks, red gums or lignum.

(d) **Deep freshwater marshes:** these include permanent wetlands, usually 1 to 2 m deep dominated by reeds, sedges, cane grass and aquatic herbs.

(e) **Permanent open freshwater wetlands:** these are usually greater than 1 m deep, contain water throughout the year, and may be natural or artificial. Billabongs are included in this category.

Trophic communities and ecosystem processes

An ecosystem is a complex, largely self-sustaining natural system in which there are causal relationships and interdependance between the living organisms and non-living components. All the interactions that bind the living (biotic) and non-living (abiotic) components together are included in the ecosystem. Whatever the size of its biological structures, certain characteristics of any ecosystem can be described. The sun's energy is fixed by plants or algae and then transferred to consumers and decomposers. Nutrients are cycled and re-cycled through the various living components of the ecosystem, via community interactions that interweave to form trophic or food webs. No ecosystem is ever completely closed, however. There is always some flow of resources and organisms into and out of an ecosystem.

Five main communities (where a community is commonly defined as all organisms occupying or using a given set of resources) can be defined in stream and wetland systems:

- autochthonous autotrophic community (algae and macrophytes)
- allochthonous autotrophic community (riparian vegetation community)
- saprotrophic community (largely bacterial)
- detritivore community
- herbivore community
- predator community

Autochthonous autotrophic community

This may be divided into two: a micro-algal community and a macrophyte (vascular plants) community. Both communities are primary producers, utilising energy from the sun to photosynthesise plant material. Micro-algae can be found either attached to rocks or as thin films on the bottom (periphyton) or growing in association with bacteria and fungi on the living surface of macrophytes (epiphytes) or suspended in the water column (phytoplankton). These algae are important food sources for many invertebrates and fish. Macrophytes can be consumed when living although considerable debate currently exists concerning the extent to which they are. Their senescent tissue, however, probably provides a significant food source as detritus in wetlands.

The seasonal succession of macrophytes (emergent, floating and submerged) is an obvious feature in many wetlands, particularly temporary marshes, with truly aquatic species being succeeded by semi-aquatic forms and then, during the dry period, by short-lived terrestrial species. Additionally, some perennial species may be maintained on the margins of the wetland. A general zonation of plant communities according to water regime has been provided for swamps in northern Victoria (Briggs 1981). Similar zonation patterns probably occur in most temporary wetlands within Australia, each with its characteristic community of different plants depending on location. Even in permanent wetlands/billabongs, the species composition of macrophyte assemblages can change markedly over time (eg. Hillman 1986).

Macrophyte distribution and abundance in rivers and streams is determined by a quite different set of factors from those operating in wetlands. Current speed (and hence substrate type), and not depth and the availability of water, is usually the main determinant. The macrophytes that are found are generally characterised by an ability to anchor to a substrate and have a pliable, robust form capable of withstanding the turbulent, unidirectional water movement. In upland streams, where light levels are generally low, few macrophytes can grow in the strong currents and rocky substrates; mosses and liverworts are among the few that can. In lowland rivers and streams, the slower currents and more silty substrates provide increased opportunities for the development of aquatic macrophytes. However, the variability in waterlevels in most years mitigates against extensive macrophyte growth on the banks, and turbidity reduces the extent of submerged macrophytes.

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Autochthonous autotrophic community — cont'd

Some common macrophytes include *Chara, Nitella, Ceratophyllum, Myriophyllum, Ranunculus, Aponogeton, Potamogeton, Vallisneria, Eleocharis, Amphibromus, Lepidosperma, Juncus, Typha, Phragmites* and *Triglochin* (Williams 1983; Sainty and Jacobs 1988).

Allochthonous riparian vegetation community

Associated with most wetlands, streams and rivers is a characteristic bankside plant community, the riparian community, well-adapted to variable hydrological conditions. Riparian zones influence habitat composition, stability and energy inputs and act as 'filters' for the exchange of water, nutrients, sediments and pollutants between terrestrial and aquatic systems (Bunn et al. 1993). Common trees in riparian communities include a number of eucalyptus species such as river red gum (*Eucalyptus camaldulensis*), manna gum (*E. viminalis*), swamp gum (*E. obata*), black box (*E. largiflorens*), and *E. wandoo* as well as *Acacia* spp. and *Melaleuca* spp. Changes to flow regimes, particularly the flooding characteristics, of riparian forests due to regulation of the associated river can have significant effects (Chesterfield 1986; Dexter et al. 1986; Bren 1987, 1988). The river red gum, in particular, requires a specific flooding regime for its propagation and survival (Dexter 1970; 1978).

Saprotrophic community

This includes bacteria, fungi and protozoans. These organisms colonise particulate organic matter and grow by breaking down the organic matter and taking up nutrients from the water column. The organic matter may in turn be consumed by detritivores. Saprotrophs such as bacteria may also live freely in the water column, or attached to solid surfaces, and metabolise dissolved organic matter. The organic layers that the saprotrophs build up on solid surfaces, eg. stones, may in turn be consumed by detritivores.

Detritivore community

This community comprises both macro- and microinvertebrates that ingest particulate detritus in the form of discrete particles or in thin layers on rocks and wood surfaces. Macroinvertebrate detritivores may be divided into functional feeding groups based on their mode of ingestion and their food selection. Basically, there are three functional feeding groups: **collectors**, which aggregate fine particulate organic matter; **shredders**, which consume large or course particulate organic matter; and **scrapers**, which scrape detritus/algal layers off solid surfaces.

Herbivore community

This community comprises animals that eat living plant material, either attached or in the water column. Scrapers, for example, can ingest living micro-algae growing on macrophyte or stone surfaces as well as non-living detrital material that forms part of the biofilm matrix. Filter feeders feed on phytoplankton. Very few animals appear to be able to ingest filamentous macro-algae or macrophytes although the topic is being extensively debated.

Predator community

This diverse community consists of invertebrates, fish, and some higher vertebrates (eg. frogs, water tortoises, platypus and water rats). These animals feed predominantly on animals of the detritivore community. There may be, and often is, more than one level of predation. For example, a detritivore (chironomid fly larvae) may be eaten by a predator (eg. dragonfly nymph) which in turn may be eaten by a further predator (eg. redfin).

River ecosystem functioning

Running water ecosystems differ from lake and wetland ecosystems in a number of fundamental ways, and, as a consequence, biological responses differ. Firstly, the unidirectional movement of water has a considerable influence on the types of plants and animals in running waters. Water velocities are higher and the unidirectional flow in streams allows upstream processes such as the breakdown of organic matter (eg. leaves and bark) to influence and in some cases determine downstream processes; in this sense, streams can be thought of as a continuum from their headwaters to their source. Second, lotic systems are 'open' in that they receive inputs, particularly of organic matter and nutrients, from their catchment and transport this food and energy source through the system. Interactions between rivers and streams and their catchments are essential to their existence, particularly so in the case of upland streams and their interactions with the terrestrial vegetation bordering them.

It is now possible to describe in broad terms the main processes that control the structure and 'health' of lotic ecosystems and as a result make tentative predictions of how any impact will influence their structure and 'health'.

Upland streams, particularly their headwaters, are characteristically within forested areas and well shaded from the sun. Because of this, little primary production can occur within the stream itself. The primary food source in these systems is particulate organic matter (eg. plant litter particularly leaves) and dissolved organic matter derived largely from the surrounding forest. This material is either directly consumed by certain macroinvertebrates (the so-called 'shredder' and 'collector' communities) or decomposed and/or 'conditioned' by the microbial community (bacteria, fungi, protozoans). The resultant surface microbial films (biofilms) are in turn consumed by other macroinvertebrates that can scrape off these films (the 'scraper' communities, eg. snails, caddisfly larvae). These macroinvertebrates are the primary food source for the secondary consumers such as fish, water tortoises and, in Australia, the platypus. Very few fish ingest living or dead plant material, perhaps the one exception being the introduced carp.

These largely shaded upland systems are termed *heterotrophic* since they depend on energy (organic matter) captured from outside the stream. They are characterised by P/R ratios of <1, since energy consumed by the community respiration (R) exceeds energy fixed by gross photosynthesis (P).

In the lower (usually foothill) reaches of the stream, which are generally wider and less shaded by riparian vegetation, primary production within the stream is greater, particularly if the water is reasonably shallow and clear. Aquatic plants such as green algal films on rocks and attached macrophytes are present. These stream sections are termed *autotrophic*, since community respiration is less than gross primary production (ie. P/R ratio >1).

The situation changes again in lowland reaches, because depth and turbidity reduce in-stream photosynthesis, and result in the system being relatively more dependent upon inputs of fine particulate matter from upstream. Macroinvertebrate 'collectors' usually dominate the fauna of these lowland streams.

Because of their lower water velocities, the larger lowland rivers, particularly those containing impoundments, develop phytoplankton and zooplankton communities. The River Murray is the only large river system that has been studied in any detail. This has a well-developed phytoplankton community with Cyanobacteria (*Anabaena, Anacystis*) dominating in the summer and diatoms (*Melosira, Cyclotella*) in the winter, and a zooplankton community dominated by rotifers, copepods and cladocerans.

Wetland ecosystem functioning

The physico-chemical features of wetlands vary enormously, being influenced by the hydrological regime, depth, sediment type, vegetation cover, inputs from the catchment and so on. Most wetlands show an annual cycle in salinity (or conductivity), with lowest values recorded in winter, when water-evels are generally highest, and highest values recorded in summer. The salinity range will depend particularly upon the amount of evaporation and the quality and quantity of surface and groundwater inputs to the wetland. Temperature, pH and nutrient concentrations also vary annually. Superimposed on these annual cycles will be a number of diel (or daily) cycles stimulated by temperature changes and the daily pattern of photosynthesis and respiration. Thus, in many wetlands, temperature, pH and dissolved oxygen concentration will vary daily. The shallowness of most wetlands generally precludes thermal stratification for any significant period, although this may not be the case in deep wetlands, for example, billabongs.

Although a number of limnological and ecological studies has been conducted on Australian wetlands over the past decade to understand better their structure and function (Hillman, 1986; Bunn and Boon 1993), consensus is that our understanding of physico-chemical changes and biological processes in wetlands are far from understood. Many of the fundamental processes require extensive elucidation, including identification and quantification of the mechanisms involved and the degree of temporal and spatial variability (Bunn et al. 1997).

Unlike stream communities which derive most of their organic matter and nutrients from the catchment, wetland ecosystems are too a large extent basically self-supporting, although enormous variability exists. Virtually all the food consumed by animals in the billabong originates from photosynthesis within the billabong. Thus the biomass (amount of living material) supported by a billabong probably relates directly to the amount of photosynthesis carried out there. The relative contributions of phytoplankton, epiphytes and macrophytes for Australian wetlands is not known. Studies by Shiel (1982) and Bunn and Boon (1993), for example, coupled with overseas knowledge, indicate that macrophytes provide an important food source for the microfauna and macroinvertebrates, at least in billabongs. These linkages have not been studied extensively in other wetland types in Australia. Additionally, there have been no comprehensive studies of phytoplankton or epiphytic algal communities in Australian wetlands, even though both may make substantial contributions to the primary production and are important food sources (Hillman 1986; Boon and Bailey 1998).

Although the process is reasonably well understood at a broad level, details are still poorly understood. In particular, the mechanisms by which nutrients (carbon, nitrogen and phosphorus) are cycled in wetlands has not been studied in detail. More fundamentally, the relative importance of autochthonous vs. allochthonous carbon sources in providing energy to drive wetland ecosystems is not known for any Australian ecosystem. Biological studies of Australian wetlands are distinguished by their small numbers and relatively confined scope (much of the available information relates to water birds) (Bunn et al. 1997). Efforts are in progress in some States to map wetland distribution and there have been several recent developments in wetland management in Australia. More details can be found in the recent National Wetlands R&D Program Scoping Review sponsored by Land and Water Resources R&D Corporation (Bunn et al. 1997).

Groundwater interactions with wetland and riverine ecosystems

Problems associated with secondary salinisation can largely be viewed in terms of aquifer recharge, which causes saline groundwatertables to rise. Rising watertables not only result in land salinisation, but directly and indirectly increase salinities within rivers and wetlands. Directly, the increase volume and pressurisation of aquifers can increase seepage of saline groundwater into watercourses (Ghassemi et al. 1995). Indirectly, salinities within rivers and wetlands can increase due to surface run-off from salinised land. Salinities tend to be higher when there are low flows as they are more strongly influenced by saline groundwater inflows. Flushing at the beginning of flow periods also increases salinities. Therefore any salinity impacts on wetland and riverine ecosystems are strongly influenced by the prevailing groundwater dynamics (see also Hatton and Evans 1998).

Salinisation of watercourses may be compounded by strategies aim at alleviating land salinisation. In particular, the drainage of saline groundwater into either river systems for disposal or wetlands for storage or evaporation (so-called 'evaporation basins'). Such practices only compound the impacts to the natural aquatic systems in ways that are still poorly understood and, more alarmingly, rarely acknowledged.

The direct impact of rising saline groundwatertables depends on the degree of interaction between the wetland and groundwater. In wetlands where groundwater is intercepted, the nature of the interchange may vary. Some wetlands may both intercept groundwater and discharge it as surface flow (springs/seeps), whilst others may only intercept it. In these systems, water quality will be influenced by the quality of both groundwater and surface water inputs. In the absence of direct groundwater discharge the presence of a shallow groundwatertable may increase salt loads into wetland systems. In summer when evaporation exceeds precipitation, waterlevels fall. If drawdown events are sufficient to promote the capillary rise of saline groundwater, salts will accumulate at the sediment surface (Froend et al. 1987). Wetlands and rivers may also become salinised via surface waterflows from saline catchments. Whilst inflow salinities may be marginal, evaporation of surface water over summer will increase salt concentrations.

If salts entering the system via groundwater discharge or surface inflows are not periodically leached from wetlands, salts will accumulate. Salts may be leached from the system laterally via surface flow, or vertically via groundwater recharge. In groundwater discharge zones, the hydraulic gradient may not permit the transmittance of surface water away as groundwater, thus hindering the leaching of salts into groundwatertables. Under these conditions, surface flow will be the prime mechanisms by which salts are removed from the system.

Note that density stratification could occur if saline water enters or is discharged into the bottom of a wetland and not mixed with the main water column. In productive water-bodies, prolonged stratification can lead to a reduction in the dissolved oxygen concentration of the bottom waters and thus a lowering of water quality. This can have significant effects on the diversity and abundances of bottom-dwelling organisms and aerobic processes. Before summarising the possible effects of increased salinity on wetland ecosystems, the magnitude and extent of likely salinity increases are considered. Clearly, because most wetlands are either not flushed or at best are poorly flushed, they may be liable to have greater salinity increases than rivers and streams. In some situations, increasing salinisation of a wetland, through natural causes or from the discharge of saline water will add a permanent additional salt load to the system. This will be cumulative with each event and will lead to irreversible increases in salinity.

Changes to community structure in river and stream ecosystems

Clearly, the change in overall in-stream salinity will depend on: (a) the concentration and ionic composition of inflowing water (groundwater or surface flow) or discharged water, (b) temporal and spatial variability of this inflow, including the way wastewater is discharged (eg. the time, continuous or pulsed releases), (c) the amount discharged, and (d) the flow conditions in the stream at the time. Much of the hydrology of saline groundwater and interaction with riverine channels appears to be well-documented. However, there seems little, if any, interaction between groundwater hydrologists and biologists/ecologists with respect to salinity effects in lotic systems. The absence of such an interdisciplinary research focus is seen as an impediment in assessing potential environmental effects of salinisation of aquatic systems.

Williams et al. (1991), Bunn and Davies (1992), Mitchell and Richard (1992) and Metzeling (1993) have investigated community structure of macroinvertebrates in rivers subjected to salinisation in south-western Western Australia and Victoria. In the study by Williams et al. (1991) surveys were made of the macroinvertebrates at several locations on the Blackwood River (WA) and Glenelg River, Victoria, both of which have drainage basins subject to salinisation from agricultural practices and a clear longitudinal salinity profile in which the upper reaches are more saline than the lower. Multivariate analysis using DECORANA and TWINSPAN did not reveal relationships between macroinvertebrate community composition and salinity. Whilst acknowledging the limitations of the survey (it was based on few sampling stations on one occasion and taxonomic determinations were incomplete), the authors suggested that either the present macroinvertebrate fauna of Australian rivers is more tolerant to salinity than has been assumed, or now represents only halotolerant forms of a once more diverse fauna. They reiterated the need for more intensive work on Australian lowland rivers, including seasonal surveys and comparisons with similar rivers not yet affected by rising salinities, and experimental assessment of tolerances and behavioural responses of riverine fauna.

The second study, by Bunn and Davies (1992), partly addressed the seasonal events. In this study, two sites on the Hotham River and four on Thirty-four Mile Brook, one of its tributaries, were sampled. Both rivers are on the Darling Escarpment, south-western Western Australia, in an area with riverine systems that are largely intermittent (Thirty-four Mile Brook), with headwaters situated in land extensively cleared for agriculture, and with water quality of marginal salinity (ie. >5,000 mg/L TSS; Schofield and Ruprecht 1989). High salinities were recorded at all sites:

on most occasions, they exceeded 3,000 mg/L, particularly during summer. Overall, the benthic fauna was characterised by high densities and low richness, diversity and evenness. This was directly caused, they suggested, by the poor water quality of the system in terms of salinity. The invertebrate fauna was atypical of that generally encountered in stream systems. Insects made up only a minor proportion (14.5%) of total invertebrates collected, the community being dominated by Crustacea, several common in salt lakes! These findings contrast with those of Williams et al. (1991) who reported no crustacean dominance or apparent relationship between macroinvertebrate community composition and salinity. Such contrast between the findings of these two studies only serves to highlight our limited understanding of the impact of rising salinity in lotic systems.

Metzling (1993) examined the invertebrate community structure at nine sites in six lowland, perennially flowing streams in central Victoria. The salinity of these streams ranged from 51 to 1,100 mg/L total dissolved solids (TDS), but had been historically higher, up to about 2,000 mg/L TDS. He found no correlation between either the number of taxa or faunal abundance with salinity. However, multivariate analyses showed distinct invertebrate communities at different salinities. Fidelity analysis identified groups of taxa at either low or high salinity. Existing information based on distribution data of the common taxa within these groups indicated that they were tolerant of wider ranges in salinity than found in this study. He further showed that rare taxa most clearly distinguished between sites of different salinities, concluding that they are possibly more sensitive to changes in salinity than the more common taxa.

Vertessy (1994), Marshall (1996) and Bailey (1998) have recently investigated the effects of experimentally increasing salinity on the invertebrate community of Hughes Creek, a 'typical' lowland river in central Victoria subject to common catchment disturbance from grazing, but not, at present, increasing salinity. Parallel to the stream, a nest of nine open-ended channels, each with substrate-filled trays that had been colonised by invertebrates over the previous month, were constructed. In the first experiment, salt concentrations were increased to 1,000 mg/L and 2,000 mg/L NaCl for six days in six channels, while the other three channels acted as controls. Comparisons of the abundance and diversity of the invertebrates and the extent of recovery after six days were made between the low and high dose and control channels. In the second experiment the effect of duration and concentration was investigated by comparing continuous release (chronic, 2,000 mg/L) of saline wastewater with pulses of higher concentration and short duration (acute, 3,500 mg/L).

Whilst little effects were observed at 1,000 mg/L, a salt concentration of 2,000 mg/L adversely affected the abundance of some invertebrates, particularly molluscs (snails). For some taxa, conditions such as stream flow and depth modified the effects. The release schedule affected more taxa including representatives from Ephemeroptera (mayflies), Coleoptera (beetles) and Diptera (true flies), and the acute release was more deleterious. It is likely that the community structure of invertebrates found in low salt impacted streams will shift to one of potentially lower diversity consisting of more salt-tolerant species if in-stream salt loads increase. These results suggest that how and when saline water is released is crucial if impacts on aquatic plants and animals are to be minimised.

Changes to community structure in wetland ecosystems

Recent research by James (K. James, Deakin University, unpublished data), Bailey (1998) and Warwick and Bailey (1996a,b,c, 1997, 1998) has investigated the effects of experimentally increasing salinity on the plant and animal communities in a temporary floodplain wetland in central Victoria. Experiments were carried out at Raftery State Forest wetland, on the Goulburn River near Shepparton. This wetland, typical of about 40–50% of wetlands throughout Victoria, remains wet for five to six months after flooding and slowly dries over summer. Two distinct phases were observed during a typical year: a 'dry' phase during which the wetland plant community comprises graceful swamp wallaby grass (*Amphibromus fluitans*), various herbaceous/pasture species, introduced weeds and an animal community dominated by a variety of terrestrial insects; and a 'wet' phase after flooding, which can occur in any month but normally happens between July and September.

During this phase, water ribbon (*Triglochin procera*), floating pondweed (*Potamogeton tricarinatus*), and water milfoil (*Myriophyllum crispatum*), mainly dormant over the dry phase, emerge and grow quickly, flowering and setting seed and forming new underground tubers. These store energy and nutrients for regrowth when the wetland is flooded again, normally the following year. Aquatic invertebrates dominated initially by crustaceans, that have lain dormant over the dry phase quickly emerge. These are followed by other animal colonisers such as winged insects and adult frogs that arrive at various times, lay eggs, and contribute to the enormous abundant and diverse animal community that inhabits such wetlands and forms the foodweb that supports fish and waterbirds.

This wetland is currently unaffected by salt, but is threatened because of its location in the Shepparton Irrigation Area. Field experiments were carried out which simulated an increase in salt concentration to levels found in the groundwater of the Goulburn Valley. Similar concentrations are likely to be experienced by the wetland if it is inundated with rising groundwater or flooded with saline water pumped into the wetland system.

During the dry phase, nine 10 m × 10 m, 50 cm high mesocosms (ie. artificial ponds) were constructed in the wetland. Each mesocosm was made of plastic sheeting designed to lie flat on the ground until after the wetland flooded, when the sheeting was pulled up and secured to enclose an undisturbed 100 m^2 of wetland. The salt concentration in six of the mesocosms was increased—three to 600 mg/L (low salt enclosures), and three to 1800 mg/L (high salt enclosures).

Measurements were made of conductivity, pH, plant growth rates and productivity, and abundance and diversity of macroinvertebrates and amphibians at 10-day intervals from October until February by which time the wetland had dried. Complementary experiments were carried out in the laboratory and glasshouse to refine the effects of salt on plants and animals present. To assess potential recovery of salt impacted communities in the following year, during the dry phase samples of soil (containing dormant stages of both macrophytes and animals) were collected from each enclosure. In the glasshouse, these samples were flooded with fresh water and emerging animals and macrophytes collected.

It was found that as the water evaporated, the concentration of salt increased by more than threefold—an important factor when considering temporary wetlands. Accompanying this increase in salt concentration, a significant decrease in pH was observed. In the enclosures with low salt concentration, pH decreased by 1.4 to almost 5.6, while in the enclosures with high salt concentration there was a reduction in pH to 4.0. It was hypothesised that similar synergistic results are likely in other low buffered wetlands of south-east Australia. (Subsequent initial surveys from 20 wetland sites across Victoria have supported this hypothesis; P.C.E. Bailey, K. James and D.W. Blinn, unpublished data.) Such acidic conditions are likely to be as deleterious to animal and plant communities, if not more so, than those caused by salt.

Plants responded differentially, according to their sensitivity; biomass of *Amphibromus* was reduced but not significantly, whereas *Potamogeton* and *Myriophyllum* both showed significant reductions in biomass. The loss of biomass of *Triglochin* was intermediate, this species was more tolerant as a fully grown plant, but far more sensitive as a juvenile and seedling. Below-ground storage and asexual reproductive structures were also reduced for some species. Additional field and glasshouse experiments have shown that salinities lower than 5,000 mg/L reduce growth. Flowering can also be completely prevented in *P. tricarinatus* by salt levels of 2–3 g/L.

Additionally, the seed germination rate for *T. procera* was reduced by 50% at 6 g/L, and almost entirely at 12 g/L. Glasshouse studies have shown that damage can be reduced by delaying the time of exposure to salt in *P. tricarinatus* until after the plant has been able to grow and initiate its storage tubers. Generally, high salinity reduced the abundances of all animal groups, particularly Cladocerans, snails, some water-beetles, dragonflies, and some dipterans. Per cent reductions compared to controls ranged from 10–81% at 800 mg/L to 32–100% at 5000 mg/L. At the same time, abundances of some salt-tolerant larvae such as mosquitoes (Culicidae) and some midgeflies (Chironominae) increased substantially, some by as much as 400%. Such increases in abundances were noticeable at concentrations as low as 750–1,250 mg/L. Increased salinity significantly reduced the abundance of individuals that emerged from the flooded substrate during recovery trials. Fewer individuals emerged from the high salinity enclosures compared to the low salinity enclosures. This pattern was common across all major taxa including the water-beetles, crustaceans and dipteran flies which commonly rely on resting/resistant life stages to initiate colonisation following the next flood. No snails emerged from the substrate collected from the high salt enclosures.

Wollheim and Lovvorn (1995, 1996) investigated the biomass and community structure of macroinvertebrates associated with macrophytes, sediments and unvegetated open water in three oligosaline (0.8 to 8.0 mS cm^{-1}) and three mesosaline (8.0 to 30.0 mS cm^{-1}) lakes in the Wyoming High Plains, USA. They found total biomass of epiphytic and benthic invertebrates did not change with salinity, but the biomass of zooplankton in open water was significantly higher in mesosaline lakes. Community composition of invertebrates differed between the two salinity categories: large grazer/detritivores (gastropods and amphipods) were dominant in the oligosaline lakes, whereas small planktivores and their insect predators were more prevalent in the mesosaline lakes. These differences were attributed to both the direct physiological effects of salinity, and a shift in the form of primary production (from macrophytes to phytoplankton).

Froend and McComb (1991) determined the sequence of events leading to the deterioration of water quality between the early 1960s and 1986 in Lake Towerrinning, a wetland in the wheatbelt of Western Australia. The decline in fringing rush (*Baumea articulata*) (around the lake) and tree vegetation (around the lake and within the catchment) due to clearing and increased salinity is thought to be the turning-point in the sequence of events. Increased inputs of water, salt and nutrients from cleared agricultural land within the catchment have resulted in a decline in the wetland vegetation and an increase in phytoplankton biomass. Algal blooms and destabilisation of sediments are the major causes of the high turbidity. Salinity varies with lake level, due to evaporation, and the overall salt load of the lake is increasing by approximately 6,500 t per year. Significant drops in the salt load occur when high rainfall causes outflow from the lake. They suggested that artificially increasing the outflow frequency and controlling lake levels could reduce lake salinity.

Roberts and Ludwig (1990) noted the great diversity of plant habitats in areas such as the north-eastern Chowilla floodplain where it is proposed that anabranches be used as salt retention ponds for intercepting saline groundwater accessions so as to reduce River Murray salinity. They found that while some wetlands were a mosaic of different vegetation types, in general there is a strong association between wetland and vegetation type. This in turn has important implications for the distribution of aquatic animals. If a particular type of wetland within a system, such as anabranches within the Chowilla floodplain, is targeted for salinity mitigation, a vegetation habitat and associated fauna may be lost from the system even though the system as a whole may show little detrimental effect. Roberts and Ludwig (1990) emphasised the urgent need to study floodplain habitats before such losses.

Bell and Froend (1990) suggested that the efforts of the WA Department of Conservation and Land Management to reafforest the upland margins of the Lake Toolibin reserves and the pumping of saline groundwaters from the lake basin environment would provide a more favourable habitat for the present population of trees and encourage natural recruitment. The Lake Toolibin reserves would be a logical place to establish a more extensive series of plots to study seedling recruitment and mortality and crown condition by age class of each of the major species of the area.

Impacts on trophic structure and ecosystem processes

Based on salinity tolerance data reviewed earlier and the few community studies above, the possible effects on each in terms of impacts to trophic structure and ecosystem processes are now discussed.

- **Microbial community/processes:** Bacteria play a vital role in aquatic ecosystems. They affect the mineralisation of organic matter, recycling of major nutrients, and significantly influence the flow of energy and materials through the trophic foodweb. As such they interact with both the biotic and abiotic components of ecosystems and, in a very real sense, can be seen as underpinning the ecosystem health of aquatic systems via these complex series of interactions.
- **Autotrophic community/primary productivity:** So little known about micro-algal communities that it is particularly difficult to draw conclusions. Based on salinity tolerance data it is likely that certain diatom and green algal species are vulnerable and so will impact on autotrophic community structure. Whether this shift will affect rates of primary production is unknown. Given the vital role that this fundamental process plays in underpinning the foodweb and health of lowland systems, it is urgent that some preliminary data on this community be gathered, particularly a quantification of shifts in community structure and changes to rates of primary production. (Preliminary examination (D. Blinn and P.C.E. Bailey, unpublished data) of epiphytic communities growing on macrophytes during the Raftery wetland experiments (Bailey et al. 1998) has shown significant reduction in diatom diversity and biomass at salinities of 3,500–5,800 mg/L).

Some macrophytes appear to be significantly affected by salinities as low as 1,200 to 1,500 mg/L. Most freshwater macrophytes disappear at around 4,000 mg/L (Brock 1981) and are replaced by halophytic forms. However, the transition time from a glycophytic to a halophytic community may be slow since time is required for the dispersal of suitable species and for equilibrium to be reached. The immediate and ongoing loss of macrophyte biomass has a number of important repercussions: reduction in plant cover causes changes in the light regime and a possible community shift towards a more phytoplankton-dominated system; reduction in the quantity and quality of living plant tissue or plant detritus affects macroinvertebrate and waterbird consumers; and alterations in nutrient cycling occur.

Poor growth of salt sensitive plants would result in their out-competition by a narrow range of salt tolerant species. These would eventually come to dominate the wetland.

Significant sublethal effects of increasing salinity include impacts on the reproductive capacity of some species. Asexual reproduction of over-wintering tubers and turions is prevented or reduced if exposure occurs too early in the growth cycle. Similarly, inflorescence emergence (flowering) is prevented completely in some species.

Increasing salinity will impact on the asexual and sexual reproduction of individual plant species and so on the age distribution and survival of species within the wetland and the colonising capacity of the species.

The plant community (micro-algae and macrophytes) contains a range of species sensitive to small increases in salt concentrations, including both lethal and sublethal increases. Concentrations as low as 1,000 mg/L may have an effect at a sublethal level, and for some species (eg. *P. tricarinatus*) lethal effects start at 2,000–2,500 mg/L. Most non-halotolerant freshwater macrophytes are salt sensitive, and are seriously affected at salinities of 4,000 mg/L., with sublethal effects, (eg. reduced vigour and absence of inflorences), at levels less than the maximum tolerated by the species.

- **Riparian vegetation:** As discussed, riparian vegetation is the source of much of the allochthonous carbon (ie. energy) in riverine and wetland systems. This carbon enters as 'coarse' particles, predominantly leaves but also wood, bark and reproductive remains. This material is processed predominantly by microbial communities in lowland river systems. However, in wetland systems, the resultant biofilms on leaves or twigs or small fragments of plant material may form an important food source for the detritivore community. Changes in the riparian community due to increasing salinity is likely to result in changes to both the amount and form of carbon entering these systems. Many higher plants associated with lowland rivers and wetlands are salt sensitive. The effect of salt stress, particularly if coupled with additional stress factors, eg. waterlogging, on the quality and timing of organic inputs is not known.
- **Detritivore, herbivore and predator communities:** Increasing salinity significantly affects some taxa from all these consumer groups. Experimental results from a single lowland stream in Victoria indicate little apparent impact on abundances and community structure following short-term exposure (ie. four to five days) at salinities of 1,000 to 2,000 mg/L. However, pulses of more saline water are more deleterious. Additional studies from other sites are required to identify whether such patterns are widespread. Community structure in streams exhibiting higher salinities appears to be variable. The numerical dominance of crustaceans over insects reported by Bunn and Davies (1992) for two rivers in SW Western Australia suggests that major shifts in community composition from salt intolerant to salt tolerant groups could occur. Whether such taxa shifts translate into significant changes to trophic structure is unknown and requires examination.

Summary of findings: impacts on river and wetland communities and processes

- Representatives from all biological communities, particularly macroinvertebrates (detritivores, predators and herbivores) and plants (diatoms/algae, macrophytes and riparian vegetation) are salt sensitive. As a result, any deleterious effects to particular taxa are likely to translate into broader ecosystem processes, such as primary productivity, decomposition, nutrient spiraling/recycling, and the flow of energy and material through trophic webs. Such processes define ecosystems and underpin their fundamental health and integrity.
- Exposure to salinities of between 1,000 and 2,000 mg/L for even short periods is likely to have significant deleterious effects on biological communities in lowland streams and rivers, and as a result impact on important ecosystem processes. More subtle sublethal and indirect effects are likely to occur at salinities below this, but there is insufficient data to assess either the likelihood, extent or magnitude of such changes.
- Given this general lack of knowledge on the likely effects of salinity on community structure and ecosystem processes in lowland streams and rivers, we recommend that biological studies be undertaken to generate an adequate knowledge base for a range of lowland systems so as to provide data on ecosystem processes. These should include short-term experiments/surveys to provide immediate data from which better informed analysis and discussion can take place, and longer-term studies on selected systems to identify/quantify any subtle changes to ecosystems likely to occur over a longer period.
- For temporary wetlands, the concentration of salts and other nutrients as water evaporates results in the exposure of biological communities to increasing salinities. Although flooding river water or groundwater may initially lower salinity, final salinities may be four to five times initial ones. In addition, combinations of high water temperatures and salinities during summer result in low concentrations of dissolved oxygen. Such low levels of oxygen, coupled with increasing bacterial respiration of organic material would further contribute to oxygen depletion. The significant shift in pH is of concern, particularly if widespread in other poorly buffered wetland systems. The more acidic conditions would undoubtedly prove harmful for the biota, in some cases more so than changing salinities.
- Significant loss of abundance (biomass) in many invertebrate taxa, reduces food availability for other taxa, including fish and waterbirds, and confounds impacts on in situ carbon/nutrient processing.
- Species diversity is significantly reduced, with more salt tolerant but less diverse taxa likely to become dominant.
- As salinities increase over the drawing-down period, significant increases in abundance of more salt tolerant fly species, including some mosquito and chironomids, are likely to occur.
- Macroinvertebrates in wetlands consist of a diverse community in terms of both taxonomy and functional role. Little is known about changes in their community structure in wetlands, and even less about functional roles and dynamics. This community appears far more sensitive to small increases of salinity—a significant reduction in species diversity occurred at 800 mg/L—compared with the community in a nearby lowland stream.

- The community includes species that are sensitive to small increases in salinity—abundance of some cladoceran species being reduced by 77% at 1,250 mg/L—but others are affected at somewhat higher salinities. In addition to some cladocerans, other taxa that appear to be particularly sensitive to small to moderate increases in salinities include: gastropod snails, some hydrophilid water beetles, aquatic weevils, dragonflies and some damselflies, and a number of dipteran flies, including some species of Stratiomyidae, Ceratopogonidae and Tanypodinae.
- Increasing salinity apparently favours some invertebrate taxa, including some mosquito and chironomid species, resulting in significant increases in abundance (of the order of 90 to 400%).
- Increasing salinity up to 5,000 mg/L significantly reduces the abundance of all major taxa, including water beetles, crustaceans, and dipteran flies, that emerged from flooded wetland sediments 12 months later. No gastropod snails emerged. Such long-term effects are significant given that such over-wintering communities are the first animals to emerge after the wetland floods and are likely therefore to represent the initial processes involving detrital material, and underpin later community development. This later community develops as a more diverse secondary wave of insect and bird consumers arrive in the wetland.

Knowledge gaps for riverine and wetland ecosystems: inadequacy of current information

- Current knowledge is insufficient to make informed statements concerning the extent and magnitude of likely impacts of increasing salinity in riverine and wetland ecosystems.
- Few studies have examined community changes in either wetlands or rivers subjected to increasing salinity.
- There is a significant lack of knowledge of fundamental processes affecting ecosystem structure and function in riverine and wetland systems. Lack of basic knowledge prevents reasonable predictions of the likely salinity effects to riverine and wetland ecosystems.
- The relative contributions of phytoplankton, epiphytes and macrophytes to net primary production in wetlands or as food source for various consumer categories, are not known.
- There has been little, if any, interaction between groundwater hydrologists and biologists/ecologists examining salinity effects in aquatic systems. The absence of such interdisciplinary research is seen as an impediment in assessing the potential environmental effects of salinisation of aquatic systems.
- A review of salinity tolerance data indicates that, although some information on the sensitivity to increased salt concentrations of certain river and stream dwelling animal and plant species is available, there is little information on the effects of salinity on possible sensitive life-history stages, behavioural responses, and of sublethal effects.
- There is a dearth of information on the effects of salinity on communities of plants and animals and their interactions. Deleterious effects on certain important taxa (so-called keystone taxa) or groups of taxa (eg. micro-algae) in a community are likely to have more significant effects on ecosystem processes, such as production or the decomposition of organic matter, than effects on other groups.
- It is difficult to predict the effects of increased salinity on lowland systems given the lack of detailed biological information. Little is known in the way of either animal and plant community structure in lowland rivers and streams, or how communities vary in space and time. Even less is known about the extent and magnitude of interactions between particular animal taxa or plant/animal functional relationships. Vital ecosystem processes within lowland streams and rivers are poorly understood and require elucidation.
- General biological knowledge of Australian wetlands is extremely poor. In only a few cases, for example, is it known what plants and animals live in wetlands apart from the obvious charismatic species, or in those few systems where extensive surveys have been conducted (eg. Swan Coastal Plains wetlands, Western Australia, Davies 1996). This lack of basic census information is the legacy of years of neglect by governments and researchers. This basic omission has been repeatedly cited as undermining informed opinion and management decisions. There is little indication that this situation is changing.
- Despite obvious links between groundwater intrusion and salinisation of wetlands and rivers, a poor understanding of the dependence of wetlands systems on groundwater exists.
- Changes in salinity over time in relation to drawdown events and flushing are rarely monitored yet they are likely to be critical to any understanding of processes.
- There is little information on how important leaching and flushing are in re-setting salinity levels, ie. what the impacts of hydrological practices on salinity in wetlands are, especially given that wetland and river systems are increasingly being regulated.

Recommendations

- As a matter of urgency, the effects of salinity on the base of the food web, periphyton/epiphyton productivity and detrital processing, be quantified in some representative streams and wetlands.
- Longer-term studies be undertaken to elucidate and quantify the effect of increasing salinity at an ecosystem level in rivers and wetlands. These studies need to examine effects on temporal and spatial variation in rates of primary production, decomposition, organic matter processing and nutrient cycling over a range of different wetland and riverine types.
- Broader inter-disciplinary studies involving biologists, hydrologists, hydrogeologists and engineers be encouraged and supported to examine and quantify interactions between groundwater intrusion, salinisation of rivers and wetlands, and associated ecosystem responses.
- Pre-existing biological survey data and related stream and groundwater salinity data from a variety of impacted streams and wetlands be collated and analysed to provide some baseline biophysical data and potential hazard maps of types of systems at risk.
- Studies be undertaken to examine and quantify the connections between salinity catchment hydrology and wetland/riverine catchment hydrology.
- Existing studies examining environmental flows be expanded to incorporate salinity, groundwater flows and groundwater salinity.
- Studies be undertaken that link engineering options to ameliorate salinity problems with biological/ environmental outcomes. The potential conservation or ecological improvement with engineering costs should be identified.
- Studies be undertaken to quantify the effects of rapid salinity increases (eg. resulting from overland flow, pulses of salt water moving down a stream) on biological communities in a variety of different riverine and wetland systems so as to identify effects and possible generic responses.
- Broadscale surveys of wetlands be undertaken to examine, validate and quantify the extent of any correlations between increasing salinity and pH changes in wetlands.
- Researchers and managers be encouraged to work together on large-scale field experiments to quantify salinity effects per se before and after management intervention.
- Changes in salinity over time in relation to drawdown events and flushing be monitored.
- Studies be instituted to determine the importance of leaching and flushing in re-setting salinity levels, ie. determine the impact of hydrological practices on salinity in wetlands, especially given that the management of wetland and river systems are increasingly involving regulation.
- Studies be undertaken to elucidate the relationships between drawdown, flushing and salinity levels in a variety of wetlands.
- Studies be undertaken to quantify the effects of various management practices on wetland and riverine health as measured by community structure, biodiversity and ecosystem processes.
- Long-term studies be set up to determine how long it takes community or ecosystem change in streams and rivers subjected to increasing salinisation.
- Given that salinity is intricately linked to environmental water flows, studies be undertaken to determine the amounts of water required to maintain wetland systems in the face of increasing salinisation.

Impact of management strategies on riverine and wetland health: six case studies

This section examines in detail the impact of salinity mitigation measures on wetland and riverine systems. Six management plans developed to protect both agricultural land and wetland and riverine systems from salinity have been selected.

Of those States with significant salinity problems, Victoria has the most detailed level of documented policy in its Salinity Management Plans which are the implementation documents for Salt Action: Joint Action. Each of the Salinity Management Plans also has an Environmental Management Strategy which outlines how the impact of secondary salinity on the environment will be minimised within the broader Salinity Management Plan. The 22 Environmental Salinity Management Plans outline a wide range of environmental impacts on riverine and wetland health and management strategies to minimise impacts.

For this review we have selected four Victorian Salinity Management Plans, the Avon–Richardson Land and Water Management Plan, the Boort–West of Loddon Salinity Management Plan, the Campaspe Salinity Management Plan and the Sunraysia Salinity Management Plan. Additionally, the South Australian Upper South East Dryland Salinity and Flood Management Plan and the Western Australian Lake Toolibin Recovery Plan have been selected as case studies. These Plans address a broad range of issues concerning secondary salinisation in riverine and wetland systems throughout Australia. The management strategies utilised in these Plans are typical of management options available throughout Australia and are used as a basis for predicting the positive and negative impact of management strategies on riverine and wetland health.

Brief outline of management areas

Lake Toolibin, Western Australia

The following site description is from Bowman Bishaw Gorham, Jim Davies and Associates, and Rural Planning (1992).

Lake Toolibin has extremely high conservation significance as one of the last remaining inland freshwater lakes in the south-west of Australia. The lake is situated approximately 200 km south-west of Perth at the head of the Northern Arthur River drainage system of the Upper Blackwood River catchment and the first in a series of nine lakes. Lake Toolibin is the only major lake in the chain which has not become saline.

The lake occurs in a low rainfall zone, with an average annual rainfall over its Catchment (approx. 483 km^2) of 370–420 mm. During dry years the lake may not fill, but during wet years the lake may be inundated continuously for several years.

The catchment has been mostly cleared for mixed grazing and cereal cropping. Only small stands of natural vegetation remain and are limited to gravelly ridges or the wetter parts of valleys.

Lake Toolibin was originally a perched freshwater wetland with a 15 m deep watertable. The salinity of the water in the lake has increased over the past 30 years due to the catchment being affected by salinisation as a result of clearing of native vegetation. The groundwater in the area is saline and the watertable has risen to the lake bed. This has had a markedly detrimental effect on the vegetation of the lake and the surrounding reserves.

The two principal management goals for Lake Toolibin are to lower the saline groundwatertable beneath the lake and the surrounding reserves and to prevent increasingly saline inflows from the catchment entering the lake. In the short term, groundwater pumping will be used to lower groundwatertables in the vicinity of the lake and it is predicted that extensive revegetation of the catchment will take over this function in the longer term. Saline inflows to the lake will be prevented by diverting saline water around the lake.

Upper South-East of South Australia

The following description is from Upper South East Dryland Salinity and Flood Management Plan Steering Committee (1993).

The area covered by the *Upper South East Dryland Salinity and Flood Management Plan* covers over 680,000 ha. Over 430 farm businesses, mainly based on beef and sheep grazing enterprises are supported by the area, which has a rural population of about 2,300.

Much of the remnant native vegetation in the region is located within the plan area. Almost 97,000 ha of native vegetation are protected in conservation or national parks, or under heritage agreements. Important wetlands exist in the watercourses, including the Watervalley Wetlands and others along the Bakers Range, Marcollat, Duck Island, West Avenue Range and Tilley Swamp Watercourses. The remnant native vegetation and wetlands in the area are considered to have high conservation value, as well as supporting rare and endangered flora and fauna species. Wetland habitat and avifauna resources in the area are of international significance.

The accelerated dryland salinity in the region is a result of the removal of nearly all native vegetation cover. This has caused increased groundwater recharge and the rise of groundwater levels. This effect has been exacerbated by the later loss of deep-rooted perennial lucerne due to the impact of lucerne aphid in the late 1970s. Wet winters and flooding further aggravate the situation.

Higher watertables also increase the rate of surface run-off during winter. Prolonged inundation can destroy ground cover, especially pastures. The salinisation process occurring through summer by evaporation brings more salt to the surface and so further destroys vegetation, which in turn results in more recharge and further raises the groundwater levels. Groundwater salinity varies from >12,000 mg/L in the north to 1,500–3,000 mg/L in the south.

Surface water moves along predominantly slow-flowing, poorly-defined watercourses whose pattern is defined by a series of dune ranges and interdunal flats. The direction of flow is generally north-westerly and the salinity of the surface water is below 4,000 mg/L TDS.

Areas experiencing salinisation or most at risk are those where the watertable is at a shallow depth. These areas are typically low-lying landlocked depressions within the dune ranges and along the eastern edge of broader interdunal flats.

The Plan consists of a major groundwater drainage scheme in the southern and central catchments of the region, with drains typically placed on the east side of the wider interdunal flats, a major surface water drainage scheme in the northern catchment, coordinated management of the region's wetlands in the form of the Wetlands Waterlink concept, a range of on-farm measures including saltland agronomy and pasture renovation, and revegetation. An outlet for the northern catchment will be to the Coorong via Tilley Swamp and Messent Conservation Park. The central catchment will require a separate outlet for the large volumes of water generated by the groundwater scheme. An ocean outfall at Henry Creek is the preferred outlet for the central catchment. The southern scheme will use the existing Blackford Drain outlet.

Sunraysia, Victoria

The following site description is from Bluml (1992).

The Sunraysia salinity Sub-Region is centred around Australia's largest arid zone horticultural area in north-western Victoria. Sunraysia covers approximately 30,700 ha of which 17,400 ha is used for irrigated horticulture. Sunraysia has two separate irrigation areas at Robinvale and Mildura. Within the Mildura irrigation area, there are three irrigation districts, including Red Cliffs, Mildura and Merbein.

The Sunraysia groundwater problem developed after the clearing of native vegetation and increased groundwater recharge from irrigation. Salting has occurred where perched or regional groundwater levels have intersected the ground surface or reached the plant root zone. It is estimated that groundwater levels have risen 10–15 metres higher than pre-irrigation levels. The formation of a groundwater mound below the Mildura irrigation area has caused major environmental damage. Groundwater discharge sites have developed in low-lying dryland and floodplain areas. This groundwater mound is slowly expanding to the south and west of the Mildura irrigation area.

To protect horticultural crops, sub-surface drainage systems were developed to control rising watertables and remove concentrated salts from the root zone. Disposal of saline drainage water has severely degraded areas of high conservation value. In Sunraysia, 28,000 megalitres of drainage water is generated each year for disposal, 56% of which drains to the Murray River and floodplain, while 44% drains to inland basins. There are 32 drainage disposal basins surrounding the Mildura Irrigation area covering 2,020 ha. Inland drainage water disposal has created artificial saline wetlands and a number of drainage disposal basins also receive groundwater inflow. The disposal of saline drainage water has had a marked impact upon the floodplain environment. In many areas, drainage water is allowed to pond in depressions and wetlands on the floodplain.

Boort–West of Loddon, Victoria

The following site description is from Lugg et al. (1993).

The Boort–West of Loddon irrigation area covers 898 square kilometres and lies within the Riverine Plain and Mallee physiographic regions of north-western Victoria.

The Loddon River is the main watercourse in the area although it is a fairly minor stream with a highly variable flow and a mean annual discharge of 201,000 ML. Water flows are controlled by upstream storages (Cairn Curran and Tullaroop) and inputs from the Goulburn River system via the Western Waranga Channel. Water is supplied to irrigators via various channels, the Loddon River, and other streams.

Most of the major lakes and wetlands in the area are used for storage of excess irrigation water. Little lake Boort is held at close to full supply level to enhance aesthetic and recreational values. A number of temporary wetlands in the western portion of the area are internal drainage systems and only hold water during wetter than average winters.

The main areas affected by salinity include:

- swamps of internal drainage to the north west and west of the Boort
- township,
- the Loddon River and associated effluent streams in the Appin–Appin South area,
- the south-east portion of Appin forest and
- parts of Kinypanial Creek near Fernihust.

Salinity in the Loddon River at Appin is inversely related to flow and generally ranges between 500 and 2,000 EC. Salinity data collected along the River indicate an increasing trend downstream, although channel outfalls to the River and other inputs result in instantaneous decreases. In 1990, salinity in the Loddon River was found to be increasing at the rate of 33 EC per river kilometre. Increases in salinity are due to saline seeps in the river banks (up to 47,000 EC) and irrigation tailwater disposal.

Salinities in wetlands generally range between 1,000 and 1,500EC, although some are very saline (eg. Bartletts Swamp—58,000 EC, Salt Lake—107,000 EC) and are due to cumulative effects of surface and groundwater inflows in the absence of surface flushing flows.

Avon–Richardson, Victoria

The following site description is from Heron et al. (1991).

The Avon–Richardson Land and Water Management Plan study area follows the Avon and Richardson Rivers catchment boundary. The area of the catchment is approximately 3,300 square kilometres, and extends from the Pyrenees foothills south -west of St Arnaud, to Lake Buloke , north of Donald.

The Avon River and the Richardson River are the major streams in the Plan area. There are also several small streams in the south of the catchment which flow into either the Avon or Richardson Rivers. These join to form the Richardson River which flows north to Lake Buloke, a terminal lake.

Salinity varies greatly throughout the Avon–Richardson catchment, with some areas contributing more salt to the river system than others. For example, Faulkner Creek and Paradise Creek have high salinities as groundwater intrudes into the Creeks and surface run-off is also saline. These tributaries contribute to the elevated salinities in the Richardson River. However, groundwater intrusion is the major contributor to the high salinity of the Richardson River.

The salinity of wetlands in the Avon–Richardson Catchment varies from fresh, such as Lake Batyo Catyo (700 EC), to hypersaline such as the lakes to the east of Lake Buloke (up to 150,000 EC). The elevated salinities of most of the wetlands are unnatural. The only naturally occurring saline lakes in the catchment appear to be the Waltons Lakes.

Rising saline watertables have intruded directly into the beds of the wetlands west of Donald. These lakes were previously fresh and would have been temporary wetlands. However, because the regional watertable is so high, they are usually filled with groundwater and are highly saline.

Excessive seepage from channels is exacerbating salinity problems associated with rising local watertables to the east of Lake Buloke where a channel runs through the lunetic soil. These soils lend themselves to excessive seepage as they are very sandy. It appears that these wetlands have become saline from the direct effects of rising regional watertables, but channel seepage is causing waterlogging problems in some areas.

Surface run-off from saline land is adding to the salinity of some wetlands.

The Avon Plains Lakes (Lake Hancock, Hollands Lake and Walkers Lake) would once have received a flushing flow from the Avon River, when it flooded. This would have washed saline water out of the lakes. These Lakes no longer receive flood water from the Avon River due to levee banking, and the salinity appears to be rising. A combination of factors is causing rising salinity in the Avon Plains Lakes. The rising regional watertable appears to be causing saline intrusion into the Lakes, and without flushing, the salt is accumulating.

Campaspe, Victoria

The following site description is from Campaspe West Sub-Regional Working Group (1989).

The Campaspe West sub-region comprises that part of the Campaspe Irrigation District west of the Campaspe River and a small part of the Rochester Irrigation Area south of the Warange Western Main Channel in North Central Victoria. It covers an area of 5,700 ha, 3,400 ha of which is irrigated. Most of the irrigated area is perennial pasture and dairying is the most important enterprise.

Groundwater seepage and surface run-off drains from the sub-region into both the Campaspe River and the Bamawm Drainage System. Murphy's Swamp and Richardson's Lagoon are two important wetlands north of the Bamawm Drainage System.

The Campaspe River is a freshwater stream in a narrow, deep channel which meanders to Echuca where it joins the Murray River. Flow varies between zero and 49,700 ML per day. For 40% of the year, it is less than 30 ML per day, and for 20% of the year it is greater than 300 ML per day.

In summer the flow of water along the river is generally lower than average and often stops at Echuca when the water is diverted for irrigation. Flows are above average in April, September and October when the river occasionally floods.

The salinity of the Campaspe River rises significantly along its length because of groundwater inflow and surface water flowing in from streams affected by dryland salinity, particularly during summer low flow periods. Water diverted to Campaspe irrigators averages 511 EC and can increase to 1,400 EC during continuous low flow periods. In summer, the salinity at Echuca is between 1,500 and 3,000 EC.

The Campaspe River is generally lined with a narrow band of river red gum woodland which is a remnant of a more extensive forest. The River provides valuable wildlife habitat and a source of passive recreation.

Murphy's Swamp is a shallow depression around 10 km long and up to 1 km wide. Richardson's Lagoon is a cut-off meander from the Murray River. Both are generally filled with irrigation drainage water. Murphy's Swamp has been modified by channelling and ponding of the drainage flow and the unseasonable flooding caused by irrigation run-off. Richardson's Lagoon is maintained at a fairly constant level as some irrigators rely on water from this source. Both wetlands have significant wildlife value and duck shooting is a popular activity.

The Campaspe West Salinity Management Plan sets an upper limit for water salinity flowing through these wetlands at 2500 EC. The Plan recognises that if salinity rises above this level some important aquatic plants will die. This limit is potentially too high to avoid species loss, as a review by Hart et al. (1991) found that the biota of rivers and wetlands would be adversely affected if salinities increase to around 1000 mg/L. In low flow conditions, saline water draining to these wetlands exceeds 2,500 EC. However, during these times, the drainage water bypasses these wetlands and discharges directly to the Murray through a constructed drain.

Case studies: summary of causes and recommendations

Saline water can enter freshwater riverine and wetland systems either from a source resulting from groundwater rise or as a result of management strategies adopted to protect agricultural land from secondary salinisation (Table 1 in Annex). In all of the six case studies summarised in Table 1, direct intrusion by rising, saline, regional watertables was a source of impact. In addition, riverine and wetland systems may be at risk from rising, saline, local watertables, saline seeps in the banks of rivers, saline tributaries delivering saline water to rivers and wetlands, and run-off from saline land. Superimposed on these risks, riverine and wetland systems may also receive saline water from on-farm and regional water management strategies such as sub-surface drainage discharge and outfalling of irrigation drainage water. Once saline water enters a wetland that is not frequently flushed, the salt will accumulate and concentrate through evaporation.

We recommend:

- **Riverine and wetland systems should not be used to transport or temporarily hold saline water.**
- **The distance that saline water is moved through natural drainage systems should be minimised.**
- **Saline water should not be directed to a wetland that cannot be easily and frequently flushed.**

Management strategies adopted and recommendations

The primary management objective of all but the *Lake Toolibin Recovery Plan* reflects the focus of such plans, that of protecting agricultural productivity from salinisation (Table 2). Protection of environmental values is generally a secondary consideration and is no more than an extension of the protection of agricultural productivity. Not surprisingly, these plans reflect the objectives of the State policies outlined above which directed their development.

The Lake Toolibin Recovery Plan has protection of environmental values as its primary objective, although protection of agricultural productivity is also an objective outlined in one of its five principal goals which is (Bowman Bishaw Gorham, Jim Davies and Associates, and Rural Planning 1992):

> to improve land use decision making and practice within the Toolibin catchment so that land management:
>
> - is sustainable, productive and profitable in the long term (over 100 years);
> - reduces the current area of degraded land;
> - favours conservation of wildlife.

This shift of emphasis is from protection of agricultural productivity as the primary objective to protection of environmental values and has been adopted by the *Western Australian Salinity Action Plan* (Government of Western Australia 1996). The Plan identifies the need to allocate resources for the protection of environmental values in their own right and this thinking will be applied to the management of the six wetlands, including Lake Toolibin, selected as 'Recovery Catchments' within the Plan.

We recommend:

- **Catchment level management plans need to have protection of wetlands and rivers as a primary objective.**

All of the Plans reviewed, except for the Avon–Richardson Salinity Management Plan, adopted strategies to slow, halt or reverse the rise of saline watertables. The management methods used to lower watertables and prevent further accession are similar and fall into three broad categories (Table 3):

1. Regional tree or deep-rooted crop planting, targeted tree planting and/or mechanical groundwater pumping are used to lower watertables and intercept water which would otherwise cause further rise in watertable levels.
2. Increased efficiency of water use is achieved by sealing water supply channels, laser leveling of land, reduction of the amount of water used, and the reuse of pumped groundwater. This increased efficiency of water use reduces the amount of water available for accession to the watertable.

3. Surface and sub-surface drainage are used to carry surplus water away from farms and from the region.

In most of the Plans, methods from more than one category are used.

The three different categories have different implications for their impact on riverine and wetland systems. Replanting with deep-rooted species and increased efficiency of on-farm water use are likely to reduce the amount of saline groundwater or surface water finding its way into riverine and wetland systems. Surface and sub-surface drainage of farmland is likely to impact adversely on riverine and wetland systems as drainage lines are often made up wholly or in part of natural systems and drainage water is usually disposed of into rivers or wetlands. Drainage water is often derived from sources with an elevated salt content such as pumped groundwater, surface run-off and irrigation drainage.

We recommend:

- **where appropriate methods involving replanting with deep-rooted species and increased efficiency of on farm water use should be used to arrest the rise in saline groundwater in preference to surface and sub-surface drainage.**

All of the six Management Plans reviewed have developed strategies to minimise the impact of saline water on their freshwater riverine and wetland systems (Table 4). The major strategy employed by all of them was to avoid putting saline water into these systems. The three categories of avoidance strategy, in order of increasing levels of potential impact on natural systems, are:

1. Regional or on-farm drainage water re-use schemes or redirection of drainage water to groundwater aquifers.
2. Directing the water to either on-farm or local constructed evaporation basins.
3. Directing saline water to naturally saline wetlands or to the sea.

We further recommend:

- **Wherever possible saline water should be disposed of on the farm or in the region of its origin.**

If it is not possible to avoid putting saline water into freshwater systems, then dilution is the approach which has been taken to protect the systems. For example:

- in the Sunraysia and Campaspe regions they release salt into the River Murray during high flow times and at a rate which is calculated not to increase the salinity of the Murray measured at Morgan in South Australia.
- Boort–West of Loddon region releases salt into the Loddon River and then increases the flow in the Loddon to ensure that the salinity levels do not rise above what are considered to be acceptable levels;
- Boort–West of Loddon, Avon–Richardson and Sunraysia regions allow saline water to enter selected wetlands that will be periodically flushed so that the salt is not concentrated to what are considered unacceptable levels by evaporation.

We further recommend:

- **Where release of saline water into natural systems is unavoidable, salinity levels of the receiving waters must be maintained at less than 1,000 mg/L (Hart et al. 1991).**

There are many options available for the protection of rivers and wetlands from secondary salinisation (Table 4). However, within any given catchment, these options are limited by the physical characteristics of the region, the nature of the farming activities carried out, and the imperative to protect agricultural productivity and resource allocation simultaneously. In reality, the manager may be left with a limited number of options. Whatever the management strategies used to minimise the impact of salinity on freshwater systems, there will be both positive and negative effects on the rivers and wetlands involved. The choice of options used must be made carefully to ensure that protection from salinity does not lead to a greater impact from another source of degradation. For example, increasing the quantity of water within a system to maintain the salinity at a low level will result in a change in the water regime which may also degrade the system.

Table 5 outlines the possible negative and positive impacts of the management strategies used in the six management plans reviewed to protect rivers and wetlands from salinisation. Within any catchment developing a strategy to protect its rivers and wetlands from salinity, this approach can be used to predict both the positive and negative impacts of the management options under consideration. Once the impacts have been predicted, better informed choices can be made.

We further recommend:

- **Negative as well as positive effects of management strategies designed to protect riverine and wetland systems from salinisation must be considered when developing a management plan.**

All of the plans reviewed recognise that protection of agricultural production and of riverine and wetland health are inextricably linked.

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Annex

Table 1. Sources of saline threats to rivers and wetlands

Threat	Region					
	Lake Toolibin Recovery Plan (WA)	Upper SE Dryland Salinity and Flood Management Plan (SA)	Sunraysia (Vic)	Boort–West of Loddon (Vic)	Avon–Richardson (Vic)	Campaspe (Vic)
Rising regional groundwater tables	✔	✔	✔	✔	✔	✔
Rising local watertables	✔	✔			✔	
Saline groundwater intrusion into wetlands	✔	✔	✔	✔	✔	✔
Saline groundwater intrusion into rivers					✔	✔
Saline seeps in river banks				✔		
Surface run-off from saline land into wetlands	✔	✔		✔	✔	✔
Surface run-off from saline land into rivers	✔				✔	✔
Saline tributaries delivering salt to rivers					✔	✔
Saline rivers/drains discharging into wetlands	✔	✔			✔	✔
Less frequent flushing of wetlands				✔	✔	
Evaporative concentration of salt in wetlands	✔	✔		✔	✔	
Saline subsurface drainage water discharge to rivers and wetlands			✔			✔
Outfalling of saline irrigation tailwater into rivers and wetlands				✔		
Outfalling of saline irrigation drainage water into rivers and wetlands				✔		✔

Table 2. Principle management objective of lowering saline groundwater levels in representative regions throughout Australia

Region					
Lake Toolibin Recovery Plan (WA)	**Upper SE Dryland Salinity and Flood Management Plan (SA)**	**Sunraysia (Vic)**	**Boort-West of Loddon (Vic)**	**Avon-Richardson (Vic)**	**Campaspe (Vic)**
To ensure the long-term maintenance of Lake Toolibin and its surrounding nature reserves as a healthy and resilient freshwater ecosystem, suitable for continued bird usage at current high levels	Protect agricultural land from dryland salinity and surface flooding	Protect horticultural crops from rising saline groundwater	Protection of agricultural productivity	Protection of agricultural productivity	Protect dairying pasture from rising saline groundwater

Table 3. Methods employed to lower saline groundwater and prevent further accession to the water-table in representative regions throughout Australia

Methods to lower saline groundwater	Region					
	Lake Toolibin Recovery Plan (WA)	**Upper SE Dryland Salinity and Flood Management Plan (SA)**	**Sunraysia (Vic)**	**Boort-West of Loddon (Vic)**	**Avon-Richardson (Vic)**	**Campaspe (Vic)**
Regional tree planting	✔	✔				
Plant trees along river(s)				✔		
Plant trees along water supply/drainage channels						✔
Plant dryland lucerne						✔
Groundwater pumping	✔			✔		✔
Reduction of amount of water applied				✔		✔
Re-use of water pumped from groundwater				✔		✔
Laser levelling of land						✔
Sealing water supply channels						✔
Extended regional surface drainage	✔	✔				✔
Regional network of subsurface drains		✔	✔			
Improving farm drainage						✔

Table 4. Proposed methods for the disposal of saline water to minimise impact on rivers and wetlands

Method of disposal	Region					
	Lake Toolibin Recovery Plan (WA)	Upper SE Dryland Salinity and Flood Management Plan (SA)	Sunraysia (Vic)	Boort-West of Loddon (Vic)	Avon-Richardson (Vic)	Campaspe (Vic)
Drainage reuse schemes			✔			✔
On-farm reuse				✔		✔
Groundwater aquifers via disposal bores			✔			
Constructed evaporation basins			✔		✔	
On-farm evaporation systems				✔		
To the sea		✔				
Existing saline wetlands	✔*	✔	✔		✔	
To the Murray			✔			✔
Increase flow in salt affected rivers				✔		
A limited number of floodplain disposal sites			✔			
Periodic flushing of wetlands	✔			✔	✔	

* Diversion of saline water around Lake Toolibin

Table 5. Predicted effect of management strategies on wetland and riverine systems

Management option	Effect			
	Wetland negative	Wetland positive	River negative	River positive
Drainage reuse schemes	Minimised Saline water may be collected and held in a regional wetland. • natural water regimes are altered.	Saline water does not enter wetlands Number of wetlands affected minimised.	Minimised Saline water may be collected and transferred to the regional holding point using a natural drainage line. • natural flow regimes are altered.	Saline water does not enter river Number of rivers affected minimised.
On-farm reuse	Minimised Saline water may be collected and held in an on farm wetland • natural water regimes are altered.	Saline water does not enter wetlands Number of wetlands affected minimised.	Minimised Saline water may be collected and transferred to the holding point using a natural drainage line. • natural flow regimes are altered.	Saline water does not enter river. Number of rivers affected minimised.
Groundwater aquifers via disposal bores	Minimised	Saline water does not enter wetlands	Minimised Saline water may be collected and transferred to the disposal bores using a natural drainage line. • natural flow regimes are altered.	Saline water does not enter rivers Number of rivers affected minimised.
Constructed evaporation basins	Minimised Constructed evaporation basins are created in low points in the landscape, probably at the site of an existing, often ephemeral, wetland. • salinity increased • natural water regimes altered	Saline water does not enter wetlands Number of wetlands affected minimised.	Minimised Saline water may be collected and transferred to the constructed evaporation basin using a natural drainage line. • natural flow regimes are altered.	Saline water does not enter river Number of rivers affected minimised.
On-farm evaporation systems	Minimised Saline water may be collected and held in an on farm wetland • natural water regimes are altered.	Saline water does not enter wetlands. Number of wetlands affected minimised.	Minimised Saline water may be collected and transferred to the constructed evaporation basin using a natural drainage line. • natural flow regimes are altered.	Saline water does not enter river. Number of rivers affected minimised.

Table 5. Predicted effect of management strategies on wetland and riverine systems — cont'd

Management option	Effect			
	Wetland negative	Wetland positive	River negative	River positive
To the sea	Minimised	Saline water does not enter wetlands	Whole or part of a river system may be used to transport salty water to the sea • natural flow regimes are altered.	Saline water does not enter river Number of rivers affected minimised.
Existing saline wetlands	Becomes more saline. • becomes less saline (eg. The Coorong, SA)	Saline water does not enter non saline wetlands	Whole or part of a river system may be used to transport salty water to the wetland. • natural flow regimes are altered. Saline water may enter river if wetland is flushed	Saline water does not enter river Number of rivers affected minimised.
To the Murray	Minimised	Saline water does not enter wetlands	Saline water enters Murray. Whole or part of a river system may be used to transport salty water to the Murray.	Minimised Number of rivers affected minimised.
Increase flow in salt affected rivers	Riverine wetlands are more likely to be flooded with saline water.	Minimised	A change in water regime	Salinity of river is reduced
Floodplain disposal sites	Saline water enters wetlands. • natural water regime altered.	Number of wetlands affected minimised.	Saline water may enter river during flood	Saline water does not enter river during periods of low flow.
Periodic flushing to terminal wetlands	Altered water regime	Salinity of terminal wetland reduced.	A 'slug' of saline water will be moved along a river downstream of the wetland.	Minimal