Water: Quantity and Quality

Kathleen H. Bowmer

Recent audits of water quality and ecosystem health show substantial impact from agricultural development in Australia. It is proposed that environmental sustainability is underpinned by the maintenance of ecosystem processes and their resilience to withstand the impact of disturbance through changes in hydrology, increased loads of salt, pesticides and nutrients, and invasion by exotic plants and animals.

Selected agricultural impacts are considered in terms of trends, methods for measurement and monitoring, possible solutions and implications for development of policy. An integrated ranking of risk is derived from an intuitive assessment of the combined extent and severity of disturbance, together with the feasibility and cost of remediation.

Finally, developments in resourcing and catchment governance are reviewed, including the use of adaptive management and shared investment in practices to improve water use efficiency and protect water quality. In Australia, as elsewhere, environmental, economic and social considerations are being integrated in emerging community partnerships, where consultative processes are used to respond to government initiatives.

1 INTRODUCTION: CONTEXT AND TRENDS

Audits and reforms

A major audit of the State of the Environment in Australia completed recently (SOE 1996), reports that many of our rivers and wetlands, estuaries and coastal regions are threatened by agricultural pollution and urban and industrial development. Critical issues of sustainable water quality including salinity, algal blooms, and water pollution with pesticides have also been considered by two presentations to the Prime Minister's Science and Engineering Council (PMSEC 1995; Cooper *et al.* 1996).

Issues of concern include the quality and quantity of surface and ground waters. It is increasingly recognised that these are inextricably linked through changes in catchment water balance caused by land clearing, and changes to instream hydrology caused by impoundment and irrigation diversion. Recognition of the importance of integrated catchment management is reflected in major new research initiatives and renewed process of community consultation at regional or catchment level (see Curtis and Lockwood, Chapter 8 this volume).

In Australia, the water reform agenda of governments aims to develop consensus on the equitable allocation of water for consumptive and environmental needs, through integration of economic, social, environmental and cultural considerations, and through sharing of investment in research and practice to improve water use efficiency.

The strategic plan for the National Land and Water Resources Audit (1998), a program of the National Heritage Trust, has recently been published. A $29.4M audit will be conducted to provide the first comprehensive appraisal of land and water degradation in Australia and its environmental, social and economic costs to the nation.

River health and ecological processes

The concept of river and catchment health (see Section 2 for further discussion) draws upon the parallels with human health and indicators of wellness (CEPA 1992). Ecological processes, such as nutrient and energy cycling, are critical to river health, but are difficult to measure. Consequently, the Commonwealth and State Governments in Australia have invested substantially in research to understand the ecological processes in rivers and wetlands, to develop appropriate management regimes, to find suitable indicators of river health, and to develop community involvement and ownership through schemes such as Landcare, Bushcare, Rivercare, Fisheries Action, Endangered Species, Farm Forestry, Murray Darling 2001, National Wetlands, National Reserve System, Waterwatch, Saltwatch, Streamwatch and Corridors of Green (see Chapter 8). Major national initiatives include the establishment of a National River Health Program. The National Heritage Trust will allocate about $1.25 billion over five years to community based projects for improving Australia's natural environment.

Integrated catchment and river management

Overall there is a recognition that a holistic approach to landscape and river management is required to achieve the ideals of sustainability and biodiversity which underpin the concept of a healthy river (CEPA 1992), and that prevention and remediation measures need to be strategically located. For example, in the Murray–Darling Basin (MDB), 80% of the water harvested and transported by the rivers in the Basin originates in 3% of the catchment (Blackmore 1998), demonstrating the importance of spatial analysis and site selection for effective catchment management. Also, the combinations of landscape, and land use practices which render underlying groundwater vulnerable to pollution need to be identified to prevent contamination wherever possible, since once groundwaters are polluted with nitrates or pesticides, reclamation is often impossible or very expensive (Kookana *et al.* 1998).

Value of water and costs of degradation

In Australia, urban and regional development is increasingly limited by access to clean water. For example, the value of water used in manufacturing in Adelaide alone is estimated at $12.3 billion; and in the Murray–Darling Basin 80% of the water that would otherwise flow to the sea is on average consumed (Blackmore 1997).

Salinity is a major concern for irrigation and dryland farmers, for water users downstream as water becomes too salty for urban or agricultural use, and for cities and towns where infrastructure, roads, pipes and buildings are being damaged. Dryland and irrigated lands affected by salt in Australia now total 2.5 million hectares, with increasing incidence in the MDB and the south-west of Western Australia (Hamblin and Williams 1995).

In the MDB the safety of stock water and domestic supplies has been threatened by more than 50 outbreaks of toxic algal blooms in 1997 (Blackmore 1997). In several Australian cities and many small towns, costs of water treatment for drinking and industrial use are also increased by odours generated by algae or by chlorinated by-products from disinfection of water containing dissolved organic matter. Toxic and carcinogenic compounds formed in water treatment are a concern for human health (Jones 1994*b*). A new Cooperative Research Centre for Water Quality and Treatment specialises in the measurement, prevention and treatment of algal blooms and associated toxins in drinking water. Additionally, there are substantial costs in loss of recreational fishing and tourism through loss of habitat, degradation of water quality and loss of aesthetic appeal.

The nation is committed through international treaties such as the Ramsar Convention to protect wetlands for bird breeding and migration, and also to protect sites of world heritage value, both inland and in coastal regions. Recognised sites of intrinsic conservation value include the Macquarie Marshes, Barmah Forest, Hattah-Kulkyne Lakes, Chowilla floodplain, the Coorong and lower lakes, Gunbower Forest, Kerang Wetlands and Lake Albacutya; as well as other significant wetland complexes listed in the Directory of Important Wetlands (ANCA 1993; Gall 1996). The land claim by the Yorta Yorta at Echuca in Victoria, which covers much of the Barmah-Millewah forest, is an example of emerging demands by the aboriginal people for conservation of water access and traditional hunting rights. It could have far-reaching implications for the conservation of native flora and fauna in the management of rivers and floodplains. The importance of floodplain ecosystems in Australia is passionately argued in a recent review (Mussarad 1997).

Sediment, nutrient and pesticide export from agricultural land to coastal waters is a concern Australia-wide, especially where sensitive ecosystems, mangroves and seagrasses are under threat. In Queensland, sediment nitrogen and phosphorus exports have been modelled by the Downstream Effects of Agricultural Practices Committee (Moss *et al.* 1992). The potential for damage to the Great Barrier Reef remains a priority issue for the Australian Institute of Marine Science and the Great Barrier Reef Marine Park Authority.

Challenges for the future

Many of the deleterious changes and impacts described above are inevitable consequences of development. The challenge now is to look for solutions and innovations, both to remedy existing problems and, perhaps more importantly, to prevent further degradation.

Fortunately, many industry leaders and agricultural communities have already recognised the urgency of the issues. For example, several new Cooperative Research Centres emphasise sustainability through programs on catchment management and irrigation water use efficiency and many of the research programs coordinated and funded by the Murray–Darling Basin Commission, the Land and Water Resources Research and Development Corporation (LWRRDC 1997) and the Rural Industries R&D Corporation (RIRDC 1997) focus on water quality and quantity in relation to specific sectors of the agricultural industry.

Many of these programs are attempting to clarify the meaning of sustainability, to explore options for the future, to build community consensus on what is acceptable, to analyse the costs and benefits of different policies, and to agree on who should pay. These major challenges to agricultural practice, catchment management and the community will be explored further in this chapter by:

(1) reporting on the developments of knowledge about ecosystem processes;
(2) analysis of the impact of selected agricultural systems on water quality and quantity;
(3) synthesising the risks to water utility and aquatic ecology; and
(4) reviewing developments in resourcing and catchment governance in relation to finding acceptable solutions by shared investment and partnerships.

2 ECOSYSTEM HEALTH

Stressor-symptom responses as mediated by the aquatic ecosystem

A conceptual framework (Fig. 1, adapted from Cullen and Bowmer 1995) links factors which impose stresses on rivers and wetlands to symptoms of degradation through the buffering influence of the ecosystem. Consequently, the response of the system, as measured by the appearance of listed symptoms, or by changes in the utility of the water, is determined by the physicochemical capacity of the system to intercept pollutants (by deposition in floodplains or filtration by riparian vegetation or wetlands) or to absorb them (for example, by long-term uptake of phosphorus into sediments). It is also determined by the fragility or resilience of the food web, its organisms and supporting ecosystem processes both to changes in water quality and to disruption in the volumes and variability of hydrological events.

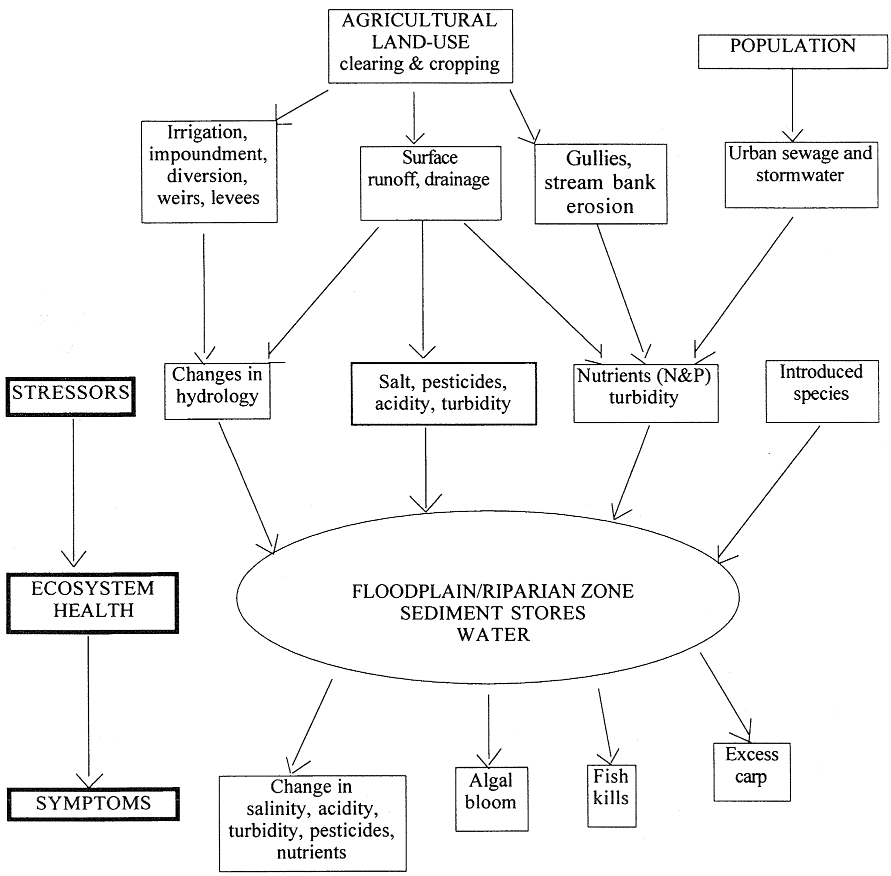

Fig. 1. Changes in land–water systems through agriculture which cause stress, and the symptoms shown by affected aquatic systems in rural Australia. Symptoms reflect the combination of stress intensity and the buffering capacity of aquatic ecosystem processes.

Note that interception and absorption (uptake) and release of pollutants may be time-dependent, reflecting both features of hydrology such as storm events and sediment suspension, and effects of system uptake capacity or saturation; and also that agricultural impacts are inter-linked with effects of other urban and industrial developments in generating stresses, so that policy and management (for effective phosphorus reduction, for example), would need to extend over several economic sectors and levels of government.

This conceptual approach of stressor, ecosystem condition and symptom (Fig. 1) has parallels with the development of a set of indicators for the next stage of the State of the Environment reporting system (Fairweather and Napier 1998). A set of indicators has been proposed which describes the *Condition* of all important elements in each biological level in the main freshwater ecosystem types, the extent of the major *Pressures*, and indicators of *Responses* to changes in the condition of ecosystems.

Ecosystem response and indicators of health

Unravelling the food web

Australian freshwater ecosystems and food web processes are being studied by researchers at Griffith, Monash, Adelaide, Murdoch and Charles Sturt Universities, amongst others, and by the Cooperative Research Centre for Freshwater Ecology. For example, Shiel in Bowmer *et al.* (1993) describes the trophic relationships between fish, zooplankton, nanoplankton, bacteria, edible algae and non-edible cyanobacteria. This kind of information is required to underpin the selection of organisms or communities for monitoring river health, and for assessing the effectiveness of changes to catchment or river management.

Power (1992) described some of the trophic interactions in North American aquatic ecosystems, with particular reference to the role of 'bottom up' control of food webs through food resources, versus 'top down' control through predators. More information is needed about the balance of bottom-up and top-down control in Australian ecosystems (e.g. Boon and Bunn 1994); the degree of redundancy of species at a given trophic level; variability in space and time (patchiness); effects of impoundment and diversion in disrupting longitudinal and lateral (river-floodplain) connections; the degree of disturbance required to maintain a diverse and resilient ecosystem; the relative effect of pollution compared with other impacts; and the rate of recovery after disturbance or major impact, for example, by recolonisation.

Important ecological processes include nutrient cycling and energy flow, including breakdown of detritus and organic matter. For example, Bunn and Boon (1993), in a study using stable isotope analysis, found that methanogenic bacteria may be driving carbon cycling. Robertson *et al.* (1996) reviewed carbon exchange and transformations between the river channels and floodplains and Arthington *et al.* (1997) has recently reviewed the potential impact on energy flow of converting catchments from forest to sugar cane.

Unfortunately, measurements of these critical ecosystem processes are not yet suitable for routine monitoring purposes, so approaches to assessment are usually based on surrogate measures using specific aquatic species or groups as indicators, or on occurrence and status of habitat, or on hydrological parameters, such as variability, frequency and duration of flow events or inundation. Changes are related by comparison to undisturbed paired sites or, in the case of hydrological characteristics, to records or simulations of pre-impoundment conditions.

Biological methods for assessing water quality and ecosystem health

Use of indicators. In a recent and comprehensive review, Walker and Reuter (1996) discussed two broad types of indicators: condition indicators which define the state of a system relative to a desired state, and trend indicators which measure how a system has changed. As summarised by Cranston *et al.* (1996): 'Many catchment activities impinge upon and are integrated with the aquatic system. Changes in the health of a catchment will be reflected in the biological community' (see also 'Stressor-symptom responses' and Fig. 1).

The use of biota to assess water quality was the topic of an international conference in Australia and the subject of a special issue of the Australian Journal of Ecology (1995). In a summary of future directions, Bunn (1995) argues for biomonitoring methods which include species that are economically important, that are important in food webs, and are broad enough in range to detect differences in sensitivity. He points out that early warning approaches using biomarkers and bioassays assume that effects occurring at the biochemical level will be translated into communities and ecosystems, but this has rarely been tested.

Condition indices. A rapid appraisal technique using a condition index based on four attributes of wetlands — soil, fringing vegetation, aquatic vegetation and water quality — has been successfully used for assessing the health of permanent floodplain wetlands in the Murray–Darling Basin (Spencer *et al.* in press). Stream condition has also been assessed by rapid methods in Victoria (DCNR 1995).

As noted in the section 'Stressor-symptom responses as mediated by the aquatic ecosystem', above, a set of key indicators has been selected for National State of the Environment Reporting (Fairweather and Napier 1998). A set of 53 key indicators are listed under categories of condition, pressure and response; under headings of groundwater, human health, environmental water quality, surface water quantity, physical change, biotic habitat quality and effective management.

At the same time, a new risk-based approach is being used to upgrade the 1992 ANZECC water quality guidelines for ecosystem protection (Hart *et al.* 1998). The draft guidelines consider seven ecosystem types: upland rivers, lowland rivers, lakes and reservoirs, wetlands, estuaries, coastal and marine ecosystems; compared with only fresh and marine subdivisions in the current guidelines. The new guidelines focus on packages of ecosystem stressors, rather than single stress factors, and use levels to trigger the need for continued monitoring. For example, a decision tree for assessing risk of cyanobacterial blooms in lowland rivers caused by irrigation return assumes a high risk at combination of total phosphorus above 15 $\mu g\ L^{-1}$ and total nitrogen above 150 $\mu g\ L^{-1}$, turbidity greater than 30 NTU and flow conditions allowing more than six days for growth.

Guideline packages are being developed for toxic heavy metals and organic compounds in the water column and in the sediments; nuisance growth of aquatic plants; maintenance of dissolved oxygen; effects due to suspended particulate matter, salinity, temperature and pH; and effects on rivers and wetlands due to changes in flow.

Ecotoxicological methods. Organisms from at least three trophic levels (e.g. a fish, a zooplankton grazer such as *Moina* or *Daphnia*, and an alga such as *Selanastrum*) are used in laboratory observations to determine the dilution of water to reach a predetermined criteria such as 'no observable effect'. This biological determination allows an assessment of toxicity without recourse to chemical analysis, but supplementary confirmation of the identity of the toxic material is usually required, especially if there are several possible sources of pesticide or other toxins. The use of toxicity identification evaluation (TIE) procedures can help narrow down the classes of pollutants or pesticides involved (USEPA 1988, 1989, 1991).

A number of biotic indices, such as the Trent Biotic Index and the Chandler Biotic Score, have been used overseas to test water quality *in situ*. These methods use the presence or absence of particular taxa which are known to be sensitive or tolerant of poor water quality (ANZECC 1992). The potential application of these methods in Australia was reviewed by Rippon and Chapman (1993).

Other ecotoxicological methods include the analysis of fish or mussel tissues which accumulate pesticides such as organochlorines and endosulfan (e.g. Nowak and Julli 1991; Napier 1992). Blood enzyme assays, or distortion of mouthparts of chironomids are other methods which help to integrate the effects of pesticides over time. The subject was reviewed by Nowak *et al.* (1993) and Clarke *et al.* (1994). Chironomid mouthpart asymmetry was used to investigate the effect of rice pesticides in drainage waters (Pettigrove *et al.* 1995) and Korth *et al.* (1995*b*) used the water flea *Ceriodaphnia* to test the combined toxicity of a range of rice and maize pesticides in irrigation drainage water. For these non-specific methods a major limitation is that it is still necessary to demonstrate experimentally that the observed effect is attributable to the suspected pesticide exposure.

Use of specific indicator species or groups. The subject has been reviewed by Bowmer (1993*b*) and Cranston *et al.* (1996). Candidate organisms include vertebrates, plants and fungi, macroinvertebrates and microorganisms.

In a comprehensive survey of fish in New South Wales rivers, Harris and Gehrke (1997) developed and modified an index of biotic integrity. Eleven attributes include species richness and composition, trophic composition and fish abundance and condition (Harris and Silveira 1997). The authors recommend further work to compare the index with macroinvertebrate monitoring data and independent tests of river or catchment health, but provisionally conclude that rivers of the Murray region and many montane New South Wales coastal rivers are in a degraded condition.

Macroinvertebrate community structure is the central plank of the National River Health Program, Monitoring River Health Initiative (NRHP 1996). By application of careful statistical analysis using a BACIP design (Before-After-Control-Impact-Paired Differences), it is hoped that anthropogenic factors can be distinguished from natural variation in time and space.

Macroinvertebrate community structure has been used to assess environmental impacts of pollutants in the Central and North West Rivers Water Quality Biomonitoring Program (NSW Department of Water Resources 1993). The number of taxa colonising artificial substrates placed in the river at sites upstream and downstream of intensive agriculture were measured. There was a large reduction in numbers of mayfly and caddis larvae at downstream compared with upstream sites. Unfortunately, further observations to investigate whether this reflected difference in habitat rather than pesticide pollution have been largely inconclusive (Brooks *et al.* 1996).

Arthington *et al.* (1993) studied artificial streams to examine the chronic effects of chlorpyrifos on invertebrate fauna, and concluded that chironomid larvae were the most diverse and useful taxonomic group for assessing stream health by measurement of richness, diversity and community structure.

However, Cranston *et al.* (1996) question whether a significant response in macroinvertebrate communities can be related to specific causes. Similarly, Bunn (1995), in reviewing the biological monitoring of water quality in Australia concludes: 'no single biological measurement will suffice to indicate the effects of pollution in aquatic systems and it is unrealistic to expect to find an all-embracing, cheap and sensitive method. Monitoring agencies should use a range of approaches that vary in sensitivity'.

Variability in habitat is an inherent feature of aquatic ecosystems of the Murray–Darling Basin. For example, the rich biological diversity of billabongs was described by Boon *et al.* (1990). Therefore the use of biotic indices or diversity index values cannot be used as wide ranging absolute indicators. Instead, comparisons of several sites in a given locality or a single site at different times must be used.

Loss of components of the ecosystem. Anecdotal evidence suggests that many inland rivers and storages were once dominated by *Vallisneria* (ribbonweed) and other submerged plants, but are now bare. For example, Roberts and Sainty (1996) described the demise of waterplants in the Lachlan River, which may reflect the combined effects of 'mumbling' by European carp, increase in turbidity, nutrient enrichment, impoundment and loss of variability in river flow. Loss of these plants, in turn, affects the ecosystem's capacity to respond to, or endure, changes in water quality.

Herbaceous riparian vegetation has also been degraded, perhaps through grazing by cattle combined with changing flow regimes, and damage to trees and forests results from too much or too little water (Roberts 1992). River regulation is only one of the various factors contributing to the degradation of 18 000 ha or 20% of flood plain vegetation between Albury and Wellington (MDBC 1990).

The increasing dominance of introduced species. Native fish have been reduced in numbers and replaced with alien species such as carp (*Cyprinus carpio*) and mosquito fish (*Gambusia holbrooki*) (Gehrke 1993; Fisher 1996). These changes may reflect changes in water quality and quantity, reduction in temperature and changes to the flooding regime in redgum forests and wetlands. They may in turn cause changes in water quality through bioperturbation of sediments and predation on zooplankton. The subject has been reviewed recently by Faragher and Lintermans (1997) and Driver *et al.* (1997).

The utility of the water. Other more generalised indicators include criteria such as 'fishable' (reflecting accumulation of toxins in fish tissue in relation to acceptable dietary loads), 'swimmable' and 'potable' (USEPA, 1988; CEPA 1992).

3 AGRICULTURE: KEY IMPACTS ON WATER QUALITY AND QUANTITY

Salt

Irrigation and salinity

In Australia we have been aware of the dangers of salinity in irrigation agriculture for a long time, although, in a study of the mass balance of salt import and export in the Murrumbidgee Irrigation Areas and Districts (MIA), Evans (1971) concluded that the accumulation of salt in soils was insignificant. The author did not take into account the effects of rising watertables, capillary rise, and accumulation of salt at the soil surface. These problems, and the related issue of disposing of large volumes of drainage water, became a political issue some years later, as a result of the keynote speech in 1984 by the New South Wales Minister for Agriculture, Mr Jack Hallam. The Irrigation Research and Extension Committee in its Farmers' Newsletter graphically described the extent of the developing salinity and waterlogging problem in the MIA (IREC 1984).

Other irrigation regions in south-eastern Australia followed a similar sequence of events, in that intensive application of water to the landscape resulted in the export of large quantities of salty water. This drained, by more or less circuitous routes, to the main river arteries of south-eastern Australia, mainly the Murray. In this respect the Murrumbidgee was unusual in that very little water was returned to the river system. Instead, drainage water was stored in a large shallow evaporation basin, Barren Box Swamp, from which water was resupplied to the irrigation districts. As a result the Murrumbidgee remained a clean and diluting influence on the Murray, though its favourable impact became progressively eroded as increasing volumes of water were diverted for irrigation of rice, pasture and horticulture.

Dryland salinity

River salinities are expected to increase by 10% by 2040 and salinisation of land to rise from 500 000 ha now to over 1.5 million ha by 2040 (Blackmore *et al.* 1995). In coming decades it is projected that between 2 and 2.5 million tonnes of salt per annum will be exported to the Murray–Darling rivers as a result of development of several million hectares of dryland salinity (Blackmore 1998). In urban areas and inland cities, rising groundwater and associated salinity damages roads, buildings and sewerage. For example, annual recurring costs of urban salinity in Wagga Wagga are estimated at nearly $0.5 million; and irrigation groundwaters continue to rise, causing waterlogging and salinity and sterilisation of low-lying parts of the landscape (White 1997).

Monitoring

Salinity is easily monitored by a surrogate measure, electrochemical conductivity, and real time measurements are reliable and inexpensive. Salt is conservative in rivers so that loads can be calculated. These features of salt measurement and transport are prerequisites of a management policy based on trading of salinity credits (see below).

Technical solutions

Irrigation agriculture. Both engineering and agronomic solutions are possible. Aids to better management from CSIRO Land and Water include a series of decision support systems for soil water and groundwater management. For example, SWAGMAN DESTINY simulates water and salt balance over 20 years, showing trends in watertable levels, soil salinity and yields; and SIRAG FIELD helps irrigators decide how to optimise application of water. CSIRO is also researching methods of reducing deep percolation in rice soils by puddling or smearing the soil surface. New methods of water application include 'leaky pipes' to introduce water into the root zone, and re-use of salty water by a series of increasingly salt-tolerant crops prior to final evaporation (White 1997).

The CRC for Viticulture and the CRC for Sustainable Rice Production also promise improved irrigation efficiencies by a variety of agronomic and hydrological methods. The former includes the AUSVIT decision support module for irrigation water management.

Dryland salinity. Solutions and amelioration require a restoration of the hydrological balance by either engineering and drainage, or by replanting vegetation to reduce recharge. Saltbush, salt-tolerant trees and deep-rooted crops such as lucerne are being used.

Coordinated schemes for whole catchments are required, leading to Integrated Catchment Management, Total Catchment Management, Salt Action, and Trees on Farms programs. White (1977) describes the issue and solutions being developed in the five focal catchments of the Land and Water Resources Research and Development Program: the Upper South East Catchment, South Australia; the Kent River, Western Australia; the Loddon-Campaspe, Victoria; the Upper Burdekin, Queensland; and the Liverpool Plains, New South Wales.

Hamblin and Williams (1995) take the view that surface management of soil or vegetation will probably not control salinity in most affected districts and acutely affected areas will have to be retired from agriculture.

Salinity and Drainage Strategy. In the Murray–Darling Basin, a mechanism to trade off salinity input to the river was developed and agreed to between the States. The Salinity and Drainage Strategy (MDBMC 1988) aims to protect the river against salinity increases above an agreed baseline and allows salinity drainage returns to be offset against reduced salt loading brought about by interception works, such as the construction of evaporation basins.

However, the strategy does nothing to protect the river system from the major consequences of flow diversion; nor does it protect the landscape, en route storages, wetlands and floodplains against the effects of too little or too much water. As discussed later, these issues are central to more recent concerns about the resilience of aquatic ecosystems, and their capacity to maintain a function which could be vital to the nation's long-term supplies of acceptable water quality.

Nutrients and algal blooms

Algae and cyanobacteria

The massive algal bloom in the Darling River in 1991 and the increasing frequency of algal blooms in general led to the urgent development of the Murray–Darling Basin Commission's draft Algal Management Strategy (MDBC 1993*b*), and several other parallel strategies at State level.

In management of algal blooms the distinction between 'blue-green' (cyanobacteria) and other algae is important (Jones 1994*a*). For green algae there may well be a crude relationship between algal biomass and the phosphorus load entering a water storage or lake, but the relationship is likely to be much poorer for cyanobacteria specifically. Cyanobacterial dominance is favoured by still, turbid water reflecting the competitive advantage of these organisms in being able to adjust their buoyancy and to scavenge the water column for nutrients, often forming scums at the water surface. Therefore, restoration of flow and destratification methods are more likely than nutrient control to achieve the desired reduction in cyanobacterial bloom frequency, at least in the short term (Jones 1994*b*; Webster *et al.* 1997).

Nutrients and algal blooms

A review of the sources of phosphorus and nitrogen by Gutteridge Haskins and Davey (1992) for the Murray–Darling Basin Commission clearly indicated the role of forestry and irrigation drainage in contributing substantial loads of phosphorus and nitrogen to the River Murray. However, concentrations of nutrients (as opposed to loads of nutrients) are low in forestry run-off waters, making interpretation difficult. In a further review, Harrison (1994) highlighted the difficulty of calculating nutrient loads in irrigation drainage because of the sparsity of concentration data and flow records. Much of the information available is gathered either at the exit from the paddock or at the entry of the drain to the river. Paddock data overestimate nutrient load since no account is made of interception in the drainage system, whereas river or end-of-drain measurements do not isolate the contribution from different land uses. The interception of nutrients in irrigation drainage systems, and the critical role of vegetation and carp in the transport process have been described by Bowmer *et al.* (1993).

Carp (Robertson *et al.* 1997) and cattle (Robertson 1997) also profoundly disturb the structure and function of floodplain wetlands, resuspending sediments and increasing nutrient concentrations in the water column.

The source of agricultural phosphorus is another important question, whether from fertilisers and the surface soil as assumed in CSIRO's catchment management support system (Cuddy *et al.* 1997), or from subsurface soil and gully erosion as suggested by Olley *et al.* (1996). This issue has important implications for effective fertiliser management.

Clearly, the allocation of equity for nutrient export is much more complicated than for salinity. Catchment management computer based support systems (CMSS) have been trialled in the Hawkesbury–Nepean Catchment, in the new urban and low density peri-urban developments near Sydney (Davis *et al.* 1998), with the object of investigating a range of strategies for minimising loads from sewage treatment plants and other major land uses including bushland, grazing land and vegetable growing. Total catchment management groups have used CMSS in 10 major catchments in New South Wales, as well as in Queensland and Victoria. In the Murrumbidgee catchment, CMSS has been used to determine the relative potential of dryland and irrigation land management practices and point sources of pollution to generate nutrients (Cuddy *et al.* 1977). Application to extensive agriculture is limited at present by the paucity of data on local export coefficients. Further developments are needed to deal with interception of nutrients instream, and especially to cope with systems where there are many internal sinks such as low lying depressions and wetlands. The generation of large nutrient loads in wet weather is another difficult problem.

In summarising the results of a three-year CSIRO program on managing algal blooms, Davis (1997) reports that 'while flow management is a practical short-term tool for managing blooms in impoundments in inland rivers we can now see that nutrient management (particularly phosphorus management) is a more limited tool for reducing algal blooms than was previously believed. Nitrogen, not phosphorus, was often the limiting nutrient in both estuarine and freshwater systems'. Other evidence that nitrogen rather than phosphorus may be limiting for cyanobacteria in freshwaters has been reported by Thompson and Hosja (1996) for the Swan River estuary, and by Wood and Oliver (1995) using cultures and natural phytoplankton populations from inland river systems. Unfortunately, nitrogen is more difficult to control than phosphorus in catchments since it leaches more readily. It can also be accessed by fixation from the atmosphere by some blue green algae.

Further, Chambers *et al.* (1997), in studies on weir pools in the Murrumbidgee River, found that sediments provided a very much larger source of nutrients than runoff from catchments. It may be necessary to change the emphasis from controlling nutrients in catchments to locking up nutrients in sediments, for example, by keeping the water aerated. For this and other reasons, the importance of river flow has now been recognised as critical and is discussed in the section 'Water for the environment ('environmental flow')' in more detail.

Guidelines and monitoring

For phosphorus and nitrogen, the measurements required are much more difficult than for salt, for several reasons.

(1) Concentrations of interest are much lower (of the order of 10–100 μg L^{-1} for phosphorus) and cannot be determined by electrochemical methods at present. More sophisticated colorimetric procedures are required which usually involve transport of samples to a laboratory, and processing such as filtration or centrifugation and/or digestion prior to determination. Fortunately, automatic equipment for nutrient monitoring using *in situ* probes and telemetry is now commercially available, although very expensive (Fitch *et al.* 1997).

(2) Sampling is difficult because of the spatial heterogeneity caused by stratification, buoyancy of algal cells, capture in surface films, diurnal movement vertically in the water column, and wind transport of surface scums.

(3) Interpretation is difficult because of the differing bioavailability of different forms of organic and adsorbed phosphorus. Phosphorus from agricultural sources is usually adsorbed onto particulate material, making it less available to fuel algal growth than sewage phosphorus (Maher *et al.* 1993). New methods for phosphorus measurement, such as those based on iron strip scavenging methods (Oliver 1993; Dils and Heathwaite 1998), may be useful to resolve these issues, but add considerably to the difficulty of measurement.

(4) Finally, most of the phosphorus load may be transported in a short time during stormflow, so that intensive monitoring is required. For example, in recent studies of the lower Murrumbidgee it was found that approximately 0.5 million tonnes of sediment were transported past Wagga Wagga per annum on average; but that in the floods of 1974, about 6 years equivalent of average load was transported in 2 weeks (Olley *et al.* 1996). Assuming that phosphorus and sediment load are correlated, as might be expected, this raises the question of the usefulness of routine monitoring programs based on weekly or monthly sampling regimes.

Other causes of blooms

Impoundment. In many Australian rivers, impoundment and diversion in summer turns rivers into a series of nearly static pools, with advantage to the buoyant blue green algae. The effects of destratification or mixing of the water column by manipulating weir pool flows have been investigated, and appear to have promise for algal bloom management (Webster *et al.* 1997). Although phosphorus has been regarded as a key nutrient for algal bloom management, it is now clear that management of flow is often a more achievable option, at least in the short to medium term.

Disruption to biological process. With the increasing national interest in aquatic ecology, biological and ecological processes are now considered more seriously (Bowmer *et al.* 1993; Brock *et al.* 1994). For example, questions include:

- whether carp (an introduced species in Australia) could be contributing to algal blooms through their effect on disturbing bottom sediments;
- whether native fish could be used to change grazing pressures on zooplankton, to manage algal blooms by manipulating the food web;
- whether pesticides could have a subtle effect on zooplankton (reducing their grazing pressure on algal blooms);
- whether bankside riparian vegetation or artificial wetlands could effectively filter out nutrients;
- and what has happened to the submerged plants? Most rivers are almost bare now. Have carp been responsible, or could low levels of herbicides be the problem? Could algal blooms partly reflect the loss of macrophytes which would otherwise absorb some of the nutrients in the water?

Several biological solutions are now being explored. For example, the CRC for Catchment Hydrology and the Land and Water Resources R&D Corporation (LWRRDC) have large projects on the use of riparian vegetation for nutrient stripping. Wetland filters are now widely used to improve water quality (e.g. Hart *et al.* 1992; IAWQ 1994), although their nutrient stripping potential has been questioned (Bowmer 1993*c*). LWRRDC have also funded several projects to explore the use of biomanipulation to control algal blooms. This 'top down' approach requires restructure of the food web to maximise consumption of noxious cyanobacteria by herbivorous zooplankton. However, Boon and Bunn (1994) report that native zooplankton are probably unable to consume noxious cyanobacteria at the rates required for the control of algal blooms.

Technical solutions and recent developments in knowledge

A review of expert opinion was obtained through a series of technical advisory groups commissioned by the Murray–Darling Basin Commission (MDBC 1993*a*). The findings were used to develop the MDBC's Algal Management Strategy.

In this strategy, storages in which water is resident for more than 6 days were identified as vulnerable sites. Permissible phosphorus inputs to these sites were calculated on the basis of reducing the probability of exceeding a selected mean annual algal biomass (initially set at a target concentration of chlorophyll *a* of 10 $\mu g\ L^{-1}$), using a modified Vollenweider model. The permissible phosphorus loading at the sites is then apportioned to upstream tributaries on the basis of their flow.

The key sites are downstream of the main tributaries and also represent points of export from defined catchments. Therefore, it was proposed that administration and implementation of the strategy would rest with catchment management groups. These groups would be responsible for reducing exports of phosphorus to the downstream node in the interests of equity in the Basin and the protection of mainstream river water quality. The protection of internal water bodies, such as wetlands and en-route storages within each catchment, would be a separate issue and a responsibility of the local community.

One of the consequences of such a strategy is the recognition that many sources contribute to total nutrient export in a catchment. These include urban treated sewage, stormwater, runoff from dryland agriculture, irrigation drainage, sewage from small towns (where treatment is often less sophisticated than for larger cities), and effluents from food processing works and intensive rural industries.

It is clear that algal blooms are affected by a complexity of physical, chemical and biological factors which particularly include changes in hydrology and revision of flow rules for river management. Clearly, any policy of 'polluter pays' involving (say) phosphorus fertiliser use would be extremely difficult to apply and justify.

Harris (1994) reviewed eutrophication in Australia, explaining some differences from assumptions and conditions in the northern hemisphere where most research on eutrophication has been conducted. Australian rainfall and runoff tends to be more episodic, soils are older and shallower, temperatures are higher and turbidity greater than in the northern hemisphere.

Banens and Davis (1998) have recently reviewed approaches to eutrophication management in Australia, and planned outcomes from the $4 million National Eutrophication Management Program. The program will focus on four catchments with contrasting environments and management problems.

In the Wilson Inlet of Western Australia the release of phosphorus from sediments and the competition of *Ruppia* and estuarine phytoplankton for phosphorus will be studied.

In the Goulburn–Broken catchment of Victoria the bioavailability of phosphorus from grazing, irrigation and sewage treatment plants will be measured to check the hypothesis that all phosphorus can become equally available.

In the Namoi River catchment of northern New South Wales the relative importance of 'native' subsoil phosphorus and fertiliser phosphorus will be compared.

In the Fitzroy River catchment of tropical Queensland the effects of flow in resetting algal growth in shallow water bodies will be investigated.

When these results are released it is probable that currently accepted management approaches will need to be modified.

Pesticides

Pesticide use and trends

Cotton. A major investigation of the effect of cotton pesticides on river health has been conducted by the Land and Water Resources R&D Corporation and the Murray–Darling Basin Commission (LWRRDC 1993; Schofield 1995). Research was commissioned on the ecotoxicology of pyrethroids and profenofos to Australian biota, the toxicity of endosulfan adsorbed on suspended and bottom sediments, distortion of chironomid larvae mouthparts as an indicator of pesticide pollution, and biomonitoring at a subcatchment scale.

A review of river health in cotton growing areas (Arthington 1994) concluded that the rivers are in poor condition particularly in the lower reaches. Many factors contribute to ecosystem decline, such as river regulation, grazing of riparian vegetation by animals, and effects of introduced species such as carp. In these complex situations it will be difficult to determine the effect of pesticides specifically.

The NSW Department of Water Resources has been conducting a major monitoring program with the cotton industry in New South Wales rivers (The Central and North West Regions Water Quality Program; NSW DWR 1993; Cooper 1996). Several insecticides and herbicides have been detected downstream of cotton-producing areas. Endosulfan, the most widely used pesticide in the cotton industry, was often found at concentrations well above the guideline concentration for protection of aquatic life (0.01 $\mu g\ L^{-1}$; ANZECC 1992) and sometimes exceeded the concentration expected to kill fish. Yet fish kills were seldom reported. Biomonitoring using macroinvertebrate communities also showed no evidence of pesticide impact (Bales and Royal 1994).

Bowmer *et al.* (1996) reviewed the impact of cotton pesticides on river ecosystems. An analysis of various lines of evidence showed apparently conflicting results, with increased toxicity to fish observed in experimental ponds yet little or no impact on biota in river systems, even though endosulfan concentrations peaked at concentrations several orders of magnitude higher than recommended in guidelines for the safety of aquatic life. Complicating factors included many differences between laboratory conditions, on which the guidelines are based, and riverine freshwater ecosystems. These included differences in species and age of test organisms, differences in water quality, temperature and flow rates during exposure to pesticides, differences in patterns of exposure, possible acclimation through natural selection of resistant genotypes, and protecting factors in the field, such as non-uniform mixing and uptake by vegetation and sediments. Recommendations included redesign of field monitoring programs, studies on the biological implications of accumulation of pesticides in sediments, studies of the ameliorating or protecting effects of vegetation in freshwater ecosystems, development of chemical fate models, and a study of the effects of cotton pesticides on the full range of organisms and trophic levels in the food web.

Recently the Cooperative Research Centre for Sustainable Cotton Production summarised the results of a comprehensive research program to improve pesticide use practices and develop alternatives, including the use of transgenic cotton (Kennedy *et al.* 1997).

Rice. Pesticide export in drainage water from rice crops has been studied by Korth *et al.* (1995*a*) using a combination of chemical and biological methods. Of the 24 pesticides monitored, 10 were detected regularly and four (molinate, chlorpyrifos, maldison and endosulfan) exceeded either ANZECC or EPA water quality guidelines.

Other irrigated crops. Pesticide levels in drainage from summer crops, including maize, sorghum and rice, were investigated by Bowmer *et al.* (1994) and Korth *et al.* (1995*b*) and reviewed by Bowmer *et al.* (1995). Bowmer (1987) reviewed the subject of herbicides in surface waters, including their intentional application for aquatic weed control. A wide range of compounds are used including acrolein, 2,2-DPA and glyphosate. Acrolein is highly toxic to fish but is rapidly lost from water by volatilisation. Glyphosate is rapidly adsorbed by sediments, whereas 2,2-DPA is only moderately persistent, and is degraded by microorganisms. The potential risks from on-farm recycling in the Murrumbidgee Irrigation Areas were studied by Bowmer and Weerts (1987). Herbicides were not detected in an on-farm recycling system, but there is a risk of damage when run-off water from one crop is recycled; for example, when atrazine from maize or sorghum might reach seedling rice or soyabeans. The run off of pesticides from cotton, sorghum and maize in the Condamine–Balonne river system was described by Rayment and Simpson (1993).

Sugarcane. The use and impact of pesticides have been reviewed recently by Arthington *et al.* (1997). Atrazine, 2,4-D and triclopyr were detected in some Johnstone River catchment streams and groundwater, but at low concentrations. Insecticides DDT and dieldrin were found at trace levels, in contrast to much higher concentrations in the 1970s, reflecting use restrictions for organochlorine pesticides.

Horticulture. Runoff water quality was investigated in Victoria (EPA 1982) and the Piccadilly Valley, South Australia (Thoma 1988). In Victoria, horticultural activities in the Yarra and Werribee catchments resulted in organochlorine and other pesticides at low levels in river water. In the Onkaparinga, South Australia, the herbicides dacthal and propyzamide were most frequently found in streams, but rarely in the reservoir, owing to degradation and dilution during transport.

Forestry. Run-off of triazines from forests in Tasmania was studied by Davies *et al.* (1994). Of 29 streams sampled, 20 contained detectable residues, atrazine and simazine occurring at the highest concentration.

Guidelines and monitoring

Concentrations relative to water uses. Guidelines for water quality have been developed (ANZECC 1992; NHMRC 1993; EPA in Korth *et al.* 1995*a*). Acceptable concentration maxima are based on the use of the water (Table 1), and for the protection of aquatic ecosystems are derived from overseas data for the response of the most sensitive aquatic organism combined with a safety factor of 20- or 100-fold, depending on the pesticide's properties. Table 1 shows that ANZECC and EPA guidelines for the safety of aquatic life are far more stringent than for drinking water (or other uses, not shown); and for some compounds, guidelines are much lower than current limits of detection.

Other challenges in monitoring for pesticides in water include: possibilities of synergy between compounds; the potential for chronic as well as acute effects on organisms; the role of sediments and suspended particles in modifying bioavailability and toxicity; and selection of appropriate protocols for sampling in space and time. Further comment and case studies can be found in Bowmer *et al.* (1995) and Korth *et al.* (1995*a*).

Table 1. ANZECC or EPA Interim Environmental Guidelines for the protection of aquatic ecosystems and ANZECC and NHMRC drinking water quality guidelines in $\mu g\ L^{-1}$

Pesticide	Protection of Ecosystems ANZECC/EPA	Drinking Water	
		ANZECC	NHMRC
Diazinon	0.00006	10	3
Chlorpyrifos	0.001	2	10
Terbufos	0.004		0.5
Endosulfan	0.01	40	30
Maldison	0.07	100	50
Trifluralin	0.1	500	50
Thiobencarb	1	40	30
Atrazine	2		20
Molinate	2.5	1	5
2,4-D	4	100	30
Metolachlor	8	800	300
Diuron	8	40	30
Simazine	10		20
Glyphosate	65	200	1000
Bensulfuron-methyl	100		
MCPA	232		
Bromacil	750	600	300

Methodology. Pesticide monitoring by chemical analysis is extremely expensive. Identification and detection limits have been improved with the development of new less expensive GC-MS equipment, but many herbicides and some insecticides require quite sophisticated derivatisation pretreatment and concentration before analysis.

For a few compounds rapid cheaper tests are available commercially. These are based on general enzyme effects such as cholinesterase inhibition by organophosphorus pesticides, or on more specific tests based on enzyme-linked immunoassay methods which are developed through a mechanism based on the formation of antibodies to a pesticide antigen in mammalian blood. Commercial kits are already available for triazines, aldicarb, 2,4-D, carbofuran, cyclodienes, alachlor, benomyl and molinate in water; and new assays are being developed by CSIRO and commercial partners for chlorpyrifos-ethyl, diuron, endosulfan, benzoyl phenylureas, pyrethroids and other compounds (Skerritt, pers. comm.). The main advantages of immunoassays are the relatively low cost (typically \$20–30 per test) and the fact that they can be carried out in the field semi-quantitatively. They could be used by water managers who need to decide when run-off or stored water is safe for release to river systems.

Other methods include laboratory-based ecotoxicological testing in which a selected organism such as *Ceriodaphnia* is used to integrate the toxicity of mixtures of compounds (e.g. Korth *et al.* 1995*b*).

However, the ultimate test of the effects of pesticides on aquatic ecology must be ecological health, which can only be assessed by biomonitoring and biosurvey. Various biological methods have been discussed in Section 2, but there have been very few reports in which pesticide pollution has been specifically linked to biological response. Arthington *et al.* (1993) has been attempting to resolve the relationship between biological community response and exposure by using artificial streams dosed with chlorpyrifos. In other studies in the Murrumbidgee Irrigation Areas, biosurvey methods in irrigation drains and in wetlands receiving contaminated drainage water are being related to chemical analysis of a suite of 30 pesticides (Napier and Fairweather 1998; G. Napier, pers. comm. 1998).

Technical solutions

Interception and recycling. Strategies for the protection of surface waters which have been suggested or trialled in Australia include the use of buffer strips, riparian vegetation and wetlands. In reviewing the subject for the cotton industry, Bowmer (1993*a*) suggested that for short-lived and volatile cotton pesticides, processes of volatilisation, photodecomposition and chemical hydrolysis may usefully reduce contamination during retention in on-farm storages. Irrigation water reuse and recycling on the farm is also being actively explored and developed as described in several Land and Water Management Plans (e.g. Coleambally LWMP 1996; Parmenter 1996; MIA LWMP 1997).

Conservation farming and minimum or no-tillage methods have great potential to reduce both particle and contaminant runoff to surface waters (Cornish and Pratley 1987; Walker and Hargreaves 1994).

Reduction in pesticide use. The breeding of pest-resistant crops is one of the most important recent developments in Australia and internationally. For example, the Bt gene in cotton has reduced insecticide use in transgenic varieties by about 80% in Australia. The commercialisation of transgenic crops including risk, benefit and trade considerations has recently been reviewed (McLean *et al.* 1997).

Precision farming is another technique of great potential. Spatial variability in weed distribution and crop condition can be detected by airborne video methods and located by the use of global positioning systems. These techniques permit restricted spraying triggered by the presence of weeds or pests. Savings of up to 70% of herbicides in broadacre cropping are anticipated (Louis *et al.* 1995).

Legislation reforms also reflect a growing international trend for more stringent approval processes and national targets for reduction in use. Recent changes in international crop protection strategies have been reviewed by Rowland (1996) and OECD (1998).

Improved application and formulation technologies continue to reduce pesticide drift, volatilisation and overspraying; and decision support systems are being developed to optimise the timing of spray application with pest or disease development. For example, AUSVIT® has recently been released by the Cooperative Research Centre for Viticulture, mainly for control of fungal diseases in grapevines.

Biological methods such as insect predators continue to be developed by CSIRO, State Agencies, Universities and Cooperative Research Centres, notably the CRC for Weed Management Systems. Outstanding successes include the introduction of biological control agents for the management of introduced aquatic weeds, alligator weed (*Alternanthera philoxeroides*) and water hyacinth (*Eichhornia crassipes*). However, many potential agents remain experimental because of the expense of development and testing and poor commercial returns. Examples include the use of mycoherbicides to control saffron thistle in pastures and starfruit in rice (N. Crump, pers. comm.).

Other types of biological methods include the enhancement of natural protectants such as the antifungal stilbene compounds in grape berries. Canopy management increases their synthesis by exposing the grapes to sunlight (C. Steele, pers. comm.). Natural weed control can be achieved by appropriate rotation of crops (allelopathy) or by transgenic introduction of allelopathic potential into crops (e.g. An *et al.* 1996).

Organic farming methods, which avoid pesticides, are increasing in Australia, with advantages both in reducing the environmental load of pesticides and of guaranteeing a 'clean, green' pesticide-free food product. However, as pointed out by Dumaresq and Greene (1996) in a recent review, potential costs include reduced yields, excessive tillage and more intensive land use.

Underpinning most of these potential solutions is the concept of integrated pest management (IPM), the practice of using management systems for pathogens, insects, nematodes and weeds which do not rely solely on chemicals but place increasing emphasis on biological methods. Decision making is based on a scientific knowledge of pest population dynamics, the economics of cropping systems, and the potential for environmental impact. Education and training is a critical feature of IPM. For example, the FARMCARE Australia Farm Chemical User Training Program has now trained over 80 000 people and is an integral part of a range of industry quality assurance programs (J. Kent, pers. comm.).

Water for the environment ('environmental flow')

Deterioration in river ecology

Several lines of evidence demonstrate a deterioration in the status of riverine ecology. These include loss of biodiversity, replacement of native species by exotic plants and animals, loss or degradation of habitat including native forests and wetlands, an increasing incidence of algal blooms and deterioration of water quality to an extent that impacts on its utility for irrigation and drinking. The large decline in native fisheries has been surveyed recently by the CRC for Freshwater Ecology and NSW Department of Fisheries (1998) and by the Australian Conservation Foundation (Fisher 1996). All of these conditions together might be called the state of river health (CEPA 1992).

As already discussed, monitoring river health is now a priority issue for Australia. Unfortunately, quantitative data beyond the last few years are sparse, yet long-term records are critical because they describe gradual changes which have occurred over many decades. There are exceptions, such as the collection of anecdotes through an oral history of the Lachlan Valley where development began over a century ago (Roberts and Sainty 1996). Records of turbidity for the

Murrumbidgee River, which stretch back over more than 50 years, also throw light on cyclic changes in water quality lasting several decades (Olley *et al.* 1996).

More water for the environment

As described above ('Ecosystem response and indicators of health' and Fig. 1), ecosystem integrity or river health is affected by a range of factors of which flow regime is only one, so it would be over-simplistic to propose a simple relationship between bulk water availability and river health, or to expect to see improvements in water quality simply by returning a greater quantity of water to the rivers. For example, damage to riparian vegetation and floodplain wetlands by trampling stock (Robertson 1997), and sediment disturbance by carp (Robertson *et al.* 1997) may have profound impacts which are unrelated to direct effects of river flow.

Further, the volume or quantity of water is not the only appropriate measure from an ecological perspective. The variability in flow patterns and frequency of flooding and drying are important; and these must be related to local conditions of geography and ecology, since river form, including banks and levees, will determine frequency of overtopping and therefore patterns of floodplain watering and drying.

In spite of these reservations, most aquatic ecologists agree that flow regulation by impoundment and weir pools and diversion of water to irrigation are the major driving forces in deterioration of river ecology. The effect of catchment clearing in changing the water balance of the landscape is also a major factor having impact on flow regime and salinisation, but is less amenable to management.

Technical solutions

All Australian Governments are now committed to reform the management of our rivers and all States are involved in developing a range of strategies for water reform. In Queensland, proposed Water Allocation Management Plans for each catchment will define shares of natural flows or reserves. Victoria has, since 1989, provided for the separation of water property rights from land title and most explicitly recognises the environment as a legitimate user of water. In South Australia the Water Resources Act provides broad guidance, but does not require water allocations for environmental purposes specifically; however, an investigation of flow options for environmental benefit, particularly for the conservation of wetlands and flood plains, has been undertaken. In New South Wales, important policies which influence the provision of water for the environment include the State Rivers and Estuaries Policy, the Environmental Flows Strategy and Land and Water Management Plans being developed for irrigation areas and districts. The subject has been reviewed by Young *et al.* (1995) as a prelude to developing a computer-based decision support system for environmental flows.

In the Murray–Darling Basin, an audit of water use (MDBMC 1995) preceded the development of a water cap (MDBMC 1996), which introduced a moratorium on further diversions, benchmarked at levels of development in 1993–94. Superimposed on the restriction of water diversion resulting from the cap, the Government of New South Wales has announced a water reform package which includes establishing interim river flow objectives for each river with a limit of 10% reduction in average long-term diversions to users as defined by the 1993–94 benchmark (EPA 1997). The opportunity to trade water rights within and across river valleys has also been introduced (NSW DLWC 1998).

The cost to some water users is high. For example, the rice industry estimates that the proposed flow rules for the Murrumbidgee could result, in an extreme year, in a 25% reduction in water available, loss of at least $53 million in export income, 280 jobs, and further uncosted long-term losses in export markets (RGC 1997). Consequently, the meaning and assessment of river health and the benefits to be obtained by revised imposition of environmental flow rules are being hotly debated at present.

4 OVERVIEW OF IMPACT CLASSIFIED BY CROPPING SYSTEMS OR REGIONS

The previous discussion in terms of relative risks and impacts imposed by a range of cropping systems and land uses is summarised in Table 2. Relative importance is derived from an intuitive combination of the severity and extent of the problem together with an assessment of the prospects and costs of remediation.

Overall, the most important issue for freshwater ecology is undoubtedly the damage caused by impoundment and diversion of water for irrigated crops, particularly cotton, rice, irrigated pasture, horticulture and grain crops for animal feeding in intensive rural industry.

For marine and coastal waters the combination of grazing, application of fertiliser, and high intensity storms creates exports of nitrogen, phosphorus and sediments, which are increased several-fold over those expected prior to settlement (Moss *et al.* 1992). The Burdekin–Haughton, North-East Cape York and Fitzroy catchments give highest estimated exports. Substantial exports of nutrients were also linked to grazing in the Hawkesbury–Nepean catchment (Marston 1993).

Broadacre farming is listed as having an impact on flow regime through its effect on changes to the hydrological cycle, which is reflected also in the high risk ranking under surface water utility for salinity.

Cotton is given a moderately high rating for pesticide impact on water utility, reflecting concerns about the wide-ranging use of pesticides and recent concerns about sublethal effects on human health, including hormone balance. It has an even higher risk ranking for aquatic ecology, reflecting the sensitivity of fish and other aquatic life to endosulfan and chlorpyrifos. The risk from cotton pesticides to surface water also reflects the difficulty of managing storm flow in the high intensity rainfall areas of Northern New South Wales and Queensland.

In contrast, drainage water from rice is either recycled regionally or diluted substantially before it returns to major river stems. Insecticide use is relatively smaller, with the herbicide molinate dominating as a concern for drinking water quality.

Table 2. Risks to water utility and aquatic ecology: a summary. The number of crosses reflects the relative importance of impacts of cropping systems on water utility or aquatic ecology with subheadings describing impacts caused by salinity, nutrients, pesticides and changes in flow regime (see text).

	Water Utility						Aquatic Ecology		
	Surface water			Ground water					
	Salt	Nut.	Pest.	Salt	Nut.	Pest.	Nut.	Pest.	Flow
Cotton		+	++				+	+++	++++
Rice	+		++				+	++	++++
Sugarcane							+++	++	+
Irrigated pasture and intensive rural industry			+		+++				++
Viticulture			+						++
Horticulture (other)			+		+	+			++
Forestry			+		+	+	+	+	
Broadacre	+++	+	+		+	+			++

Sugarcane is listed as a risk to aquatic ecology to reflect emerging concerns about impact of suspended sediment, nutrient and pesticides on coastal regions and natural heritage areas such as the Great Barrier Reef.

Forestry has a potential impact on groundwater pollution with pesticides, particularly atrazine; and studies in Tasmania suggest that atrazine and pesticides in runoff may have an impact on riverine aquatic ecology. In terms of nutrient export, a study of the Murray–Darling Basin showed that although phosphorus loads from forestry in the rim of the Basin dominated the nutrient balance in Basin waters, concentrations (as opposed to loads) were low. This is reflected in the low risk ranking assigned to forestry impact on aquatic ecology.

A major risk from intensively irrigated pastures and intensive rural industries is pollution of groundwaters with nitrate, especially on a local scale. This subject was reviewed by Bowmer and Laut (1992).

5 THE CHALLENGE FOR AGRICULTURE

Who should pay the cost?

Cost sharing. Recent trends in natural resource and river basin management reflect a change in balance to increase the share of costs paid by the polluter relative to the beneficiary.

However, the methodology for valuing environmental benefit is still being developed, and the high degree of uncertainty in assessing river health has been already described. Consequently, the application of polluter-pays principles might be more feasible than an assessment of benefits from river health in some circumstances. However, some pollutant monitoring is extremely expensive and needs to be frequent to detect the impact of storm runoff. Also, the links between chemical analysis and environmental impact are often extremely complex or tenuous, as described earlier.

Natural resource managers are asking to what extent public investment in private land or on-farm activities is justified to bring about downstream public benefits, and the extent to which public investment should be targeted and focused in the landscape. Examples include recharge management using tree planting or location of wetlands for pollutant interception, or protection of vulnerable groundwaters from pollution through controlling overlying land use and agricultural practices.

Strategies and incentives are also required to prevent pollution, rather than to partition up the costs after it has occurred. Prevention is particularly important in groundwater protection where remediation may be expensive or irreversible, and where cause and effect may be centuries apart.

Levies or taxes on producer. Another approach is the possibility of imposing specific levies or taxes on commodities such as food and wine or products such as cotton. The principle was proposed by Meyer (1997) in the context of transferring some of the costs of environmental protection and improved water use efficiency to consumers, but his proposal was firmly rejected by the agricultural sector and commodity groups. They fear the effect of price rises on competition from cheap imports, and complain that their tax contributions are already too high.

Water as an economic good. A central plank of the water reform process in Australia is the separation of land and water rights, allowing trading of water by individual farmers with the basic aim of re-allocating water to higher value use for the economic benefit of both the seller and the purchaser. Briscoe (1997), in a review of international experience on the practice of treating water as an economic good, gives several examples where the aim has been achieved with environmental benefit. They include the transfer of water from low value fodder and food grain crops to high value fruit, vegetable and nut agriculture in California; and from badly salinised mixed farming land to higher value dairying and horticultural areas in Victoria. However, in confirming the approach as useful and practical, there is a need to take account of externalities generated. That is, in transferring water from one location to another, irrigation drainage containing salt, pesticides and nutrients may be generated and threaten third party interests downstream. In Australia this problem is being anticipated by the requirement before transfer for approved farm plans which include adequate drainage management.

The environmental imperative: the challenge for agriculture

Recurrent themes in considering the relationship between agriculture and water are the needs to explore the meaning of healthy rivers and catchments, and to understand the complex interaction between water quality and water quantity. To progress these issues, models of community partnerships seem to be emerging in Australia. These involve 'bottom up' consultative processes to respond to government initiatives ('top-down control').

As noted in an international overview on catchment governance for sustainability (Dorcey 1995), there is increasing consensus that environmental, economic and social sustainability ('the three legs of a stool') must be considered together, and that in the long term environmental goals should take priority. Although past approaches to catchment management have increasingly considered utilitarian values, sustainability approaches are now also being conditioned much more strongly by ethical concerns and judgements. Concerns about local or industry-specific issues are expanding into global consideration of ecological integrity and compassion for present and future generations. Such ethical choices cannot be resolved by cost–benefit analysis but only by deliberation among all stakeholders and their representatives.

Over the last two decades, theoretical and empirical research has altered preconceptions of ecosystem dynamics; and particularly in Australian aquatic ecology the importance of maintaining natural variability has been recognised. The challenges for agriculturalists, along with other stakeholders, are to cope with this complexity, to expect uncertainty and to base management strategies on knowledge about the fragility or resistance of the ecosystem being affected. As described in several examples above, the complexity of the issues results in the science being highly incomplete, and the future to a large extent unpredictable. To make decisions and develop policy requires new approaches to learning and management and has led to the concept of adaptive environmental assessment and management (AEAM).

A key to the success of AEAM in practice is the bringing together of diverse interests and expertise to develop consensus and commitment. In Australia the framework and opportunity is provided by the National Landcare program, a nation-wide network of about 2500 community landcare groups involving representatives of around 30% of commercial farming operations in Australia (Lockie and Vanclay 1997). However, Vanclay (1997) warns that in spite of the apparent success of the movement there is a tension between the professed bottom-up ideology of Landcare and the bureaucratic top-down control exerted by agencies over its functions and corporate identity. He argues that since farmer representatives are seldom in the majority on any committee, they are easily marginalised. Another major concern is that the farmer representatives are seldom representative of all farming styles, since they are often chosen not because they are farmers but because of their corporate experience. So there is a need to develop effective representational skills and processes in order to have influence and credibility in community forums.

These days, agriculture includes not only farmers of diverse backgrounds and interests but also policy-makers, educators, corporate water managers and representatives of commercial companies associated with water and pesticide distribution. There is also a realisation that viable agricultural and rural communities are critically dependent on the provision of services in education, transport, health and commerce. A holistic view of agriculture, community and environment and development of knowledge and representational skills are now becoming increasingly important in meeting the challenge of achieving sustainability.

REFERENCES

An, M., Pratley, J.E., and Haig, T. (1996). Differential phytotoxicity between *Vulpia* plant parts. *Allelopathy Journal* **3**(2):

ANCA (1993). *A directory of important wetlands in Australia. National compilation*, S. Ubach and R. James, (eds), Australian Nature Conservation Agency.

ANZECC (1992). *Australian water quality guidelines for fresh and marine water: 2. Protection of aquatic ecosystems.* National water quality management strategy, November, 1992.

Arthington, A. (1994). State of the rivers flowing through the areas of irrigated cotton within New South Wales including the Border Rivers shared with Queensland, LWRRDC, June 1994.

Arthington, A.H., Pusey, B., and Ward, S.M. (1993). *Indicator systems to monitor pesticide contamination in streams using community structure and function.* Final Report, Land and Water Resources R&D Corporation Project GRU 1.

Arthington, A.H., Marshall, J.C., Rayment, G.E., Hunter, H.M., and Bunn, S.E. (1997). Potential impact of sugarcane production on riparian and freshwater environments, In: Keating, B.A., and Wilson, J.K. (eds), *Intensive sugarcane production: meeting the challenges beyond 2000*, pp. 403–21. CAB International, Wallingford, UK.

Bales, M., and Royal, M. (1994). *Central and North Western Regions Water Quality Program 1992/93 Report on Biological Monitoring*, NSW Department of Water Resources, April 1994, TS 94.08.

Banens, R.J., and Davis, J.R. (1998). Comprehensive approaches to eutrophication management: the Australian example. *Water, Science and Technology* **37**(3): 217–25.

Blackmore, D. (1997). In: Doyle, R. (ed.), *Rural Australia Towards 2000 conference*, pp. 11–13. Centre for Rural Social Research, Charles Sturt University, Wagga Wagga,.

Blackmore, D (1998). The cost of salt. *Water* (Journal Australian Water and Wastewater Association): **25**(1) pp. 3.

Blackmore, D.J., Keyworth, S.W., Lynn, F.L., and Powell, J.R. (1995). The Murray–Darling Basin initiative: a case-study in integrated catchment management, In: *Sustaining the agricultural resource base*, pp. 61–80. Prime Minister's Science and Engineering Council. AGPS, Canberra.

Boon, P.I., and Bunn, S.E. (1994). Consumption of cyanobacteria by freshwater zooplankton: implications for the success of 'top-down' control of cyanobacterial blooms in Australia, *Australian Journal of Marine and Freshwater Research* **45:** 875–887.

Boon, P., Frankenberg, J., Hillman, T., Oliver, R., and Shiel, R. (1990). Billabongs. In: *The Murray*, pp. 183–200. Murray–Darling Basin Commission, Canberra.

Bowmer, K.H. (1987). *Herbicides in surface water.* In: Hutson, D.H., and Roberts, T.R. (eds), *Herbicides — Progress in Pesticide Biochemistry and Toxicology*, Vol. 6, pp. 270–355. Wiley & Sons Ltd, Chichester.

Bowmer, K.H. (1993a). Eliminating on-farm contamination. *The Ausralian Cottongrower* **14**(2): 44–47.

Bowmer, K.H. (1993b). Environmental impacts of irrigation on the riverine aquatic environment and water quality downstream, In: *The future of irrigation in the Murray-Darling Basin.* Symposium proceedings, Griffith, NSW, 10–12 August 1993. Australian Irrigation Council, Australian Society of Soil Science, CSIRO Division of Water Resources and Charles Sturt University.

Bowmer, K.H. (1993c). *Wetlands in urban water systems — fashionable or feasible?* CSIRO Division of Water Resources Technical Memorandum No. 93/12.

Bowmer, K.H., and Korth, W. (1994). *River pollution with agricultural chemicals*, final report, LWRRDC Research Support Grant No. CWN5 (89/14).

Bowmer, K.H., and Laut, P. (1992) Wastewater management and resource recovery in intensive rural industries in Australia. *Water Research* **26**: 201–8.

Bowmer, K.H., and Weerts, P.G. (1987). On-farm recycling and herbicide residues. Australian Water Resources Council Research Project 84/163 final report, June 1987.

Bowmer, K.H., Boon, P., Brock, M., Cheng, D., Gehrke, P., Matveev, V., and Shiel, R. (1993). Instream biological processes, In: Technical Advisory Group Report, *Algal Management Strategy*, pp. 91–102. Murray–Darling Basin Commission and Land & Water Resources Research & Development Corporation.

Bowmer, K.H., Korth, W., Thomas, M., and McCorkelle, G. (1994). *River pollution with agricultural chemicals*, Murrumbidgee River Research Forum, Griffith 8 April 1992, Roberts, J. and Oliver, R.L. (eds), pp. 7–19. CSIRO Division of Water Resources.

Bowmer, K.H., Korth, W., Scott, A., Thomas, M., and McCorkelle, G. (1995). *Agricultural pesticides in the irrigation areas of south-western NSW,* CSIRO Division of Water Resources, Griffith, NSW, Consultancy Report No. 95/18.

Bowmer, K.H., Fairweather, P.G., Napier, G.M., and Scott, A.C. (1996). *Biological impact of cotton pesticides*, Land & Water Resources R&D Corporation, Canberra.

Briscoe, J. (1997) Economic growth. *Water Quality International*, Sep/Oct 1997: 12–15.

Brock, M.A., Boon, P.I., and Grant, A. (eds) (1994). *Plants and processes in wetlands. Australian Journal of Marine and Freshwater Research* **45**(8).

Brooks, A., Westhorpe, D., and Bales, M. (1996). *The impact of pesticides on riverine environments. Subcatchment biomonitoring study.* Report on biological monitoring during 1994/5 cotton growing season along a section of the lower Macquarie River, Water Quality Services Unit, TS96.003, January 1996, NSW Department of Land and Water Conservation.

Bunn, S.E. (1995). Biological monitoring of water quality in Australia: workshop summary and future directions. *Australain Journal of Ecology* **20**: 220–227.

Bunn, S.E., and Boon, P.I. (1993). What sources of organic carbon drive food webs in billabongs? A study based on stable isotope analysis. *Oecologia* **96**: 85–94.

CEPA (1992). *Towards healthier rivers.* Commonwealth Environment Protection Agency, Canberra.

Chambers, L., Olley, J., Crockford, H., and Murray, A. (1997). Conditions affecting the availability and release of phosphorus from sediments in the Maude Weir Pool on the Murrumbidgee River, New South Wales, In: Davis, J.R. (ed.), *Managing Algal Blooms*, pp. 41–50. CSIRO Land and Water, Canberra.

Clarke, G.M., Arthington, A.H., and Pusey, B.J. (1994). Fluctuating asymmetry of Chironomid larvae as an indicator of pesticide contamination in freshwater environments, In: *Proc. 4th Internat. Conf. Chironomidae*, pp. 101–109. CSIRO, Australia.

Coleambally Draft Land and Water Management Plan (1996). District Summary, 28 pp.

Cooper, B. (1996). Central and North-west regions water quality program 1995/6 report on pesticide monitoring, NSW Department of Land and Conservation, TS 96.048.

Cooper, B., Jones, G., Burch, M., and Davis, R. (1996). Agricultural chemicals and algal toxins — emerging water quality issues, In: Prime Minister's Science and Engineering Council, pp. 89–107. AGPS, Canberra.

Cornish, P.S., and Pratley, J.E. (1987). *Tillage — new directions in Australian agriculture*, Inkata Press, Melbourne.

Cranston, P.S., Fairweather, P., and Clarke, G. (1996). Biological indicators of water quality, In: Walker, J., and Reuter, D.J. (eds), *Indicators of catchment health: a technical perspective* , pp. 143–154. CSIRO, Australia.

CRC for Freshwater Ecology/NSW Fisheries (1998). *Rivers and fish in stress: the NSW Rivers survey:* 6. URL: http://lake.canberra.edu.au/crcfe/ and
URL: http://www.fisheries.nsw.gov.au.

Cuddy, S., Young, Bill, Davis, R., and Farley, T. (1997). Trialing the catchment management support system in the Murrumbidgee Catchment, New South Wales, In: *Managing algal blooms*, pp. 103–13. CSIRO Land and Water, Canberra.

Cullen, P., and Bowmer, K.H. (1995). Agriculture, water quality and algal blooms, In: *Sustaining the agricultural resource base*, pp. 18-30. A paper prepared by an independent working group for consideration by the Prime Minister's Science and Engineering Council at its 12th meeting, 23 June 1995, Office of the Chief Scientist, Department of the Prime Minister and Cabinet, Canberra.

Davies, P.E., Cook, L.S.J., and Barton, J.L. (1994). Triazine herbicide contamination of Tasmanian streams: sources, concentrations and effects on biota. *Australian Journal of Marine and Freshwater Research* **45**: 209–226.

Davis, J.R. (1977). The CSIRO multi-divisional blue-green algal program — outcomes and successes, In: *Managing algal blooms* pp. vii–ix. CSIRO Land and Water, Canberra.

Davis, J.R., Farley, T.F.N., Young, W.J., and Cuddy, S.M. (1998). The experience of using a decision support system for nutrient management in Australia, *Water Science and Technology* **37**: 209–216.

DCNR (1995). *Development of an index of stream condition.* Department of Conservation and Natural Resources Waterways Unit, Melbourne.

Dils, R.M., and Heathwaite, A.L. (1998). Development of an iron oxide-impregnated paper strip technique for the determination of bioavailable phosphorus in runoff, *Water Research* **32**: 1429–1436.

Dorcey, A.H.J. (1995). *Catchment governance for sustainability: collaborating to put principles into practice.* Keynote paper for total catchment management: adaptive management and community decision making, ANZAAS, 1995, Newcastle, NSW, 25–27 September 1995, Working Draft: 32pp. The Institute for Community and Regional Planning, University of British Columbia, Vancouver.

Driver, P.D., Harris, J.H., Norris, R.H., and Close, G.P. (1997). The role of the natural environment and human impacts in determining biomass densities of common carp in New South Wales rivers, In: Harris, J.H., and Gehrke, P.C. (eds), *Fish and Rivers in Stress*, pp. 225–250. NSW Resource and Assessment Council.

Dumaresq, D.C., and Greene, R.S.B. (1996). Major reviews of industry, In: *Organic Agriculture in Australia*, pp. 95–109. Rural Industries R&D Corporation, Paper No. 97/14.

EPA (1982). Pilot survey of pesticide levels in water and sediments of streams in agricultural catchments. EPA Victoria Publication No. 142, pp. 1–38.

EPA (1997). *Proposed interim environmental objectives for NSW waters: inland rivers.* Environmental Protection Agency, Chatswood, NSW.

Evans, G.N. (1971). On the water and salt balance of the Murrumbidgee Irrigation Areas, In: *Conference on current work in irrigation research.* Advisory and Services Committee, CSIRO Griffith, August 1971.

Fairweather, P., and Napier, G. (1998). *Environmental indicators for national state of the environment reporting — waters, Australia: State of the Environment (Environmental Indicator Reports)*, Department of the Environment, Canberra.

Faragher, R.A., and Lintermans, M. (1997). Alien fish species from the New South Wales Rivers Survey, In: Harris, J.H., and Gehrke, P.C. (eds) *Fish and rivers in stress*, NSW Resource and Conservation Assessment Council: pp. 201–223.

Fisher, T. (1996). *Fish out of water.* Australian Conservation Foundation Special Habitat Supplement, October 1996.

Fitch, P., Skyring, G., and Bianting, S. (1997). Automatic remote monitoring of algal blooms, In: *Managing algal blooms*, pp. 89–101. CSIRO Land and Water, Canberra.

Gall, B. (1996). Information paper for the Wetlands and Migratory Wildlife Unit of the Australian Nature Conservation Agency.

Gehrke, P.C. (1993). Effects of flooding on native fish and water quality in the Murrumbidgee River, In: Roberts, J., Oliver, R.L. (eds), *Murrumbidgee River Research Forum.* Griffith, 8 April 1992, CSIRO Division of Water Resources.

Gutteridge Haskins and Davey (1992). *An investigation of nutrient pollution in the Murray–Darling River system.* Report prepared for the Murray–Darling Basin Commission, Canberra, January 1992.

Hamblin, A., and Williams, J. (1995). Soils: key issues in sustaining the land resource base, In: *Sustaining the agricultural resource base*, pp. 31–39. Prime Minister's Science and Engineering Council, AGPS, Canberra.

Harris, G.P. (1994). *Nutrient loadings and algal blooms in Australian waters — a discussion paper*, Occasional Paper No 12/94, Land and Water Resources Research and Development Corporation, Canberra.

Harris, J.H., and Gehrke, P.C. (eds) (1997). *Fish and rivers in stress: The NSW rivers survey.* NSW Fisheries Office of Conservation; Cooperative Research Centre for Freshwater Ecology; NSW Resource and Conservation Assessment Council.

Harris, J.H., and Silveira, R. (1997). Assessing the condition of rivers in New South Wales, Australia: a test of the index of biotic integrity, In: Harris, J.H., and Gehrke, P.C. (eds), *Fish and rivers in stress*, pp. 133–168. NSW Resource and Conservation Assessment Council.

Harrison, J. (1993). *Review of nutrients in irrigation drainage in the Murray–Darling Basin.* CSIRO Division of Water Resources, Griffith Series No. 11, pp. 1–149.

Hart, B.T., Royle, R., Poulson, S., and Morris, S. (1992). *Integrated catchment and reservoir management: Candowie and Lance Creek Reservoirs.* Water Studies Centre, Monash University, Melbourne.

Hart, B.T., Maher, W., and Lawrence, I. (1998). New risk-based water quality guidelines, *Journal Australian Water and Wastewater Association* **25**(3): 24–5.

IAWQ (1994). *4th International Conference on Wetland Systems for Water Pollution Control Proceedings*, 6–10 November 1994, Guangzhou, Peoples Republic of China. International Association on Water Quality.

IREC (1984). *Irrigation agriculture in the Riverina* (Text of speech to Ricegrowers' Association of Australia, 14 June 1984 by Mr Jack Hallam, Minister for Agriculture and Fisheries). Farmers' Newsletter Special Edition August 1984, Irrigation Research and Extension Committee, Griffith.

Jones, G. (1994*a*). Bloom-forming blue-green algae (*Cyanobacteria*), In: Sainty, G.R. (ed), *Waterplants in Australia.* 3rd edn, pp. 267–285. Sainty & Associates, Sydney.

Jones, G. (ed.) (1994b). Cyanobacterial Research in Australia. *Australian Journal of Marine and Freshwater Research* **45**(5):193.

Kennedy, I.R., Harris, C.R., Sánchez-Bayo, F., Kimber, S.W., Southan, S., Hugo, L., Caldwell, R.A., Shivaramaiah, H., Feng, L., Vanzwicken, L., Lee, W.J., Beasley, H., Wang, S., and Skerritt, J.H. (1997). Cotton pesticides in perspective, Volume 1, CRC for Sustainable Cotton Production and Department of Agricultural Chemistry and Soil Science, University of Sydney.

Kookana, R.S., Baskaran, S., and Naidu, R. (1998). Pesticide fate and behaviour in Australian soils in relation to contamination and management of soil and water: a review. *Australian Journal of Soil Research* **36**: 715–764.

Korth, W., Thomas, M., McCorkelle, G., and Foster, S. (1995a). Pesticide and toxicity testing of MIA drainage water. CSIRO Division of Water Resources, Griffith, NSW Consultancy Report No. 95/25.

Korth, W., Thomas, M., Foster, S., McCorkelle, G., and Bowmer, K.H. (1995b). Toxicity of rice and maize pesticides to Ceriodaphnia c.f. dubia: implications for management of irrigation drainage water in Australia, *Australian Journal of Ecotoxiclogy* **1**: 55–66.

Lamb, D.W., and Weedon, M. (in press). Evaluating the accuracy of mapping weeds in fallow fields using airborne digital imaging: a case study — Panicum effusum in oilseed rape stubble. *Weed Research.*

Lockie, S., and Vanclay, F. (eds) (1997). Critical Landcare. Key Papers Series, Number 5, Centre for Rural Social Research, Charles Sturt University, Wagga Wagga, NSW.

Louis, J.P., Lamb, D., McKenzie, G., Chapman, G., Edirisinghe, A., McLeod, I., and Pratley, J.E. (1995). Operational use and calibration of airborne video imagery for agricultural and environmental land management applications, In: Mausel, P.W. (ed.), Proceedings of 15th Biennial Conference on Colour Photography and Videography, in Resource Assessment Terre Haut Indiana, *American Journal of Photogrametry and Remote Sensing.*

LWRRDC (1993). *Ecotoxicology specialist workshop proceedings*, 1–2 March 1993, Wee Waa, Land & Water Resources R&D Corporation Occasional Paper No. 07/93.

LWRRDC (1997). *Annual report 1996–7.* Land and Water Resources Research and Development Corporation, Commonwealth of Australia (URL: www.lwrrdc.gov.au).

Maher, W., Moore, J., Liston, P., Cullen, P., and Wade, A. (1993). *Review of ACT water quality and environmental criteria.* ACT Planning Authority, Canberra.

Marston, F.M. (1993). Nutrient generation rates for land uses in the Hawkesbury–Nepean system. Consultancy Report 92/23, CSIRO Division of Water Resources, Canberra.

McLean, G.D., Waterhouse, P.M., Evans, G., and Gibbs, M.J. (eds) (1997). *Commercialisation of transgenic crops: risk, benefit and trade considerations.* Bureau of Resource Sciences, Kingston, ACT.

MDBC (1990). *Riparian vegetation of the River Murray.* Report prepared by Margules and Partners Pty. Ltd., P. & J. Smith, Ecological Consultants, Department of Conservation, Forests & Lands, and Murray–Darling Basin Commission, Canberra.

MDBC (1993a). *Technical advisory group algal management strategy.* Murray–Darling Basin Commission, Canberra.

MDBC (1993b). *Algal Management Strategy.* Murray–Darling Basin Commission, Canberra.

MDBMC (1988). *Salinity and drainage strategy.* Murray–Darling Basin Ministerial Council, January 1988.

MDBMC (1995). *An audit of water use in the Murray–Darling Basin*, Murray-Darling Basin Ministerial Council, June 1995.

MDBMC (1996). *Setting the cap: report of the independent audit group*, Murray–Darling Basin Ministerial Council, November 1996.

Meyer, W. (1997). Food for water: is Australia getting the best deal? *Univation: Innovation and Research in Australia's Universities*, AVCC, **12**(2): 5.

MIA (1997). Murrumbidgee Irrigation Areas and Districts Draft Land and Water Management Plan.

Moss, A.J. Rayment, G.E., Reilly, N., and Best, E.K. (1992). *Sediment and nutrient exports from Queensland coastal catchments, a desk study.* Department of Environment and Heritage and Department of Primary Industries, Queensland.

Mussarad, D. (1997). *Living on floodplains*, Cooperative Research Centre for Freshwater Ecology and Murray–Darling Basin Commission.

Napier, G.M. (1992). *Application of laboratory-derived data to natural aquatic ecosystems.* PhD Thesis, Macquarie University, Sydney.

Napier, G.M., and Fairweather, P.G. (1998). An approach to biomonitoring wetlands to assess impacts of agricultural drainage In: McComb, A.J., and Davis, J.A. (eds), *Wetlands for the future*, Proceedings of INTECOL's 5th International Wetlands Conference. Gleneagles Press, Adelaide (in press).

National Land and Water Resources Audit: Draft Strategic Plan — 1998 to 2001. Land and Water Resources Research & Development Corporation, Canberra.

NHMRC (1993). *Australian drinking water guidelines draft summary*, National Health and Medical Research Council, Agricultural and Research Management Council of Australia and New Zealand, Canberra.

Nowak, B., and Julli, M. (1991). Residues of endosulfan in wild fish from cotton growing areas in New South Wales. *Toxicological and Environmental Chemistry* **33**: 151–67.

Nowak, B., Clarke, G., Pettigrove, V., Hughes, J., and Madden, C. (1993). *Biological indicators and biomonitoring of water quality in agricultural areas*, In: Specialist workshop in ecotoxicology proceedings. Wee Waa, 1–2 March 1993, Land and Water R&D Corporation.

NRHP (1996). The National River Health Program. URL:
http://www.environment.gov.au/portfolio/epg/nrhp/NRHP.html

NSW DLWC (1998). *Water sharing in New South Wales – access and use.* A discussion paper, NSW Department of Land and Water Conservation, Sydney.

NSW DWR (1993). *Central and North Western Regions Water Quality Program 1991/92. Biomonitoring—provisional connections between landuse, irrigation and other environmental factors and the in-stream macroinvertebrate biota.* Report prepared for the Review Board, February 1993, New South Wales Department of Water Resources.

OECD (1998) Pesticide risk reduction, URL: http://www/oecd.org/ehs/pest_rr.html

Oliver, R.L. (1993). Phosphorus dynamics and bioavailability in turbid waters, In: *Proceedings of the national workshop on phosphorus in Australian freshwaters*, pp. 93–103. Charles Sturt University, Wagga Wagga, NSW, No 03/93.

Olley, J.M., Caitcheon, G., Donnelly, T.H., Olive, L.J., Murray, A.S., Short, D.L., Wallbrink, P.J., and Wasson, R.J. (1996). *Sources of suspended sediment and phosphorus to the Murrumbidgee River.* CSIRO, Division of Water Resources Consultancy Report No. 95/32.

Parmenter, M. (1996). Lowbidgee Land and Water Management Plan NRMS. NSW Department of Land and Water Conservation, Hay, 83 pp.

Pettigrove, V., Korth, W., Thomas, M., and Bowmer, K.H. (1995). The impact of pesticides used in rice agriculture on larval chironomid morphology, In: Cranston, P.S. (ed.), *Chironomids – from Genes to Ecosystems*, pp. 81–88. CSIRO Publishing, Melbourne.

PMSEC (1995). *Sustaining the agricultural resource base.* A paper prepared by an independent working group for consideration by the Prime Minister's Science and Engineering Council at its twelfth meeting, 23 June 1995. Office of the Chief Scientist, Department of the Prime Minister and Cabinet. AGPS, Canberra.

Power, M.E. (1992). Top-down and bottom-up forces in food webs: do plants have primacy? *Ecology*, **73**: 733–46.

Rayment, G.E., and Simpson, B.W. (1993). Pesticide audit for the Condamine–Balonne–Culgoa Catchment, In: Kenway, S.J. (ed.), *Water quality in the Condamine–Balonne–Culgoa catchment*, pp. 102–166. Condamine–Balonne Water Committee, Dalby, Queensland.

Rice Growers' Cooperative Limited (1997). *Preliminary impact assessment of proposed irrigation flow rules on rice industry*, 28 November 1997, Australian Consulting Partners, (Note part of this report is commercial in confidence).

Rippon, G.D., and Chapman, J.C. (1993). *Laboratory procedures for assessing effects of chemicals on aquatic animals*, In: Specialist workshop in ecotoxicology proceedings, Myall Vale Research Station, Wee Waa, 1–2 March 1993, Land and Water R&D Corporation Occasional Paper No. 07/93, pp. 40–52.

RIRDC (1997). *Research compendium 1997.* Rural Industries Research and Development Corporation, Canberra. URL: http://www.dpie.gov.au/rirdc

Roberts, J. (1992). *Water regime and wetland/riparian plants.* Final Report, AWRAC Project M86/09, June 1992, Australian Water Resources Advisory Council.

Roberts, J., and Sainty, G.R. (1996) *Listening to the Lachlan*, pp. 62–81. Sainty & Associates, Potts Point, Australia.

Robertson, A.I. (1997). Land–water linkages in the floodplain river systems: the influence of domestic stock, In: Klomp, N., and Lunt, I. (eds), *Frontiers in ecology*, pp. 207–218. Elsevier Science.

Robertson, A.I., Boon, P.I., Bunn, S., Ganf, G., Herzceg, A., Hillman, T., and Walker, K.F. (1996). *A scoping study into the role, importance, sources, transformation and cycling of carbon in the riverine environment*, Consultancy report to the Murray–Darling Basin Commission, Charles Sturt University, Wagga Wagga, (unpublished).

Robertson, A.I., Healey, M.R., and King, A.J. (1997). Experimental manipulations of the biomass of carp (*Cyprinus carpio*) in billabongs. 2. Impact on benthic properties and processes, *Australian Journal of Marine and Freshwater Research* **48**: 435–43.

Rowland, P. (1996). *Recent changes in international crop protection practices: the growing trend to reduce pesticide use and pesticide risk.* Bureau of Resource Sciences, Canberra.

Schofield, N.J. (1995). Minimising the impact of pesticides on the riverine environment, *Proceedings AWWA 16th Federal Convention*, Sydney, 2–6 April 1995, Vol 2: pp. 411–417.

SOE (1996). *State of the Environment Australia 1996*, CSIRO Publishing, Collingwood, Vic, pp. 1/1-10/30 + App.

Spencer, C., Robertson, A.I., Curtis, A. (in press). Development and testing of a rapid appraisal wetland condition index in South-eastern Australia, *Journal of Environmental Management.*

Thoma, K. (1988). *Pilot survey of pesticide residues in streams draining a horticultural catchment*, Piccadilly Valley, South Australia, SA Department of Agriculture, Technical paper No. 131.

Thompson, P.A. and Hosja, W. (1996). Temporal dynamics of nutrient limitation of phytoplankton from the Swan River estuary, W.A. *Australian Journal of Marine and Freshwater Research* **47:** 659–667.

USEPA (1988, 1989, 1991) *Methods for aquatic toxicity identification evaluations. Phase I, II and III* (3 volumes), United States Environment Protection Agency, EPA/600/3-88/034;035;036.

Vanclay, F. (1997). The social basis of environmental management in agriculture: a background for understanding Landcare. In: Lockie, S and Vanclay, F. (eds), *Critical Landcare*, pp. 9–27. Centre for Rural Social Research, Charles Sturt University, Wagga Wagga, NSW.

Walker, J., and Reuter, D.J. (1996). *Indicators of catchment health: a technical perspective.* CSIRO, Australia.

Walker, S.R., and Hargreaves, P.A. (1994). Herbicide management for herbicide residues in conservation cropping, Land & Water Resources R&D Corporation, Project No. QP/1, Final Report.

Webster, I., Jones, G., Oliver, R., Bormans, M., and Sherman, B. (1997) Control strategies for cyanobacterial blooms in weir pools, In: *Managing algal blooms*, pp. 31–40, CSIRO Land and Water, Canberra.

White, M.E. (1997) *Listen — our land is crying: Australia's environment: problems and solutions*. Kangaroo Press, Kenthurst, Australia.

Wood, M.D., and Oliver, R.L. (1995). Fluorescence transients in response to nutrient enrichment of nitrogen- and phosphorus-limited *Microcystis aeruginosa* cultures and natural phytoplankton populations: a measure of nutrient limitation, *Australian Journal of Plant Physiology* **22:** 331–40.

Young, W.J., Davis, J.R., Bowmer, K.H., and Fairweather, P.G. (1995). The feasibility of a decision support system for environmental flows. CSIRO Division of Water Resources. Final report to Murray–Darling Basin Commission, NRMS Project No. 5060.

PERSONAL COMMUNICATIONS

Crump, N. (1998) Charles Sturt University Farrer Centre, Wagga Wagga.

Kent, J. (1998), Charles Sturt University Farrer Centre, Wagga Wagga.

Napier, G. (1998) CSIRO Land and Water, Griffith Laboratory, Griffith, NSW. (unpublished manuscript).

Skerritt, J. (1998) CSIRO Division of Plant Industry, Canberra.

Steele, C. (1998) Charles Sturt University National Wine and Grape Industry Centre, Wagga Wagga.

Salt-Affected Soils: Their Cause, Management and Cost

Philip L. Eberbach

Damage to the productive capacity of soils by salts is a major form of land degradation in the winter dominant–high rainfall areas of southern Australia. Recent surveys suggest that at present, 2.5 million hectares of non-irrigated land are affected by salt, while approximately 360 000 hectares of irrigated land in the Murray–Darling Basin are salt-affected. Increases in salt in the root zone of irrigated crops and pastures have occurred by the over-application of irrigation water, or by the application of salt in irrigation water where insufficient leaching occurs. Conversely, dryland salting has occurred mainly as a result of clearing of native vegetation and its replacement by agricultural crops and pasture species, resulting in a net deficit of water use and an increase in groundwater recharge. Due to the cause of dryland salting, the amount of land affected is likely to increase with time.

Whereas the causes are well understood, the socio-political mechanisms to prevent salt damage or to restore salt-affected land are less clear. Farmers are frequently accused of causing salt problems and are then expected to pay. However, salting is also a community problem. Therefore this problem should be shared financially by the three major stake holders: government, consumers, and agricultural producers.